

**Site Classification for Seismic Hazard Assessment in
Low Seismicity Regions**

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the Doctor of Philosophy (PhD) degree
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Declaration

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Abstract

Probabilistic Seismic Hazard Assessment of low seismicity regions has significant uncertainty due to the limited catalogue of earthquake records. Part of this uncertainty relates to the modification of ground motions by near-surface geo-materials: site amplification. If the repeatable site amplification from strong ground motion stations (SGMS) is characterised, this uncertainty is reduced. Consequently, the uncertainty demands upon safety critical infrastructure can decrease, enhancing its resilience.

However, the characterisation of site amplification effects is complex. Effective parameters can be prohibitively expensive to measure, particularly if full shear-wave velocity (V_s) profiles are required for multiple sites. This thesis aims to investigate an economical method to characterise near-surface site amplification.

For 15 of the UK SGMS, geological models are developed and compared to the newly established Global V_s Database. The database is used to examine relationship of V_s with geological parameters. Relationships investigated include age and origin, but were only predominant in depth and grain size. A new Site Specific Proxy probabilistically correlates these characteristics with the geological profiles, making it possible to infer a probability distribution of a time averaged shear wave velocity (V_{s30}) for each site.

Horizontal to Vertical Spectral (HVSr) ratio testing is performed to verify these station models. This *in situ* method, though indeterminate, is economical and proved accurate when examined against verification testing. The HVSr testing results of the UK SGMS correlate well with the Site Specific proxy estimates, having a mean difference within 18%, which is a significant decrease from other proxy methods.

A method of Bayesian updating is developed for refining the V_{s30} profiles and shows that one *in situ* test is generally sufficient to halve the standard deviation of the Site Specific proxy method. Thus, the economical combination of the Site Specific proxy and HVSr testing is recommended for site characterisation in low seismicity regions.

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List of symbols and abbreviations

AOD	Above ordinance datum
b.g.l.	Below ground level
BGS	British Geological Survey
CPT	Cone Penetrometer Test
d	Depth
DEM	Digital elevation model
e	Void ratio
EAF	Empirical Amplification Functions
EC8	Eurocode 8 (2004)
FEMA	Federal of Emergency Management Agency
f_0	Fundamental frequency
f-k	Frequency wave number ambient noise array (Appendix 1)
G	Shear modulus
$G_{\max}$	Small strain shear modulus
GMPE	Ground Motion Prediction Equation
GSC	Geological Survey of Canada
h	Thickness of a soil layer
HE	Eastern horizontal Spectra for HVSR
HN	Northern horizontal Spectra for HVSR
HVSR	Horizontal/Vertical Spectral Ratio
H_{av}	Averaged horizontal spectra for HVSR
i	A number counter for a loop e.g. t_i is the thickness of the i^{th} layer
MASW	Multi-channel Analysis of Surface Waves
M	Earthquake magnitude (moment magnitude)
n	Sample size
N	Result from SPT (number of blows per 300mm)
NEHRP	National Earthquake Hazards Reduction Program
OCR	Over Consolidation Ratio

PEER	Pacific Earthquake Engineering Research Centre
PI	Plasticity index
PSHA	Probabilistic Seismic Hazard Assessment
Q	Attenuation
ReMi	Refraction Micro-tremor (Appendix 1)
SASW	Spectral Analysis of Surface Waves (Appendix 1)
SCPT	Seismic Cone Penetrometer Test
SGMS	Strong ground motion stations
SPAC	Spatial Autocorrelation (Appendix 1)
SPT	Standard Penetration Test
S_u	Undrained shear strength
V_p	Primary/p wave velocity
V_s	Shear wave velocity
V_{s30}	Time averaged shear wave velocity over the upper 30m (Equation 2.2)
V_{sz}	Time averaged shear wave velocity over the upper z m (V_{s10} over 10m)
UBC	Unified Building Code
USGS	United States Geological Survey
α_z	Impedance ratio
ρ	Density
σ'	Effective stress
γ	Shear strain

UK SGMS names: CAA1, ELSH, FOEL, GDLE, HPK, HTL, JDG, LBWR, LMK, MCH1, OLDB, SWN1, WACR, WLF1, WPS. (Please refer to Figure 1-2 or Station Appendix for station locations.)

CHAPTER 1

Introduction

Site amplification of seismic waves can have a significant effect on built structures. However, it is a challenging effect to characterise systematically. The descriptive parameters that are most effective in describing expected levels of site response are also expensive to measure. In particular, shear wave velocity (V_s) and damping profiles are known to contain important information about site response, but both are demanding to characterise. This challenge is substantial in regions of low seismicity, such as the UK, where expenditure on pre-emptive seismic design and analysis is harder to justify than in active regions. The aim of this research is to develop a geologically rigorous method to determine V_s profiles in areas with little data. This would enable a more cost effective, but reliable alternative to characterising site amplification in low seismicity regions.

1.1 Importance of site amplification

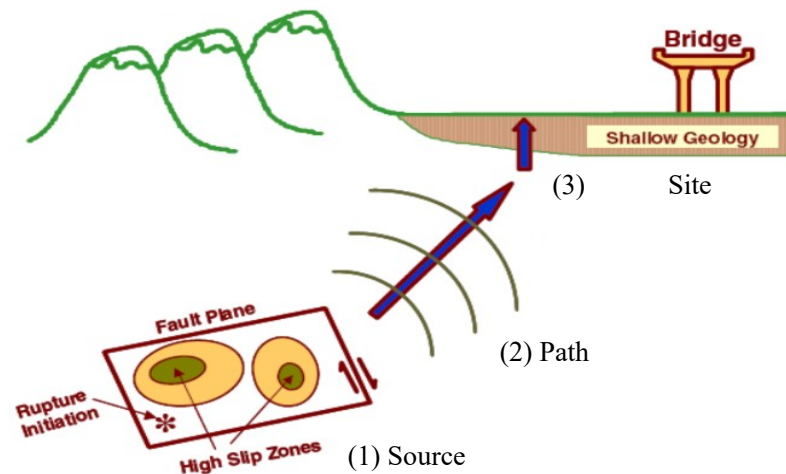


Figure 1-1: Contributions to ground-motions that are observed at the surface: (1) source with the rupture plane, (2) the path of the seismic waves to the site, (3) the effects of the shallow geology of the site (After Stewart *et al*, 2001).

The ground motions that arrive at the base a structure arise from processes that are often separated into three phases (Figure 1-1): the fault rupture mechanism at the source, the path of the wave

transmission to the site and the near-surface effect of the site itself or site effects (Bommer & Boore 2005). All three components are associated with significant levels of epistemic uncertainty and so all contribute to the overall uncertainty in the levels of shaking that should be expected at any given location.

In practice, the source rupture process is highly complex and can occur at significant depths. When combined with the difficulty of modelling the entire propagation path from source to site, this complexity dictates that epistemic uncertainties associated with source and path components are relatively difficult to reduce. In contrast, epistemic uncertainty associated with near-surface site effects can be reduced with direct investment into ground investigation, even if the cost of investigation is non-trivial. Therefore, in Probabilistic Site Hazard Assessment (PSHA), it is common for levels of ground-shaking to be predicted to the base of a site profile and for the uncertainty in source and path effects to be associated with that prediction (McGuire 2004). Subsequently, above this bedrock or reference velocity horizon, the site-specific site effects can be modelled and the uncertainty associated with this component can also be isolated. These site-specific effects are influenced by both geological and topographic features of the site in question (Kramer 1996).

The method to combine the uncertainty at bedrock level with that of the site effects to estimate the overall uncertainty at the ground surface is complex and still under development. Site response generally is accounted for in PSHA through the convolution of the rock hazard curve at the base of the soil profile and amplification curves developed in site amplification analysis (Pehlivan *et al.*, 2016).

The uncertainty associated with the V_s profile within site response analysis has been investigated EPRI (2012). The widespread method uses three base cases for V_s profiles: the mean expected profile; the 10th percentile (or lower bound) of uncertainty associated with the mean profile; and the 90th percentile (upper bound). These three base cases are used in numerical site response analysis to develop the amplification functions for the site. The amplification functions are then introduced into the PSHA logic tree assessment to be incorporated into the overall uncertainty of the shaking at ground level. However, the EPRI (2012) method has been criticised for breaking the principle that higher uncertainty should imply higher seismic hazard (Green *et al.*, 2016). It is also noted that the

amplification function is sensitive to the method of calculation (for example, whether from time history or random vibration theory, equivalent linear) and by levels of variability considered in the shear wave profile (Pehlivan *et al.*, 2016).

Site effects are known to manifest in at least four forms including site amplification, topographical amplification, basin effects and liquefaction (Kramer 1996). The focus of this research is the first: site amplification. This is the modification of ground shaking caused by changes in impedance and damping as waves propagate toward the ground surface. These changes are primarily associated with a reduction of the material stiffness (shear modulus, G) in the near surface (Kramer 1996). In some cases, impedance contrasts can result in an amplification of input motion amplitudes by a factor of more than twenty times (Chavez-Garcia 2007). In the M8.1 1985 Mexico City Earthquake, site amplification occurred at a notably large epicentral distance due to convolution with other factors, specifically the fundamental frequency of the earthquake and building stock (Campillo *et al.* 1989).

Conversely, the seismic waves can also be de-amplified by the near surface deposits depending on the frequency of the earthquake waves and the strength of the input motion. That is, when the input motions are sufficiently large to induce nonlinear response in the near-surface materials then the combination of degrading stiffness and hysteretic damping can cause motions to de-amplify (Kramer 1996).

However, site amplification is challenging to characterise due to three factors: the actual dynamic characteristics of a site can only be determined to a certain level of precision; these characteristics evolve overtime either by degradation in the long term or non-linearity during the earthquake; and the input excitation is inherently variable (Kramer 1996). Ground motion prediction equations (GMPEs) aim to characterise the effects of site response and have an essential role in hazard and risk analyses (Musson & Sargeant 2007). Thus, it is important to gain a better understanding of the site characteristics and their influence upon seismic waves to effectively account for them in design.

1.2 Site characterisation in low seismicity regions

While earthquakes occur with reduced frequency in low seismicity regions, when events do occur, the effects of site amplification are naturally governed by the same physical processes as in active regions. Significant site amplification has been inferred in smaller amplitude earthquakes such as the **M5** 1996 Annecy earthquake, France (Thouvenot *et al.* 1998). During this earthquake, Pleistocene lake deposits increased the surface shaking by approximately eight times the bedrock motion, causing damage amounting to approximately \$50 million (Thouvenot *et al.* 1998). Site amplification has also been indicated in **M4.0** 2007 Folkestone earthquake, in the UK, where the highly weathered chalk rock is thought to have formed a soft, amplifying layer over the region (Ottemöller *et al.* 2009). Despite the importance of these effects in low seismicity regions, site characteristics are often better known in moderate-to-high seismicity regions, because of a history of observation.

Generally, site amplification is measured through extensive, invasive testing which is effective, but highly expensive (Bard 1999). For seismically active regions, such as California and Japan, this type of investigation has proceeded over a number of years providing a detailed catalogue of *in situ* measurements, for example the NGA database (Chiou *et al.* 2008). These data are then used for the development of proxy methods that can be applied to obtain estimates for regions where there have not been previous investigations (Wills *et al.* 2000). However, in regions like Northern Europe and Canada where seismic hazard is much lower, the cost of undertaking a sufficiently detailed ground investigation over large and geologically varied regions is harder to justify from a short-term economic point of view.

Without these invasive measurements, intraplate regions have been left without a clear method to infer the necessary site characteristics to account for site amplification. Although proxy methods, used in active regions, can prove useful results over large regions for GMPEs (Wald & Allen 2007), for individual sites or smaller spatial regions they are generally imprecise and naturally cannot reflect the site-specific features of the location (Thompson & Wald 2015). Thus, there is concern about the quality of the assumptions being made during site characterisation as well as the amount of geotechnical site investigation that is appropriate (Lubkowski *et al.* 2004).

1.3 The UK strong ground motion network

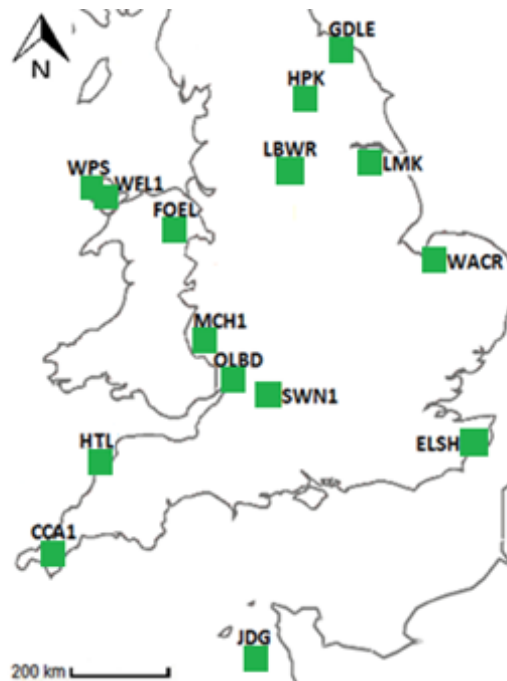


Figure 1-2: The locations of the 15 of the 24 UK strong ground motion stations considered in this study (Station Appendix).

A good example of this problem is the UK Strong Ground Motion Stations (SGMS). A total of 24 stations form the UK strong ground motion network (at the time of writing), 15 of which are considered in this study (Figure 1-2). The stations were installed from the 1970s onwards (Browitt 1991). The locations for the stations are often chosen to minimise anthropogenic noise and are, therefore, can be remote from concentrations of human population.

The stations are uncharacterised in terms of site response and little information is known about the ground on which they are situated except from geological maps (Laughlin 2014). The characterisation of the geology and shear wave profile at the stations will inform site response analysis. Thus, current models of the UK geological environment for input into GMPEs could be better constrained or validated, promoting reliable design of sensitive infrastructure *i.e.* nuclear facilities.

1.4 Aim and objectives

The research has a dual aim. The first is to create a geologically rigorous method to characterise a site for site amplification in areas with little data. The second will be to use this method to characterise the ground conditions under UK SGMS to determine detailed shear-wave velocity (V_s) profiles and the respective uncertainties.

Therefore, to complete this aim, the following objectives are developed:

- To review the current knowledge of performing site characterisation for site amplification.
- To develop a database of previously measured V_s profiles in the UK and similar environments worldwide to examine the controlling factors for V_s values for different geological units.
- To develop a method of determining V_s profiles for sites with little data.
- To trial this method on the UK SGMS and perform geotechnical site investigation on these sites to verify and calibrate the method.
- To improve the classification of uncertainty in the original method, having analysed the results from the investigation and the database.

1.5 Scope

The field work and analysis was performed over 3.5 years and, therefore, is limited by this time frame. Other limitations included the budget of £10 000 for any *in situ* testing, provided by grants and external funding, excluding CPT testing which was carried out in kind by In Situ Site Investigation. V_s profiles were specifically investigated. The research does not go beyond this to discuss the use of parameter derivatives of V_s velocity in GMPEs, PSHA or other methods. Practices and results from other nationalities are considered, specifically in the database, current practice and the fieldwork, but the focus of the research is the UK. Therefore, the main code used is the Eurocode 8 (EN 2004).

1.6 Outline of chapter contents

Chapter 2: Shear-wave velocity profiles and geological parameters

Initially parameters describing site amplification are reviewed, specifically the time-averaged shear-wave velocity over the top 30m of ground (V_{s30}) which is the primary method used worldwide. Previous studies of the relationship of V_s profiles and geology are also examined to determine any fundamental parameters linking them. The Global V_s Database is then presented and the data used to extend, it is outlined. The database is analysed to determine any controlling factors in the relationship between V_s velocity and geological parameters.

Chapter 3: Proxy methods for determining V_{s30}

A review of the current proxy methods for characterising site amplification is presented. This review focuses on use of parameters in the proxy methods and the current state of practice in intraplate regions, with a particular focus upon the UK. The new Site Specific proxy method, based on geological and engineering practice as well as the Global V_s Database, is outlined. The application of this method to a variety of situations is shown using 15 stations from the UK SGMS Network.

Chapter 4: *In situ* testing methods for V_s characterisation

In situ methods for determining V_s are outlined including invasive and non-invasive methods. These methods are assessed in terms of value to a ground investigation; the additional information the methods provide about a site; the usefulness of different methods to different geological situations; and a comparison with the cost of each method.

The methods used during the research are described. A specific consideration of the Nakamura (1989) Horizontal/Vertical Spectral Ratio (HVSr) method is given with relation to the passive seismic technique in microtremor measurement. The method is often used in combination with other techniques and has specific limitations. In order to be used as the predominant investigation method, it is validated.

HVSr have been performed in known environments and are compared with Multi-Channel Analysis

of Surface Waves (MASW) and Seismic Cone Penetrometer Test (SCPT). Its dependence on environmental conditions and the spacing of the measurement points are also discussed. Finally, its usefulness in an extreme and unknown environment such as in the Kathmandu Valley after the M7.8 2015 Gorkha earthquake is investigated.

Chapter 5: Testing results

The geotechnical testing performed at each UK SGSM is described. The results of the HVSR testing are examined and the final V_{s30} values are compared with the results of the newly developed proxy method as well as a simplified version of the topographical method.

Chapter 6: Application of Bayesian updating to site characterisation

An application of Bayesian updating is introduced into the newly developed proxy method. This is used to account for the uncertainty in the final estimate of the combined proxy method and geotechnical testing results. The measurement of V_s is often assumed to be completely correct which is a large assumption, given the inherently variable site conditions in the UK. Therefore, the impact of the uncertainty in the V_s can be accounted for in GMPEs.

Chapter 7: Conclusions

The final section contains a summary of each chapter and conclusions from the main results determined. In addition, possible further research that could be continued from this study is outlined.

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CHAPTER 2

Shear wave velocity profiles and geological parameters

2.1 Introduction

Numerous engineering applications make use of parameters to account for site amplification. These include the development of ground motion prediction equations (GMPEs), characterisation of site conditions at strong ground motion stations, evaluation of liquefaction resistance and microzonation studies. The most commonly used parameter to characterise site amplification is an index of the shear wave velocity (V_s) profile of a site. The shear-wave velocity for a particular medium is directly linked to its stiffness (shear modulus), G , and density, ρ , of the medium (Kramer 1996):

$$V_s = \sqrt{\frac{G}{\rho}} \quad [2.1]$$

However, only considering an average of the V_s velocity profile to represent stiffness over a site, in order to predict all features of site response is known to be a simplified and indirect approach (Borcherdt & Glassmoyer 1992). Site conditions are often complex and cannot to be defined fully by one parameter (Wald *et al.* 2011). Therefore, significant research is being carried out to determine superior or complementary parameters to improve estimates.

Yet, V_s profiles are rarely studied in conjunction with the geology they describe. It is generally assumed that V_s increases with depth (Kramer 1996), but beyond this little is known or can be assumed about the geological factors that control V_s as a proxy for stiffness of the material. Although, the compatibility of deposits between different regions are considered in GMPEs, further understanding of effects such as age and geological nature of material could improve the accuracy of these comparisons.

This chapter examines the parameters used to characterise site amplification, specifically the parameter V_{s30} and its use in common practice. The relationship between V_s and geology is then

examined by extending a global database of V_s results and geological logs. This database is used to analyse the effects such as rock type, age and depth to determine possible controlling factors for V_s profiles.

2.2 Parameters describing site amplification

2.2.1 V_{s30}

V_{s30} is the time-averaged shear-wave velocity of the top 30m of ground (Kramer 1996):

$$V_{s30} = \frac{30}{\sum_{i=1}^n \frac{h_i}{V_{si}}} \quad [2.2]$$

where n is the number of layers in the top 30m, i is the layer number, h_i is the thickness of the layer within the boundary of the upper 30m and V_{si} is the V_s velocity of the layer. Therefore, the V_{s30} is not the average V_s over the top 30m, but instead the inverse of the average slowness (Kamai *et al.* 2016).

Borcherdt (1994) formally introduced V_{s30} to replace the previously used qualitative descriptors: hard rock, soft rock or soil. In the Borcherdt (1994) proposal, the V_{s30} values were grouped into four main classes. These were used to form four generalised site response spectra shaped depending on the classification. These classes are the basis of the current National Earthquake Hazards Reduction Program (NERHP) code for V_{s30} (Table 2-1). This is the current standard used in North America,

Table 2-1: NERHP site classifications for seismic site characterisation (BSSC 2009)

Site Class	Description	V_{s30}	SPT N-Value	Undrained Shear Strength (S_u)
A	Hard rock	>1500m/s	-	-
B	Rock	760 - 1500m/s	-	-
C	Very dense soil and soft rock	360 – 760m/s	>50 bpf ^s	>100 kPa
D	Stiff soil	180 – 360 m/s	15 – 50 bpf	50 -100 kPa
E	Soft soil ¹	<180m/s	< 15 bpf	<50 kPa
F	Soils requiring site specific evaluations ²	-	-	-

¹ Site Class E also includes any profile with more than 3 m of soft clay, defined as soil with Plasticity Index >20, water content > 40%, and undrained shear strength 25 kPa.

² Site Class F includes: (1) Soils vulnerable to failure or collapse under seismic loading (i.e., liquefiable soils, quick and highly sensitive clays, and collapsible weakly-cemented soils). (2) Peat and/or highly organic clay layers more than 3 m thick. (3) Very high plasticity clay (PI > 75) layers more than 8 m thick. (4) Soft to medium clay layers more than

36 m thick.

³bpf is blows per foot

including the USA, and also in the International Uniform Building Code (Building Seismic Safety Council 2009). The NEHRP code simply formalised the original Borchardt (1994) groupings by introducing more quantitative measures from V_{s30} and also correlations with SPT or S_u (Chapter 4).

Eurocode 8 (EN 2004) groupings for the V_{s30} classes, used in this research, vary from the NEHRP classifications (Table 2-2). For example, Eurocode 8 (EN 2004) Class A for hard rock almost encompasses the Classes A & B of hard rock and rock of NEHRP (Building Seismic Safety Council 2009). However, the difference between these V_{s30} ranges for the groupings appears to be slight. Little site amplification from change in stiffness of the near surface deposits is generally expected at rock sites. Thus, NEHRP Class A & B could be expected to produce similar acceleration results, explaining the combination of the groups in Eurocode 8 (2004).

The main disadvantage of this technique is the hard boundaries of the classification groups. Neither code considers overlapping or gradational boundaries between site classifications. A site with a V_{s30} of 361 m/s would be an EU (2004) Class B, despite any uncertainty associated with the *in situ* testing method (Chapter 4). As codes are minimum requirements, this had led to a fragmented response in how to counteract this issue. Wills *et al.* (2000) introduced the solution most commonly used which consists of intermediate classes which overlap the main groups. The example site would be classed as BC with a V_{s30} grouping of the means of the B and C classes: 270-560m/s.

There is also much controversy surrounding the V_{s30} parameter itself. It is not a fundamental soil property, but rather an index of that property (Kamai *et al.* 2016). Joyner *et al.* (1981) had suggested $\frac{1}{4}$ wavelength from the surface would be a suitable depth to measure. This is a clearer site specific property, but would lead to inconstant and likely larger depths being measured. Other alternative depths have also been studied in the form of V_{sz} . Gallipoli & Mucciarelli (2009) determined that, for profiles without velocity inversions, V_{s10} combined with fundamental site frequency could be just as successful or better at classifying Italian sites than V_{s30} alone. However, V_{s10} without fundamental site frequency was less successful.

Table 2-2 Eurocode 8 site classifications for seismic site characterisation (EN 2004)

Site Class	Description	V_{s30} (m/s)	SPT N-Value (blows/30cm)	S_u (kPa)
A	Rock or other rock-like geological formation, including at most 5m of weaker material at the surface.	>800m/s	-	-
B	Deposits of very dense sand, gravel or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	300-800/s	>50	>250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180 – 360m/s	15-50	70-250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	<180	<15	<70
E	A soil profile consisting of a surface alluvium layer with V_s values of type C or D and thickness varying between about 5m and 20m, underlain by stiffer material with V_s >800m/s			
S ₁	Deposits consisting, or containing a layer at least 10m thick, of soft clays/silts with a high plasticity index (PI>40) and high water content.	<100 (indicative)	-	10-20
S ₂	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A-E or S ₁			

Frankel *et al.* (2002) and Park & Hashash (2004) raised the implications of the effects of deeper soil on site amplification. These are not accounted for by the V_{s30} velocity. Wald & Mori (2000) also found that the correlation is decreased when topographical effects or soil inversions are present.

It should be highlighted that two sites could have the same V_{s30} despite having differing ground profiles. This would include a soft rock of 750m/s with no topsoil or significant impedance boundaries and rock valley of 1000m/s with 10m of soft sediment of 500m/s. Little amplification would be expected in the first scenario while in the second there is a significant impedance boundary which could give rise to large accelerations. Yet, both sites have the same V_{s30} value of 750m/s.

This is demonstrated in a study by Papaspiliou *et al* (2012a). This compared several methods of calculating the amplification functions for two sites with different geological profiles, but analogous V_{s30} . This showed the overall amplification functions to be dissimilar between the two sites for each

method of calculation for the amplification functions, despite the similarity in V_{s30} (Figure 2-1).

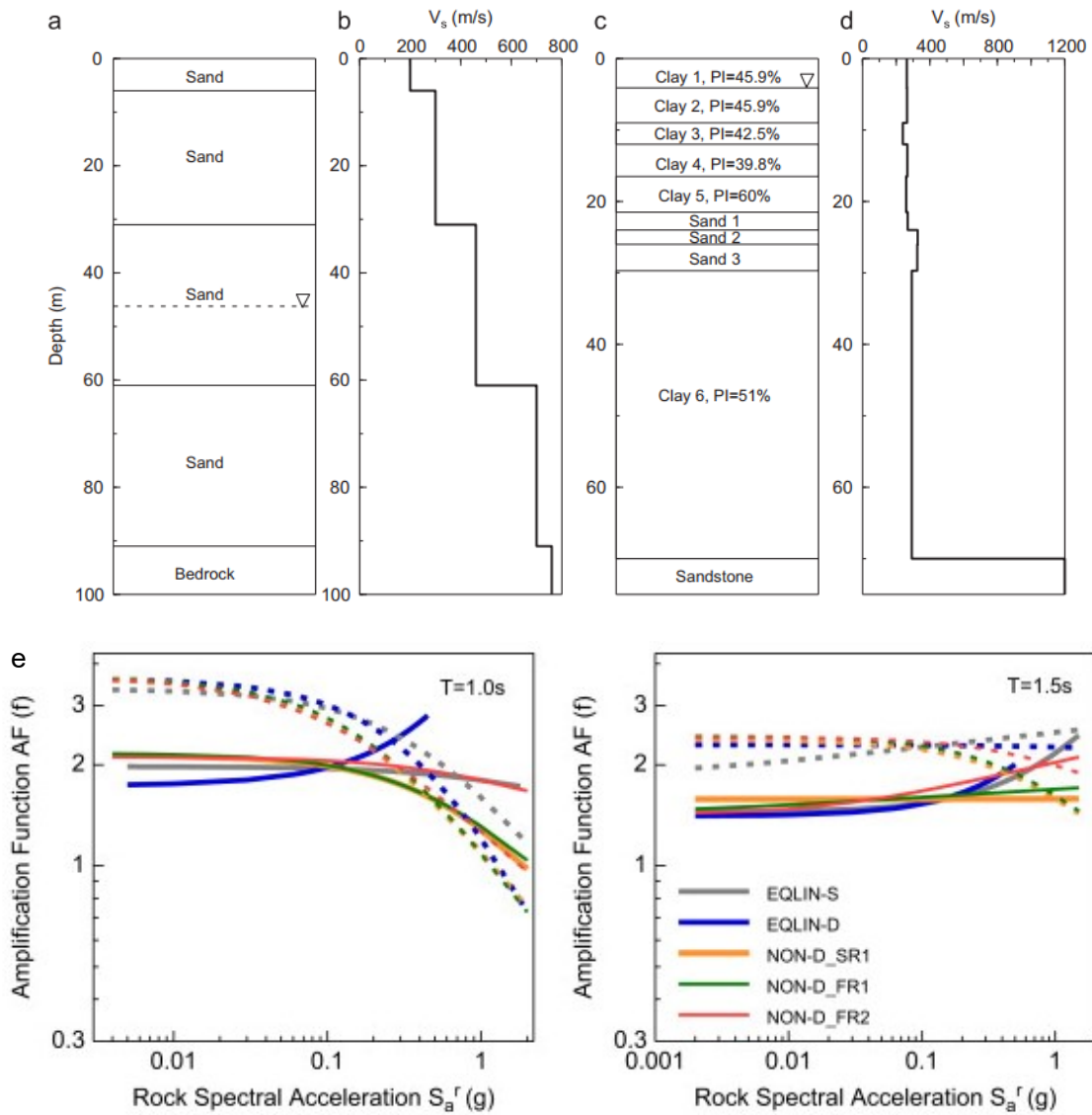


Figure 2-1: Papaspiliou *et al* (2012a) investigation of V_{s30} from two different sites: Figures 2-1 a/b and c/d. These had different site stratigraphy (a & c) and V_s profiles (b & d). However, the V_{s30} values for the sites were within 4m/s of each other. Papaspiliou *et al* (2012b) determined median amplification functions for the two different sites at different spectral periods: 1.0 and 1.5s (Figure 2-1e). The dashed lines represent the response from site a/b and the solid, site c/d. Despite the similarity in V_{s30} , the responses of the two sites are very different.

Despite the arguments against the V_{s30} , a large body of work supports its use (Rathje & Navidi 2013). It has been repeatedly shown that in the absence of a full site characterisation much of the amplification can be successfully correlated with V_{s30} proxies (Kamai *et al.* 2016). This has led to the almost universal usage of V_{s30} to describe site amplification, both in industry and academia.

2.2.2 Complementary parameters to V_{s30}

As the limitations of V_{s30} as a single parameter for site amplification become defined, increasing investigations are being carried out to provide complementary parameters. These new inputs aim to counteract the shortcomings of the V_{s30} as well as being easily measurable. The most common parameters chosen are depth to bedrock and site frequency.

A depth to bedrock factor can improve the correlation of low V_{s30} estimates with site amplification, particularly in deep basins which have a higher than average site response (Steidl 2000). Park & Hashash (2004) determined that the long-period ground motion, often associated with deep soil deposits, has a significant correlation with depth to bedrock.

Having tested over 500 sites, Cadet *et al.* (2008) showed that site fundamental frequency, f_0 , had a poor correlation with V_{sz} in the range 5-30m and so can be used as an independent parameter. f_0 provides further information on the surface stiffness and the thickness and stiffness of the sedimentary cover complementary to the V_{s30} . Both Luzi *et al.* (2011) and Cadet *et al.* (2008) show that the combination of V_{s30} and f_0 parameters gave the most accurate response. However, when comparing the two parameters singly for the same sites, f_0 gave the best results for site classification when considered as a single parameter (Cadet 2008).

These two parameters have been included in national building design codes. In the Armenian code (Grevorgyan 2004), site period and minimum thickness for deposits are standard. While in Australian and New Zealand codes (Standards Australia 2007; Wotherspoon *et al.* 2015), the lower classes ($V_{s30} < 360\text{ms}$) are not characterised by V_{s30} , but instead on site period and depths of soil with specific geotechnical parameters. For example, a site Class D in the Australian code (Standards Australia 2007) must have a site period of greater than 0.6s and less than 10m thickness of soil with $S_u < 12.5\text{kPa}$. This further classification has been found particularly critical in New Zealand when assessing liquefaction susceptibility. Wotherspoon *et al.* (2015) confirmed that V_{s30} alone was not sufficient to characterise the difference in soil behaviour within the lower velocity classes and their likely ground response.

A number of countries have also used these complementary parameters to improve the V_{s30} correlations with their specific geology. Both in South Korea (Sun *et al.* 2005) and Canada (Benjumea *et al.* 2008), soil deposits are often thicker than found those found in California. In California, a 30m ground profile is generally sufficient to encompass the first large impedance boundary, thus V_{s30} has a good correlation (Sun *et al.* 2005). This is not the case in inland South Korea or Ottawa, Canada. Therefore, site fundamental frequency, f_0 , was used to improve the correlations between the V_{s30} and observed site amplification (Sun *et al.* 2005).

However, it is critical how these parameters are applied to the site response spectra and it is still not concluded which complementary factor is the most valuable. The solutions are difficult to compare as they are predominantly formed from empirical factors or further classification schemes (Park & Hashash 2004). Therefore, although both have been shown to improve V_{s30} estimates, neither have yet become widespread.

2.2.3 Alternatives to V_{s30}

Due to the prevalence of V_{s30} , only a few true alternatives have been suggested including the VFZ (V_s , resonant frequency and depth of cover layer) matrix and Empirical Amplification Functions (EAF). Castellaro & Mulargia (2014) suggested the VFZ matrix based on a three layered model. This model assumes the first layer to be a cover layer of superficial material of lower V_s velocity than the second layer beneath (Castellaro & Mulargia 2014). The impedance boundary between the first and second layers is assumed to be the largest in the ground profile, while the final layer is assumed to have an exponential curve of V_s velocity down to bedrock at 2km (Castellaro & Mulargia 2014).

The VFZ model depends chiefly on three parameters: $\langle V_s \rangle$ which is the average V_s of the cover layer; f , the resonance frequency of that layer; and Z the impedance contrast between the two layers (Castellaro & Mulargia 2014). A series of graphs have been plotted based on numerical analysis of these parameters using a Ricker Wavelet. These are used to classify the expected site amplification (Figure 2-2). However, it is noted that the resulting amplification factor, F_a , is relative and not absolute due to its dependence on other variables not yet considered (Castellaro & Mulargia 2014). Thus, it

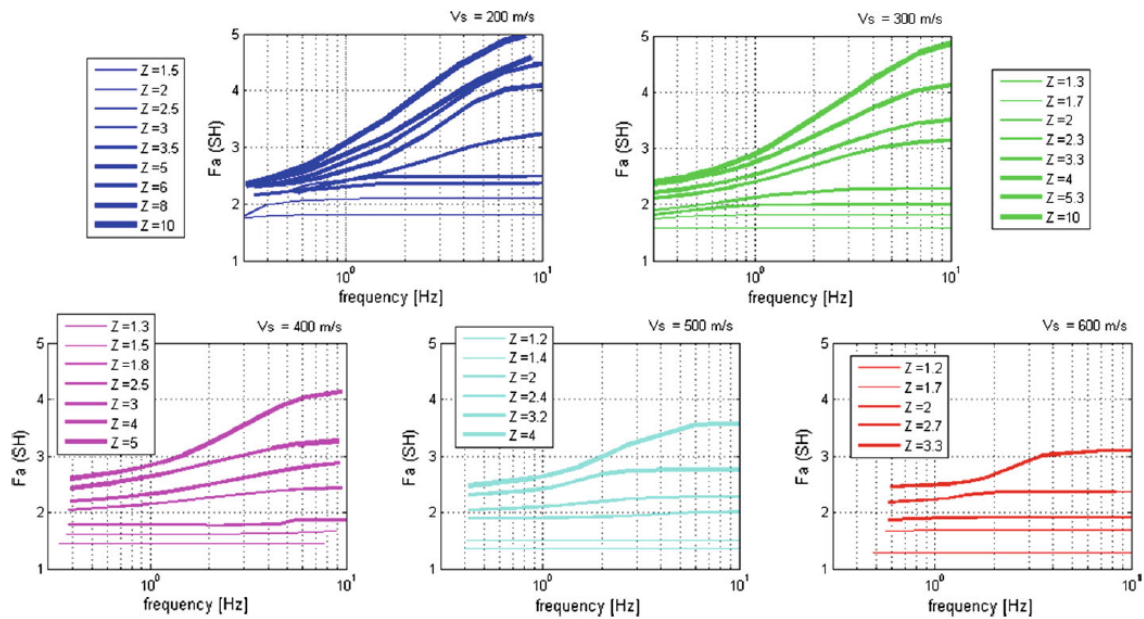


Figure 2-2: Castellaro & Mulargia (2014) graphs for site amplification factors (F_a) from the VFZ matrix.

should only be used to classify high or low amplification.

This method is based on robust, physical parameters all of which are known to affect site amplification. However, although the averaging of the V_{s30} parameter is not ideal, it prevents subjective estimates and standardises the measurements. In the VFZ models the engineer must make a judgement about the location of the boundaries between three layers. In a weathered material, this may be very subjective. In addition, the relative nature of the linear amplification factor dramatically limits this technique's usefulness. The factors which affect this parameter need to be defined more clearly.

The method of Thompson & Wald (2016) for EAFs is not based on external testing of a site, but rather recording of previous earthquakes. When compared to the averaged earthquake record, the residuals for each site are assumed to be caused by the site response (Thompson & Wald 2016). Although this makes the method more open to epistemic uncertainty as all the factors may not be correctly accounted for, Thompson & Wald (2016) used stations that have recorded at least five earthquakes to ensure reliability. This could be the ideal choice for site amplification as V_{s30} estimates always require correlation to the site amplification, while EAFs are derived directly from the earthquake records.

Both alternative and complementary parameters and methods are being developed to improve site amplification. Nevertheless, without consensus, these parameters are unlikely to supplant V_{s30} due to its ease of measurement and consistency of use (Yong 2016). However, it should be noted V_{s30} alone is not considered sufficient to characterise a site fully and effort should be made onsite to ensure other parameters are also measured while testing.

2.3 Previous studies of V_s profiles and geology

In an initial study of the controls on V_s by geological characteristics, Hardin & Drnevich (1972) determined that a variety of material conditions and parameters affect both the V_s and the small strain shear modulus (G_{max}). The primary parameters included soil density, effective stress and void ratio. However, Hardin & Drnevich (1972) also recorded secondary parameters: soil type, depositional environment, age, cementation and stress history. Grain characteristics for soils are also important, but are defined by soil type and depositional environment.

Dobry & Vucetic (1987) studied the dynamic properties of soft clay deposits, determining five main parameters that influenced the dynamic loading: overburden stress, void ratio, geological age, cementation and strain rate/cyclic frequency. Yet, unlike Hardin & Drnevich (1972), the Over Consolidation Ratio (OCR) is considered as significant. In summarising several studies, Sykora (1987) also considered OCR as important for cohesive soils, but indicated that void ratio and effective stress state were the primary variables influencing *in situ* V_s velocity.

In geological terms, the secondary parameters for soils could be interpreted to relate to age which has been studied extensively in California (Fumal & Tinsley 1985). The increase of V_s relates strongly with the increased bonding or cementation due to geological age and other the pedogenic processes (Park & Elrick 1998). This forms the basis of the main proxies methods used to determine V_{s30} over a large scale (Wills *et al.* 2000; Yong *et al.* 2012). For example, Holzer *et al.* (2005) found Pleistocene sediments in Northern California generally have 20-50% higher V_s than Holocene sediments with similar geotechnical properties.

For rock, age also determines the likelihood of weathering in certain regions. Australia's geology has had little to no recent tectonic instability or glacial episodes to remove superficial sediments (Campbell 2014). Therefore, deeply weathered horizons are common in ground profiles. McNally (1993) showed Triassic sedimentary rock has a significant decrease in V_s velocity with greater weathering. Consequently, weathering is considered in the Australian code (Standards Australia 2007) where site classes are divided by superficial soil depth and age.

Wair *et al.* (2012) note rock deposits are affected predominantly by fracture spacing and density, hardness and weathering. Fumal (1978) studied V_s and physical rock properties in the San Francisco Bay area. This included a limited number of sites where the degree of weathering differed significantly from site to site. Therefore, the main parameters considered included weathering state, hardness (toughness and strength) and fracture spacing. Fumal (1978) determined that correlation to detailed surface geology included age and texture for soils or age, weathering and fracture spacing for rocks.

Weathering generally decreases V_s velocity and it has been noted that harder rocks decrease more rapidly in V_s with degradation (Fumal 1978). The influence of fracture spacing is more significant than that of lithology or hardness and is the most important factor (Fumal 1978). Wills & Silva (1998) also found, when correlating geological units with V_s , that volcanic plutonic and metamorphic rocks are likely to have a high V_s , but are strongly influenced by fracture spacing and weathering state.

These parameter effects are summarised in Table 2-3. However, although each has a clear effect on V_s , the parameters themselves are highly interdependent. For example Hussein & Karray (2016) note that the main influence of grain size is to change void ratio. Equally Sykora (1987) reports that quite different V_s velocities can be produced from soils of the same relative density and confining pressure, but different soils of the same void ratios generally have the same V_s velocity. Therefore, it is critical when defining the relationship between V_s and geological factors to consider the main geological characteristics that control V_s .

Table 2-3: Adapted from Campbell (2014), summary of geological parameters and their effect on V_s velocity.

Parameter	Influence on V_s velocity
Age	Increasing age results in increasing V_s
Cementation	Increasing cementation results in increasing V_s
Density	Increasing ρ results in increasing V_s
Depositional environment	-
Effective stress σ'	Increasing σ' results in increasing V_s
Fracture spacing	Increasing fracture spacing results in increasing V_s
Hardness	Increasing hardness in increasing V_s
Soil type	-
Strain rate or frequency	Increasing rate of strain results in increasing V_s
Stress history	Increasing OCR results in increasing V_s for cohesive soil
Void ratio, e	Increasing e results in decreasing V_s
Weathering	Increasing weathering results in decreasing V_s

2.4 Global V_s Database

For an MSc dissertation conceived and co-supervised by the author, Campbell (2014) produced a database of V_s profiles from global locations was created both from *in situ* and lab tests, sourced by Campbell and the author. The aim of the project was to combine high-quality geological data with V_s profiles. Many geological parameters are considered in the database including, material, origin, depth of testing, geological age, degree of weathering, fracture spacing and RQD (Campbell 2014). However, only records from direct tests of V_s were included and each were required to have a sufficiently detailed geological log, from which these parameters could be clearly determined.

The Campbell (2014) database consisted of 6531 V_s results. Each record is a single V_s measurement and therefore, is associated with a specific depth and geological deposit. Thus, one downhole test (Appendix 4-1) may be included into the database as several records of V_s at different depths. For example, the record of the USGS 82_833-62 Leona Valley F.S. borehole has three downhole measurements and would be recorded into the database as three separate records, each with its own material description (Table 2-4).

Table 2-4: Summary of Leona Valley F.S. borehole entry in Global V_s Database

Record ID Code	Source ID FK	Depth (m b.g.l.)		V_s (m/s)	Material
		From	To		
1604	USGS 82_833 - 62_Leona Valley F.S.	0	8	240	SAND
1605	USGS 82_833 - 62_Leona Valley F.S.	8	13	330	Sandy Clay Loam
1606	USGS 82_833 - 62_Leona Valley F.S.	13	20	390	Gravelly SAND

The database datasets include both open access and proprietary sources (Table 2-5). It is noted that the data has been collected from a variety of sources for different uses, not necessarily specifically for a V_s profile database. Therefore, not all records would have equal amounts of detail on all the parameters considered. This is augmented by the fact that a variety of methods have been used to measure the profiles (overview of methods in Appendix 4-1). Consequently, not all of the data is complete and in

Table 2-5: Summary of sources for Version 1 of Global V_s Database, adapted from Campbell (2014).

Source	Method of determination	Number of sites	Number of records	Completeness of data
USGS 1970s (San Francisco Bay)	Downhole	58	127	High
USGS 1980s (LA Country and Oxnard-Ventura)	Downhole	84	203	High
USGS 1980s (Central California)	Downhole	10	32	High
USGS 1990s (Stations that recorded Loma Prieta)	Downhole	26	172	Low
Turkish Database	MASW	136	1129	High
Geological Survey of Canada	Downhole	20	60	Medium
	SCPT	1	4	Medium
PNSN, Washington	MASW and MAM	67	249	Medium
Industry Sources- United Kingdom Sites	SCPT	60	258	Variable
	Crosshole	27	543	
	Downhole	14	109	
	CSW	1	4	
	Refraction	36	72	
	PS Logger	7	229	
Engineering Geological Database for TSMIP	PS Logger	25	306	Medium
NATO Science for Peace Project- Bucharest, Romania	Downhole	21	110	Medium
Geoscience Data Repository for Geophysical Data (GSC)	Piezoelectric transducer		2860	Medium
Laboratory database of silicate rocks	Piezoelectric transducer		64	Medium
Total		594 Field	3607 Field 2924 Lab	

some cases the data has been “normalised” as many different countries used different classification schemes such as weathering levels. Any changes were kept to a minimum, but those carried out are outlined by Campbell (2014).

In addition, the database itself was aimed to be a comparative measure for the UK Strong Ground Motion Station (SGMS) geology (further in Chapter 3). Therefore, a stronger emphasis than is general was placed on the V_s of rocks and residual rocks. Soil deposits are also considered, but to a lesser extent.

One prominent result from Campbell (2014) is from the comparison of the lab and *in situ* testing datasets (Figure 2-3). The lab results are significantly higher than the *in situ* and the results. Further the results are highly separated possibly indicating the lab and *in situ* tests are measuring different parameters. This could be caused by the size of the laboratory samples which are small compared to the volume of soil tested in *in situ* tests. Such small samples are generally “intact” and thus, the influence of macroscale structure (including bedding, layering, fissuring) will not be realised. Thus, it is expected that laboratory results they might not be representative of *in situ* velocities.

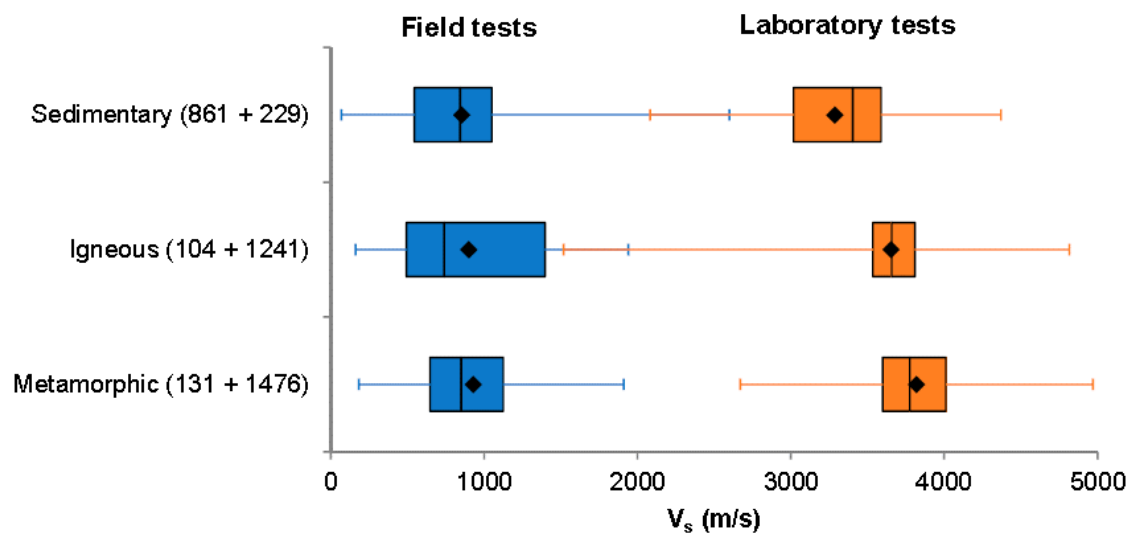


Figure 2-3: Comparison from *in situ* and laboratory tests, categorised by rock origin form Version 1 of Global V_s Database (Campbell 2014). See Figure 2-7 for explanation of box & whisker plot.

However, whatever the possible causes, it is clear that currently the lab and *in situ* data do not correlate. For this study, the aim is to utilise the database to constraint possible *in situ* values of V_s (Chapter 3). Therefore, with the current time limitations, it was decided to focus on the *in situ* records of the

database. Further results from Campbell (2014) will be detailed in Section 2.5 in order to compare and contrast it to the new version of the database.

2.4.1 Additions to the Global V_s Database

The aim of this study is to extend the Global V_s Database to see the effect of additional data on the results of Campbell (2014). However, for this specific study, the database results will also be compared to UK geology in a proxy method (Chapter 3). The *in situ* data in Campbell (2014) are predominately sedimentary in origin and include softer sedimentary rocks from the US and Turkey (Figure 2-4). Therefore, the additional datasets are required to have higher proportions of igneous and metamorphic deposits. This ensures the comparison with Northern England and Wales which are expected to have ‘hard’ geological environments and improves the range of the database. The use of high quality records is still critical with each input required to be a direct measurement of V_s velocity and to have at least an associated geological log (Appendix 2-1). Finally, an aim of the data compilation was to double the number of *in situ* results in order to ensure a statistical difference to the results of Campbell (2014).

Therefore, the two predominant datasets added are measurements from the ITACA Italian seismic station network (INGV 2015) and the Japanese KIK-net seismic station (Aoi *et al.* 2004). Both datasets are extensive and both have high quality records. These are specifically chosen as the geological environments of these networks contain more igneous and metamorphic deposits and therefore, are expected to be more similar to the UK geology (Appendix 2-1).

2.4.2 ITACA dataset

The Italian ACcelerometric Archive (ITACA) is a database of the strong-ground motion records measured by the Italian seismic station network (INGV 2015). This includes metadata on the stations themselves including their location, the earthquake recordings and information on their housing. During 2010 many of the stations were tested via *in situ* methods (INGV 2015), possibly as an upgrade for the stations. Several different methods were used: crosshole, downhole, SPAC, MASW, HVSR (Appendix 4-1 for further information).

This dataset had high quality recordings with clear logs for those stations tested. For many of the stations tested with non-invasive methods more than one type of test was carried out and the results compared (INGV 2015). The geological environment included metamorphic rocks and marls from the hillier geomorphology. Several glacial deposits were also included as well as clear recordings of weathered bedrock (INGV 2015). However, more volcanic deposits and tuffs are present than would be found in the UK.

The main disadvantage of these data is the lack of classification in terms of weathering and fracturing. These are often referred to in the description (INGV 2015), but are not formally classified. This limits the usefulness of the logs as both parameters are possibly key constraints for the V_s velocity.

Conflicts within the dataset also prevented all of the records for testing at the stations from being included. Geological logs were not necessarily provided for non-invasive testing or where the geology conflicted with the recordings (INGV 2015). Several records also had conflicting geology, between different testing method reports and the testing results. These conflicting records are not included into the database as it is not clear which would be accurate. This may cause a bias towards the invasive tests all of which had geological logs. Indirectly, softer soils are also more likely to be included as these were generally tested invasively.

2.4.3 KIK-net dataset

The KIK-net is one of several seismic networks installed across Japan. Setup by NIED, the network has a nationwide coverage with over 1000 strong-motion stations (Aoi *et al.* 2004). Each station is installed alongside a borehole of at least 100m depth, many of which have a second seismometer installed at depth (Aoi *et al.* 2004). The associated downhole V_s profiles and geological logs are made available by NIED (2016).

This dataset was chosen for the high quality of the velocity profiles. All are recorded using downhole measurements which are accompanied by geological logs (Aoi *et al.* 2004). The geological environments recorded are varied, but contain a high proportion of igneous and metamorphic rocks

(NIED 2016). Although these may be considerably younger than the same rock types encountered in the UK, the geological environment is comparable. The database also includes weathered profiles similar to those found in the UK (NIED 2016).

As with the ITACA dataset, the main disadvantage of the data was the lack of clear or well-defined classification of the fracturing and weathering. These are often mentioned in the logs, but informally (NIED 2016). In addition, the age classifications of the logs were occasionally very broad, particularly in consideration of the older rocks. When these overlapped more than three time periods or more than two time eras, the age classifications were not used as it was not clear if the true age was known or it was simply an indication.

2.4.4 Other additions

Several other sources are also included within the database (Table 2-6). These consisted of data from academic papers encountered during this study as well as from confidential industrial sources made available for this research. These include a variety of testing types, but were predominantly from UK locations. The complete Global V_s Database, including both Campbell (2014) and the new additions are considered by data source (Figure 2-4) as well as the methods by which they are collected (Figure 2-5).

Table 2-6: Summary of additional sources for Version 2 of Global V_s Database (Appendix 2-1)

Source	Method of determination	Number of sites	Number of records	Completeness of data
ITACA Seismic Station Database	Crosshole	21	1504	Medium
	Downhole	4	96	
	MASW	4	11	
	Microtremor	5	102	
	Combined	7	166	
KIK-net Seismic Station Database	Downhole	557	3089	Medium
Industry Sources- United Kingdom Sites	PS Logger	9	215	Variable
	SCPT	59	760	
Industry Sources- International	Downhole	4	21	Variable
	MASW & HVSr	4	18	
Total		674	5982	

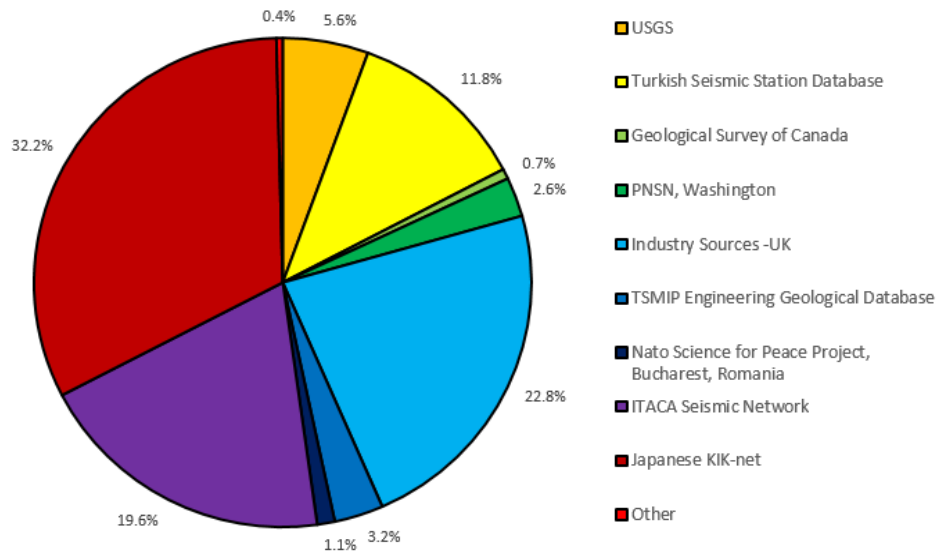


Figure 2-4: Global V_s Database breakdown of sources for Version 2 with Campbell (2014) *in situ* data and new additions.

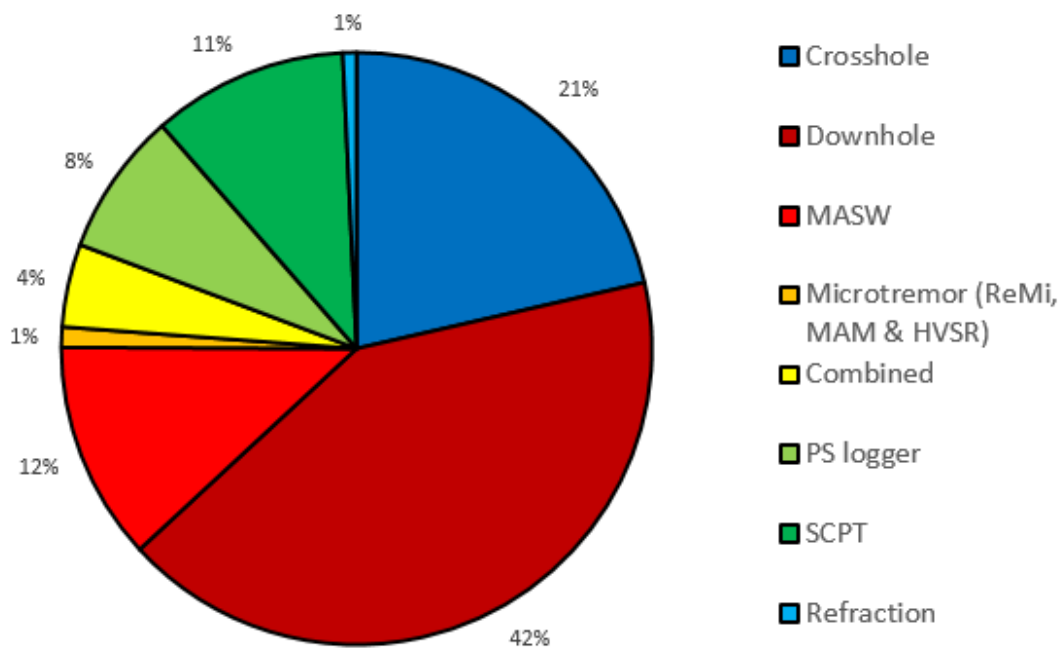


Figure 2-5: Global V_s Database breakdown of testing methods for Version 2 with Campbell (2014) *in situ* data and new additions (Appendix 4-1 for details of the methods).

2.5 Analysis of the Global V_s Database Version 2

This study aims to determine the geological factors that control or have significant influence on the V_s . These factors could be as simple as older rocks generally having twice the V_s velocity of younger rocks or that sandstone V_s velocities increasing linearly with depth. However, if the controlling factors can be clearly identified, further testing or analysis could determine average trends within deposits which can be used to predict V_s velocity accurately. If such relationships could be defined they would remove the need for specialised site-specific seismic testing.

This study extends the original Campbell (2014) database. It is important to determine whether any changes have occurred in the results of Campbell (2014) following the inclusion of new sets of data. One specific method of analysing data used by Campbell (2014) is the box and whisker plot (Figure 2-6) which is also used to examine the combined data. Appendix 2-2 contains the full statistics for each plot.

Three parameters have been chosen specifically on which to focus: origin, depth and age of deposit. Origin and age form the basis for many proxy models for V_s velocity (Chapter 3) and so are widely assumed to be controlling factors while increasing V_s with depth forms the basis for many V_s models (Toro 1995). Therefore, the aim is to determine if three parameters in fact influence V_s velocity and the extent of that influence.

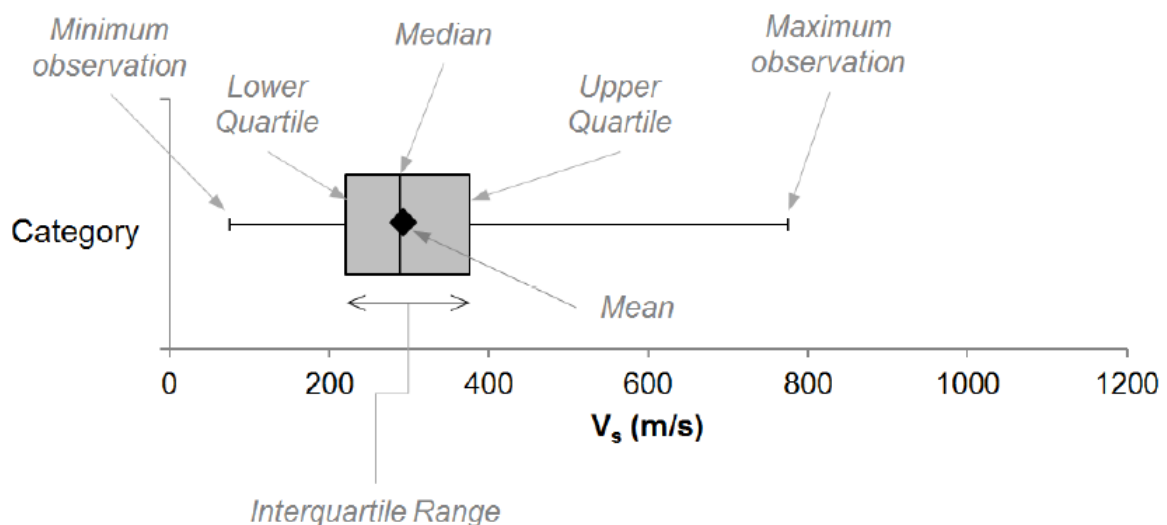


Figure 2-6: Campbell (2014) explanation of the components of a box and whisker plot. Note the number given after each category name is the number of recordings used from the database.

2.5.1 Rock origin

Although laboratory results are not considered the Version 2 of the database, Campbell (2014) separated the lab testing of rocks in Version 1 by classing them into three types: igneous, sedimentary or metamorphic rocks. The overall V_s observed in lab testing are significantly higher than the field data, with mean over 300% greater than the *in situ* data (Figure 2-3). The lab tested means tend to increase in V_s velocity from sedimentary to igneous to metamorphic rocks (Figure 2-7). This trend relates well to the increasing strength and inter-grain bonding strength of the rock types.

However, the results also show small interquartile ranges on average of 350m/s for igneous and metamorphic rocks. These materials generally have higher initial V_s than sedimentary rocks. Therefore, if they undergo fracturing or weathering, the consequent drop in V_s velocity from the fresh rock can be proportionally larger than any in a sedimentary rock (Wills & Silva 1998). Thus, they would generally be expected to show a greater range of V_s to sedimentary rocks reflecting a broad range of geological histories including weathering and deformation.

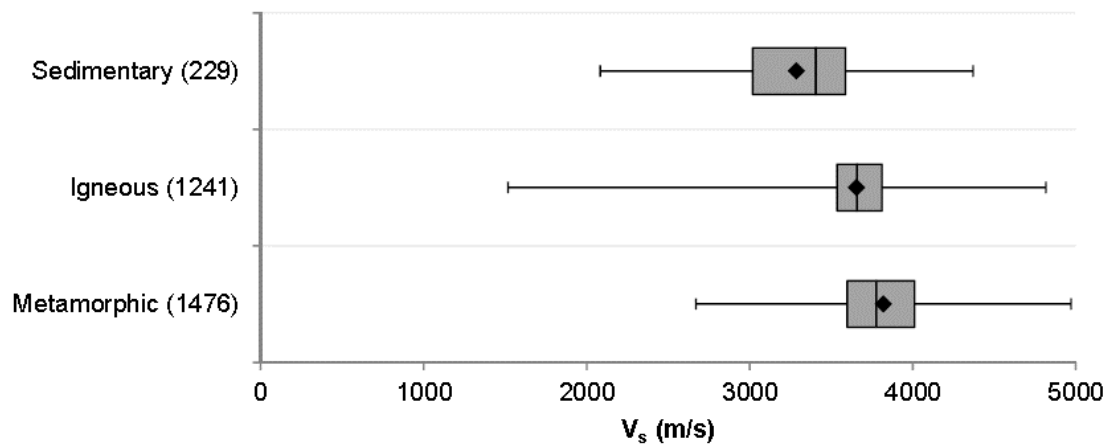


Figure 2-7: Campbell (2014) results for all lab tests on intact rock. Note the number after each category is the number of recording used for the database.

The increased interquartile range of V_s for igneous and metamorphic rocks is observed in the *in situ* tests presented in Campbell (2014) *in situ* tests used in the version 2 database (Figure 2-8). This difference between lab and *in situ* test results could be caused by the small lab test samples not taking into account the influence of macroscale structure and fabric on V_s . Notably, the *in situ* igneous rocks

have a lower mean V_s than the sedimentary rocks; the opposite of what is observed in the lab testing. This relative decrease in mean V_s for igneous rock may reflect a greater proportion of extrusive deposits in this dataset which are likely to have a larger amount of macrostructure than intrusive materials.

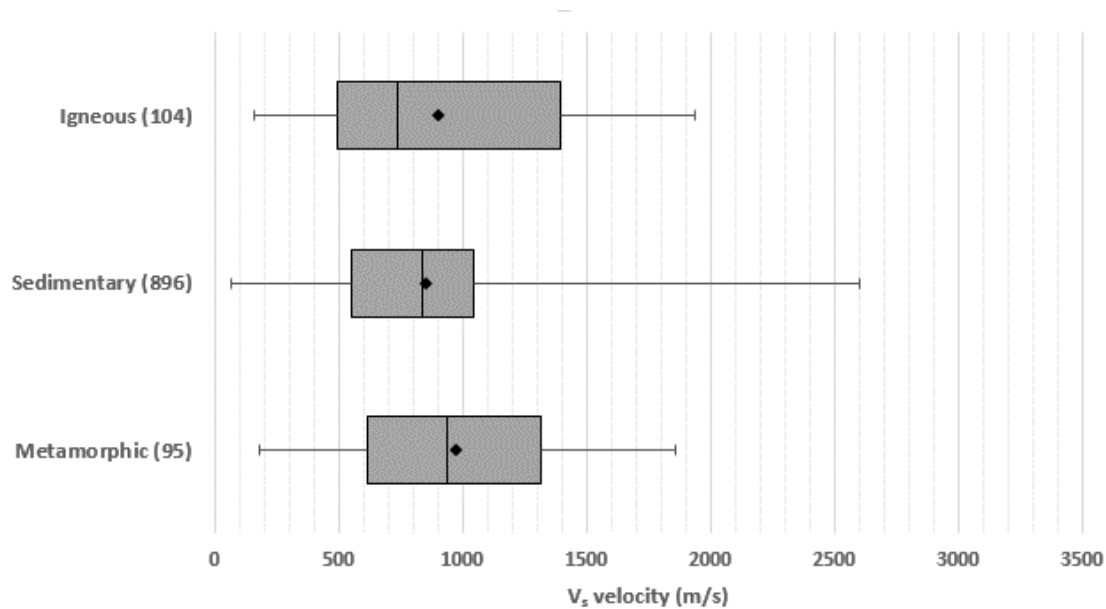


Figure 2-8: *In situ* records categorised by rock origin, adapted from Campbell (2014).

When the new *in situ* results are considered Version 2 of the database, the trend of increasing mean velocity from sedimentary to igneous to metamorphic rocks is re-established (Figure 2-9). The interquartile ranges of the igneous and metamorphic rocks are also increased by 35% and 25% respectively, while the sedimentary results are only slightly increased by 143m/s from Campbell (2014).

The full ranges of the deposit types are also extremely similar. Several low values, that would not generally be considered to as 'rock' classification, were found within these results as shown in the full range which is 100m/s-3100m/s. This occurred as the database was sorted by description and so the assessment includes highly weathered deposits which are possibly more soil like in their current state.

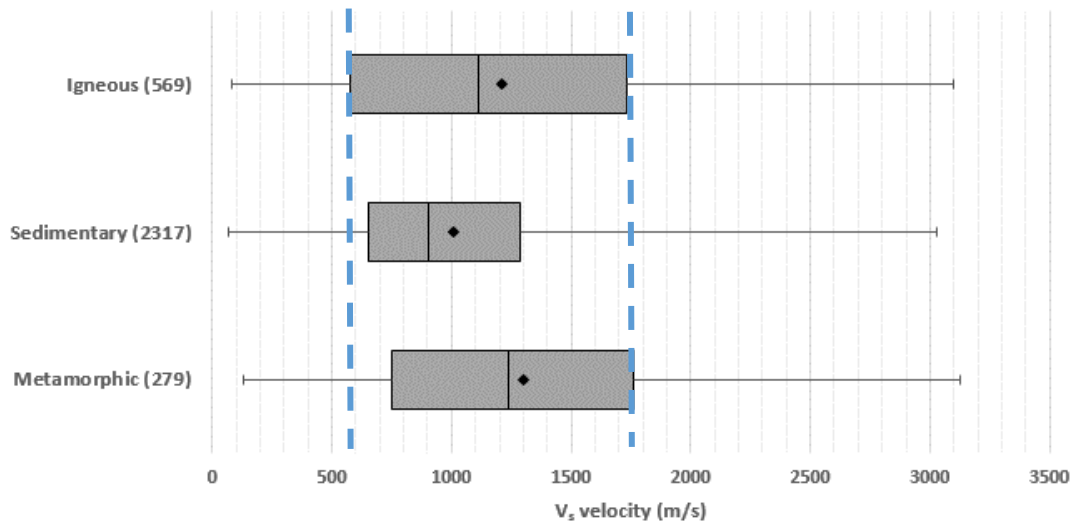


Figure 2-9: Combined results from Version 2 of Global V_s Database, when *in situ* rock deposits are divided by origin (Appendix 2-2).

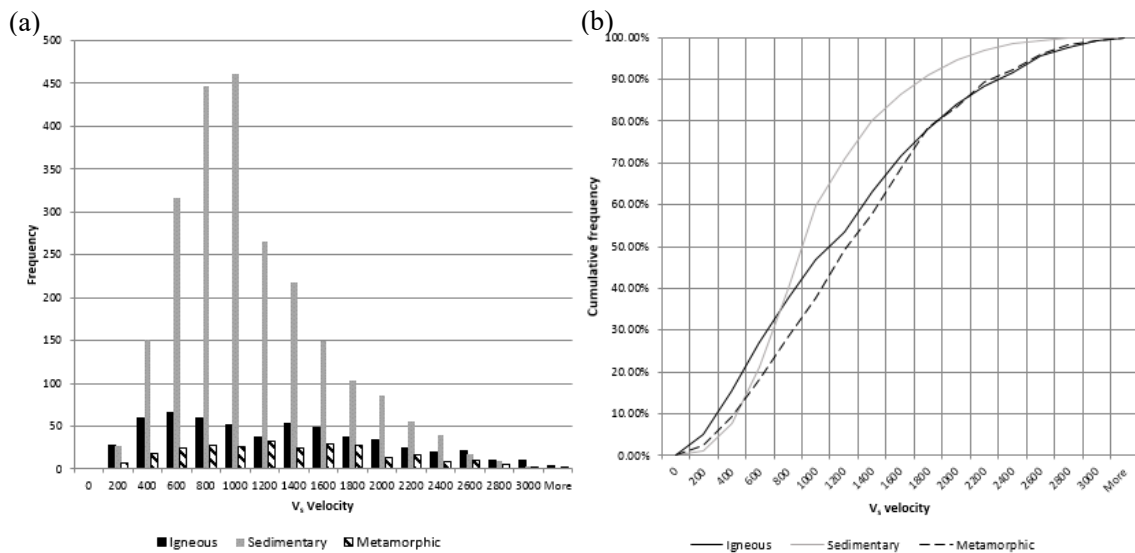


Figure 2-10: Combined results from Version 2 of Global V_s Database, when *in situ* rock deposits are divided by origin (a) histogram and (b) empirical cumulative distribution.

The results from the Version 2 of the Global V_s Database are uniform with, over 50% of the V_s velocities for all rock deposits lie between 600 and 1800m/s. This result correlates well with the code classifications of rock both for NERHP (Building Seismic Safety Council 2009) and EN (2004) . The igneous deposits have the largest standard deviation of 749m/s, while the sedimentary have the smallest of 511m/s. This is an extremely narrow range, given the variety of data included. The distribution of the sedimentary deposits is also clear and approximately lognormal (Figure 2-10) which reflects the input dataset. This is similar to the igneous distribution though this is more positively skewed, while the metamorphic appears as an approximately normal in distribution.

2.5.2 Rock origin and depth

The increase of V_s with depth is one of the main assumptions of most V_s models (Kramer 1996). Although not analysed by Campbell (2014), this is often assumed to be the controlling factor in V_s . If the depth is considered using box plots (Figure 2-11), the range of the scatter is shown to be fairly broad with the average interquartile range being 713m/s. This range increases by 74% from the top 10m to 80-90m.

The means at each depth form an approximate curve which could be logarithmic or piecewise linear with depth. The distribution of the mean becomes more vertical from 40-50m to 60-70m depth. It could be that at this depth other factors become more important. However, the effect of fewer records would also need to be investigated as the statistical significance of the groups below 40-50m will be lower and may not correlate due to lack of records. This is particularly noticeable at $50 \leq x < 60$ which has less data than any other depth, while metamorphic rocks are found to have 1000m/s velocities at

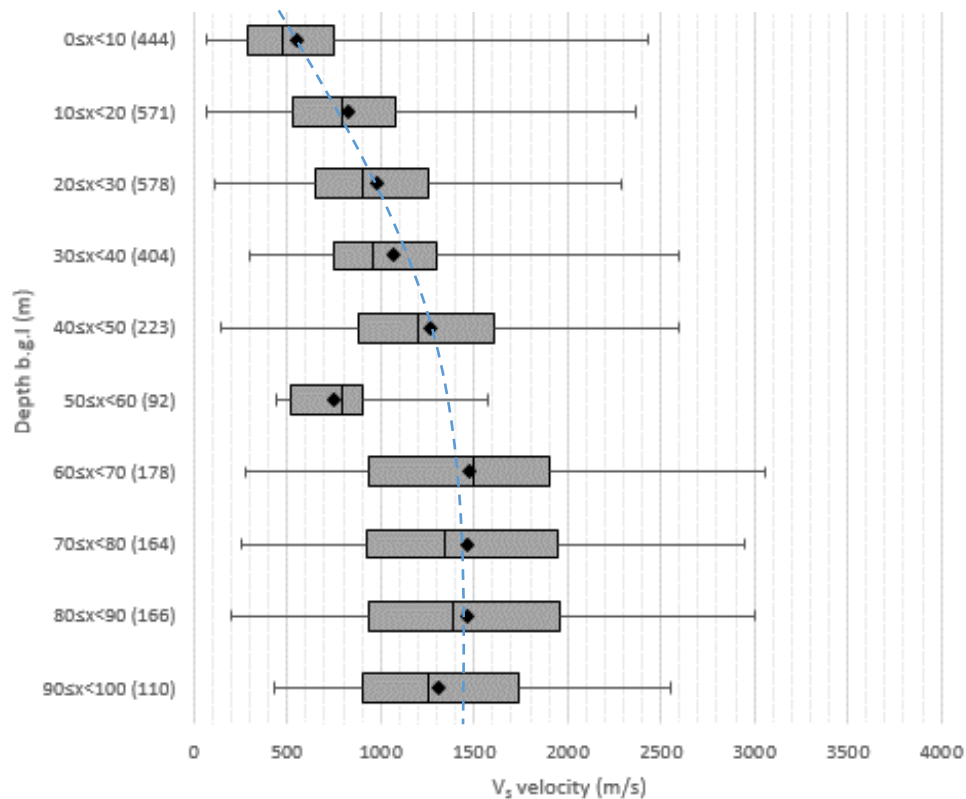


Figure 2-11: Variation in V_s velocity with depth at 10m intervals.

over 600m depth. Either the assumption of high V_s with depth or the accuracy of the testing techniques is, therefore, questionable, particularly at 100-200m depth as more results are present.

Several anomalous results were removed from the data due to their unfeasibility and considered likely to be the result of a measurement inaccuracy or error. For example, from the Japanese KIK-Net, in a strong slate deposit producing a V_s value of over 3000m/s. The result is extremely high at less than 141m depth and this may be due to the large range it is assumed to be measuring from (84-198m depth). It is likely, that in reality, this is including velocities from deeper rocks.

When the data are examined for different rock types, there are clear similarities (Figure 2-12). All the records appear to have an exponential shaped upper boundary, but different ranges in the near-surface velocities. These near-surface ranges appear much smaller in the igneous and metamorphic records (Figure 2-13a & c). From ground level to up to 5m depth there is a range from 0 to 600m/s in the igneous records and 0 to 250m/s in the metamorphic. These low velocities would not normally be considered rock values, but are associated with rock materials in description. This may be caused by

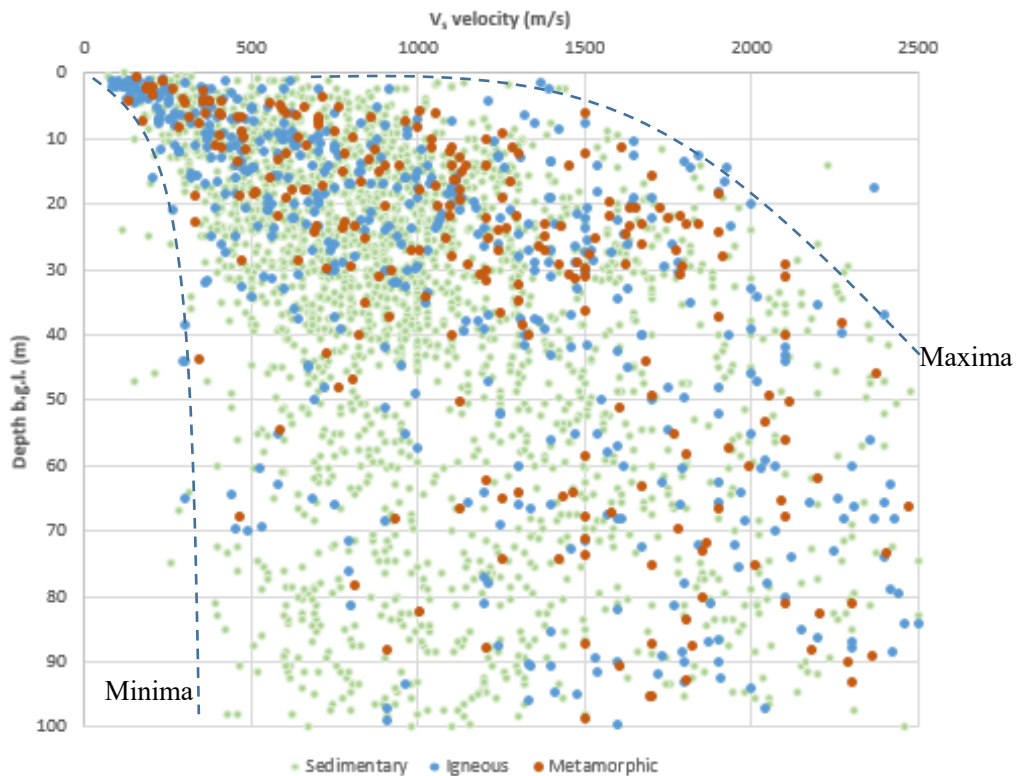


Figure 2-12: The relationship of V_s velocity and depth for all the results in the Global V_s Database to 100m depth. Maxima and minima lines are drawn via visual inspection.

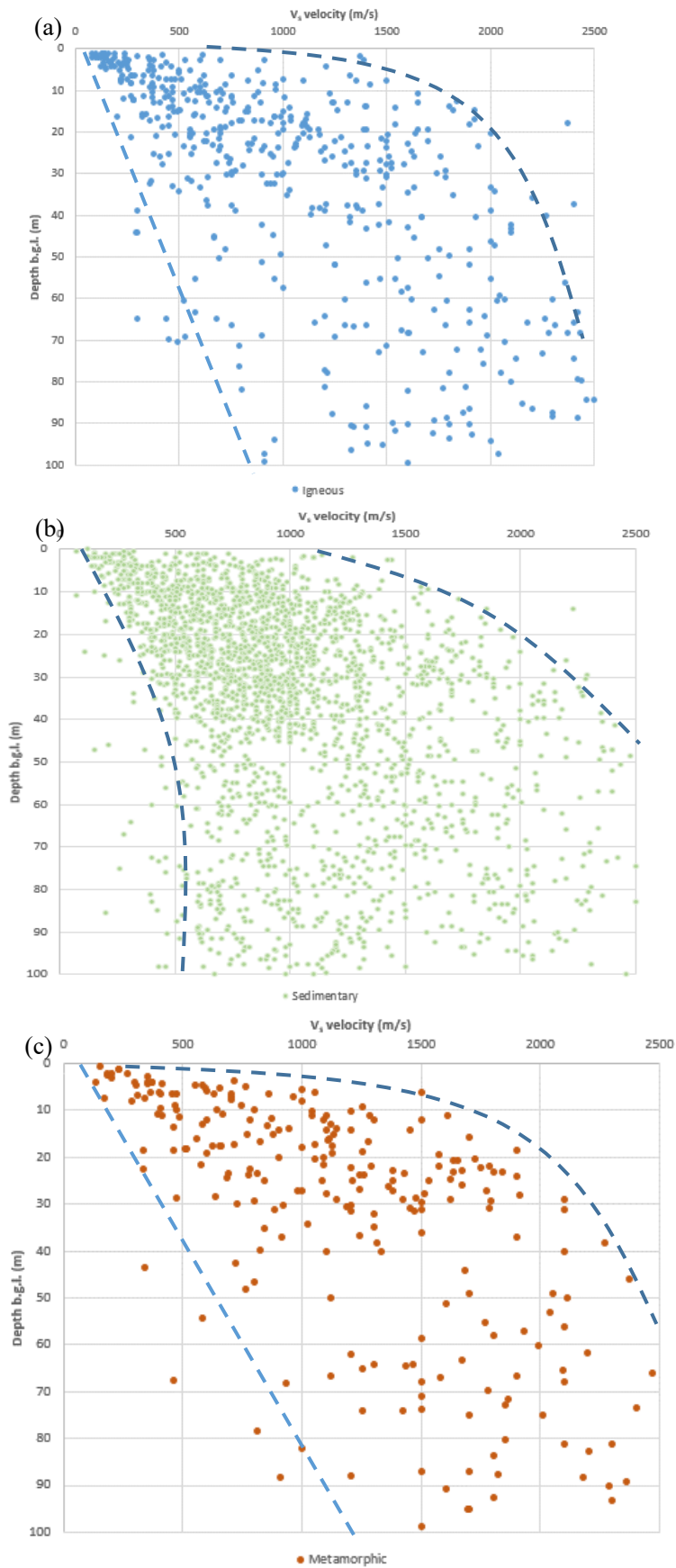


Figure 2-13: The relationship of V_s velocity and depth for (a) igneous rocks, (b) sedimentary rocks and (c) metamorphic rocks. Maxima and minima lines have been included via visual inspection.

fewer records of these rock types in the near surface or failure in the recordings to recognise these as residual soils rather than intact rock. For the sedimentary deposits, the near surface range is large and V_s can be higher. However, the increase of the lower boundary V_s with depth is less well defined. Igneous and metamorphic measurements appear linear at this scale (Figures 2-13a & c). However, the sedimentary is more curved (Figure 2-13b).

It was decided to investigate other factors that might explain the large degree of scatter, rather than to develop a marginal prediction model simply in terms of depth. However, if fitted, a power law model in the form $V_s \sim a \cdot z^b$ where z is depth and a & b are constants appeared to be most appropriate. All three lines appearing fairly similar altering only slightly in gradient. Therefore, it is clear there is a relationship with depth, but there are other controlling factors to be considered in order to account for the scatter.

2.5.3 Igneous rock

Campbell (2014) examined how the depositional environment and the mineral character of igneous rock affected V_s velocities. Using the laboratory database not considered in Version 2 of the database, it was determined that felsic materials had slightly lower V_s velocities than mafic (Figure 2-14). Therefore, the combined *in situ* results of the Version 2 of the Global V_s Database (Table 2-7) are categorised as suggested by Campbell (2014).

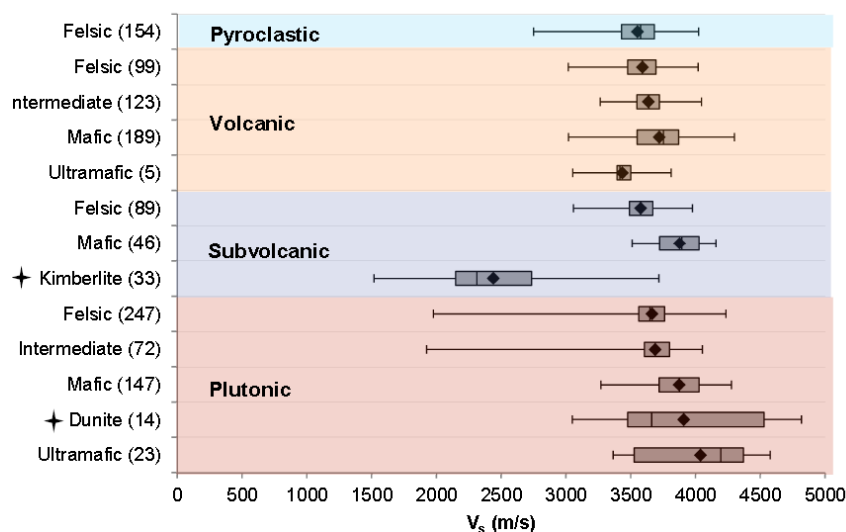


Figure 2-14: Campbell (2014) analysis of lab records for depositional environment and mineral characteristics.

Table 2-7: Adapted from Campbell (2014), the breakdown of igneous rock from Version 2 of the Global V_s Database that could be classed by depositional environment or mineral character. Not all could be separated into these classes and were thus excluded. Numbers of records in the database are included in brackets.

	Felsic	Intermediate	Mafic
Pyroclastic	Acid Tuff (28) Pumice (16)	-	-
Volcanic	Dacite (6) Rhyolite (23)	Andesite (44) Andesitic lava and volcanics (3) Quartz Andesite (5)	Basalt (28)
Subvolcanic	Porphyry (10)	-	Diabase (3)
Plutonic	Granite and biotite granite (201) Granodiorite (69) Monzonite (2)	Diorite (22)	Gabbro (14)

From the *in-situ* results of the combined Global V_s Database, the mean velocity increased by over 1000m/s from pyroclastic to sub-volcanic (Figure 2-15). This could be caused by the increasing coherence and uniformity of these deposits. However, it would then be expected that the plutonic rocks would have the highest V_s . Plutonic rocks have a 35% wider range than the average of the other categories. This could be caused either by other factors influencing the material such as weathering, the depth of the measurement or the number of results associated with each class. The V_s for all environments are similar to the overall igneous class as all of the means and medians lie within the igneous interquartile range. Thus, no overall trend with depositional environment is clear.

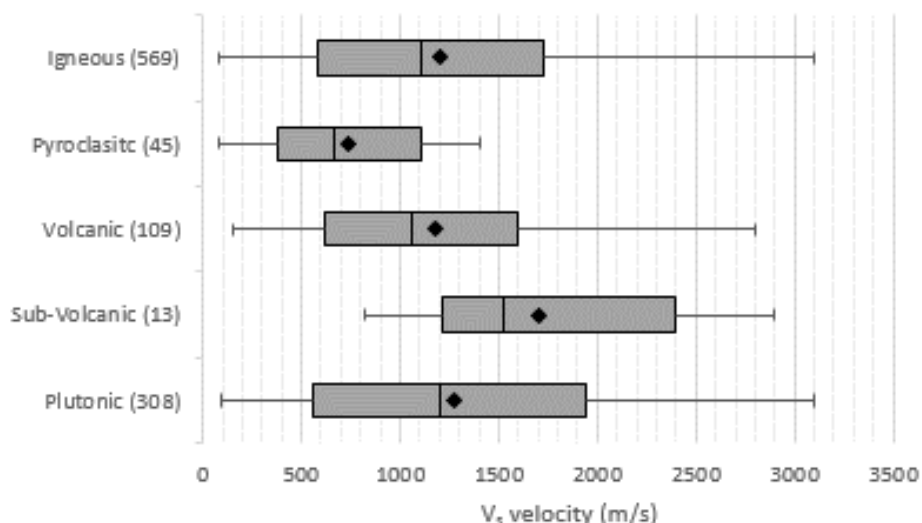


Figure 2-15: *In situ* results from version 2 of Global V_s Database of igneous rocks divided by mode of formations.

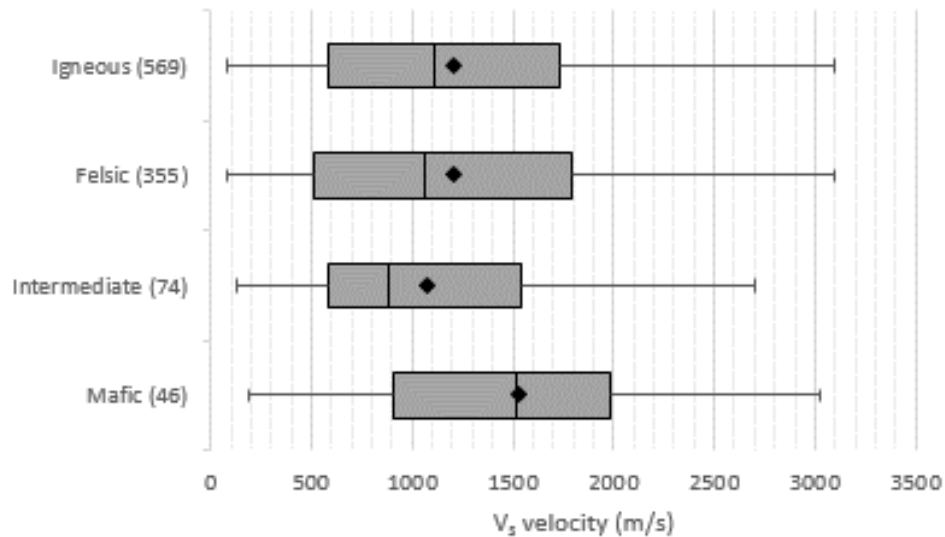


Figure 2-16: *In situ* results from version 2 of the Global V_s Database of igneous rocks divided by mineral character.

In situ measurements show that mafic rocks have a higher V_s on average compared to felsic deposits. The mean increases by 300m/s from the mafic to the felsic (Figure 2-16). Unlike the excluded laboratory results (Figure 2-14), intermediate rocks do not follow a trend of increasing V_s with increasing silica content. However, it is noted that none of the categories vary significantly from the overall igneous class.

Compared to the results of Campbell (2014) from the lab section of the database, the *in situ* results have a larger interquartile and overall range. The interquartile range is generally large than 1000m/s in the *in situ* measurements. If depth is also considered, there is little difference between the categories in terms of scatter or trend in the data (Figure 2-17).

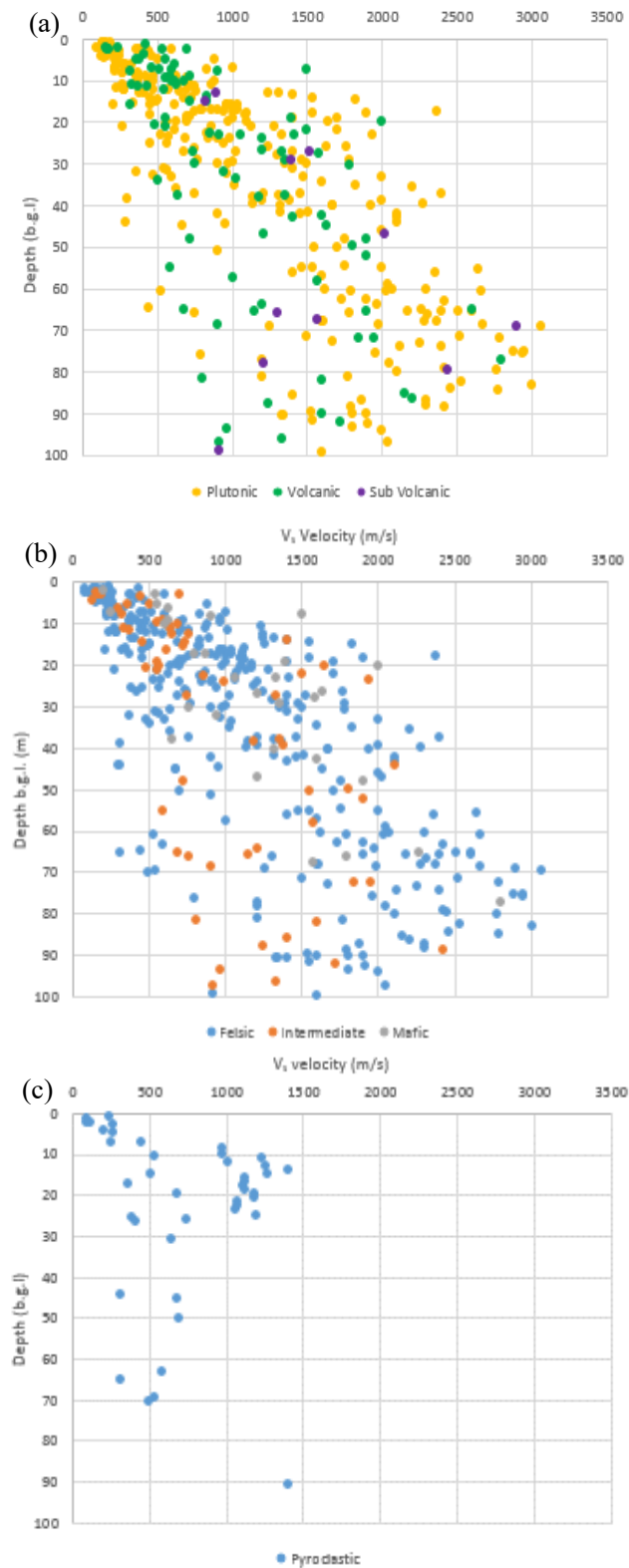


Figure 2-17: *In situ* results from version 2 of Global V_s Database. Relationship of V_s velocity and depth with igneous rocks divided by (a) depositional environment, (b) mineral character and (c) pyroclastic rocks.

2.5.4 Sedimentary rock

Campbell (2014) separated the excluded laboratory data for sedimentary rocks by composition and grain size. However, the results showed no clear trend, all being similar in V_s velocity (Figure 2-18). The same result is found in the extended *in situ* database (Figure 2-19). The results again appear similar to the overall sedimentary class. The mean V_s value for each category is within 215m/s, except for the silts & sands and conglomerates.

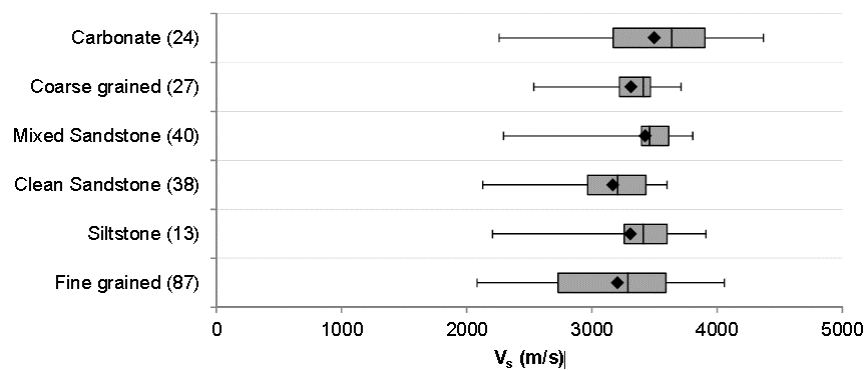


Figure 2-18: Campbell (2014) results from lab data of sedimentary rocks divided by grain size.

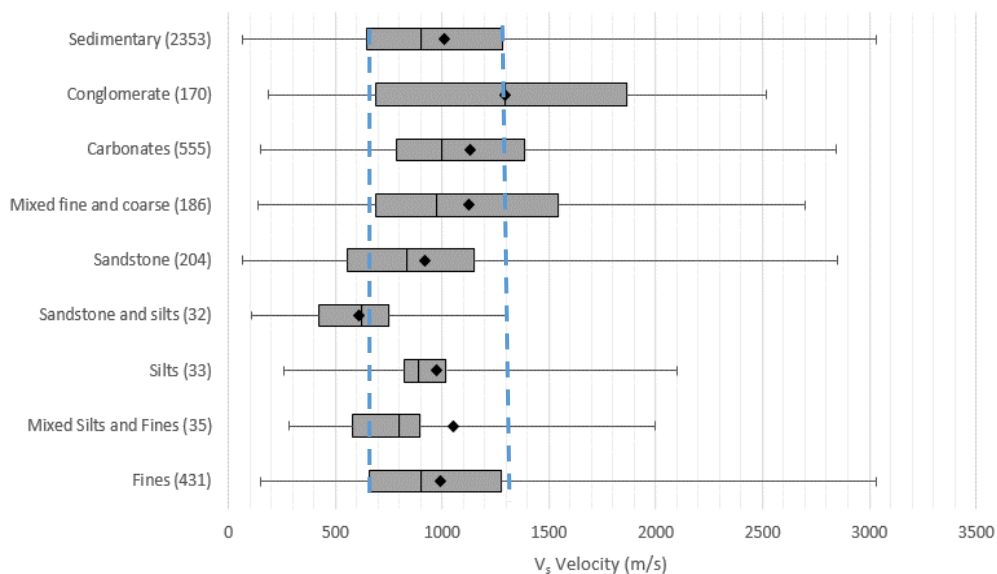


Figure 2-19: *In situ* measurements of V_s in sedimentary rocks divided by grain size. The overall sedimentary class is shown in the top rock and the vertical dashed lines mark the 25th and 75th percentiles.

The change in V_s with depth is similar between carbonates and fines (Figure 2-20a) and sandstones and conglomerates (Figure 2-20b). Fine grained sedimentary rocks do show an increase in V_s with depth, particularly in the upper 40m (Figure 2-21a). However, compared to the overall sedimentary

category (Figure 2-12b), the variation in the near surface is reduced to under 750m/s and more similar to the igneous scatter. The carbonates and fines generally have a smaller interquartile range, but similar overall variability to the sandstones and conglomerates. Both groups maintain a relatively constant V_s velocity below 40-50m. Several of the sandstones have very high velocities from 0-5m depth below ground level (b.g.l.) and are not considered reliable. These are generally from non-invasive measurements, which are less accurate in the near surface.

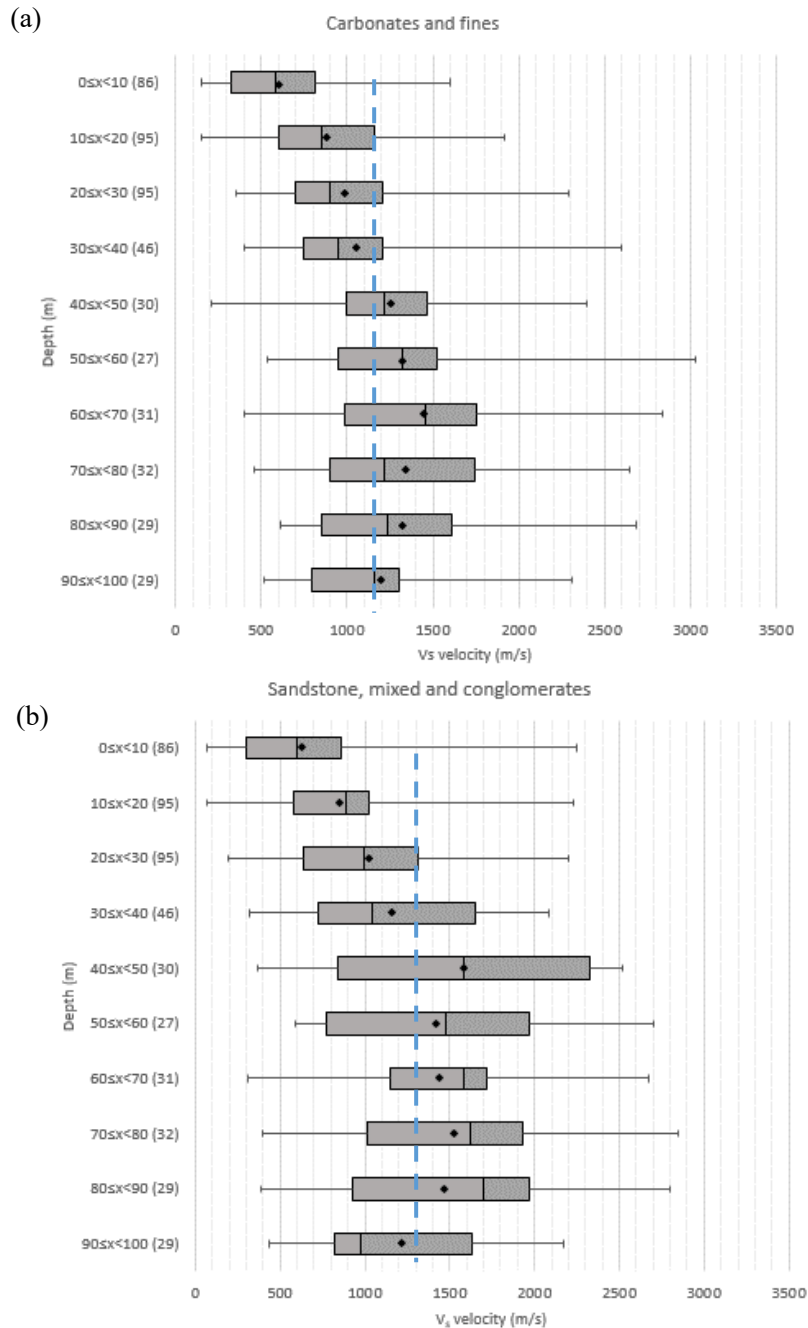


Figure 2-20: Relationship of the V_s velocity of *in situ* records of sedimentary rocks with depth: (a) Carbonates, carbonates & fines and fines; sandstones, mixed fines & sands and conglomerates. The average value for all depths is marked with the dotted line.

Siltstones are much more scattered with no clear trend, but the number of results are low (Figure 2-21b). This is similar to the pyroclastic igneous rocks. Finally, sandstones, mixed and conglomerates also show increased V_s with depth, but with greater scatter (Figure 2-21c). This is also evident in the near surface where velocities of over 2000m/s are visible. However, overall the distribution of V_s in these groupings are more similar to the igneous and metamorphic due to the removal of the fines and carbonates.



Figure 2-21: Relationship of the V_s velocity of *in situ* records of sedimentary rocks with depth divided by grain size: (a) Carbonates, carbonates & fines and fines; (b) fines & silts, silts and silts & sands; (c) sandstones, mixed fines & sands and conglomerates.

2.5.5 Metamorphic rocks

Campbell (2014) divided the metaphoric rocks in the laboratory database by origin. Although the laboratory data is not included in Version 2, the original categories included sedimentary and igneous origins, as well as gneiss which is a known to be formed through both sedimentary and igneous origins (Campbell 2014). Contact metamorphism and fault-zone metamorphism are also included. However, records of fault-zone metamorphic rocks are not yet included in the extended *in situ* database, so the categories are limited to four.

From the lab measurement database (Figure 2-22), the results were fairly consistent with the overall interquartile range of 3512-4299m/s (Campbell 2014). In comparison with *in situ* measurements, the mean of these values is extremely high and differed from the means of the extended *in situ* results database by 2551m/s. However, the *in situ* test results show greater scatter (Figure 2-23). Meta-igneous rocks have a 50% lower mean than meta-sedimentary rocks. The mean and the median of the contact metamorphism group are higher than the third quartile of the overall metamorphic group. Although there is no clear trend, there are also few results associated with these categories, only the sedimentary origin having over 30 records.

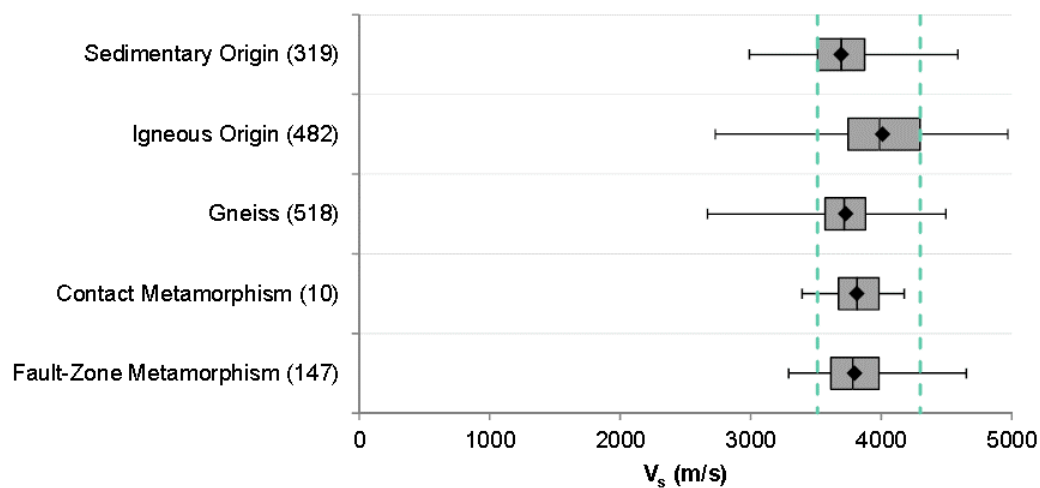


Figure 2-22: Campbell (2014) laboratory tested metamorphic rocks divided by origin excluded from Version 2 of the database.

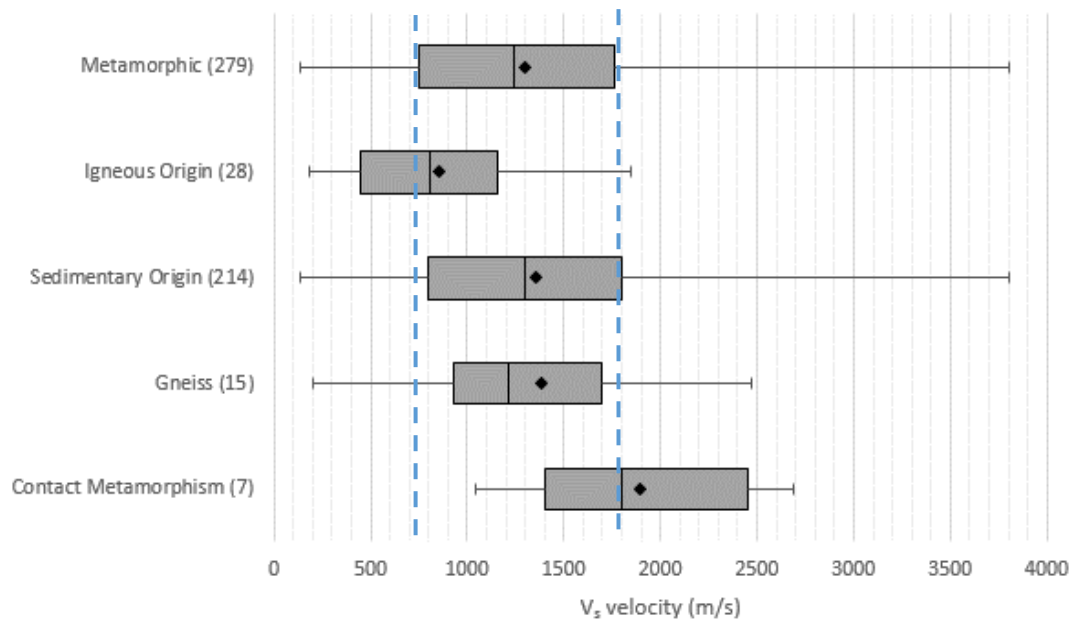


Figure 2-23: *In Situ* records from Global V_s Database for metamorphic rocks categorised by origin. The overall metamorphic class is shown in the top rock and the vertical dashed lines mark the 25th and 75th percentiles.

Metamorphic rocks show a stronger V_s correlation with depth than both igneous and sedimentary rocks (Figure 2-24). The range of V_s found at the surface is particularly narrow with all records being below 500m/s. This is significant as range of velocities would normally be associated with soil deposits. There is uncertainty in considering the description to for determining rock rather than rock velocities. However, this could have significant implications for site amplification if metamorphic rocks can be degraded to this extent in the near surface.

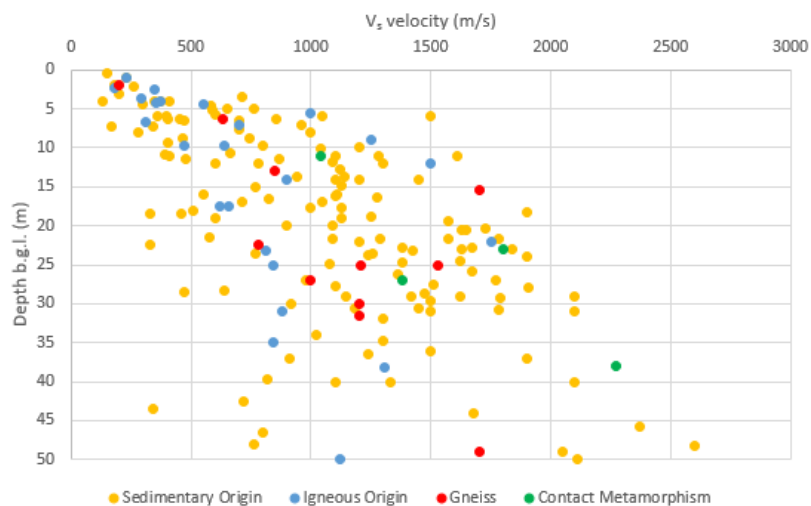


Figure 2-24: *In Situ* records from Global V_s Database for metamorphic rocks categorised by origin and depth.

2.5.6 Influence of rock age: Era

Age is expected to be a controlling factor on V_s velocity as it gives an indication of the likely cementation associated with the rock fabric (Park & Elrick 1998) (Appendix 2-3). Campbell (2014) determined a trend of increasing V_s velocity with increasing age from the *in situ* results (Figure 2-25). However, due to the unequal time periods, it is unlikely the trend will be linear. It should also be noted that in this analysis rock and soil deposits were not separated (Campbell 2014).

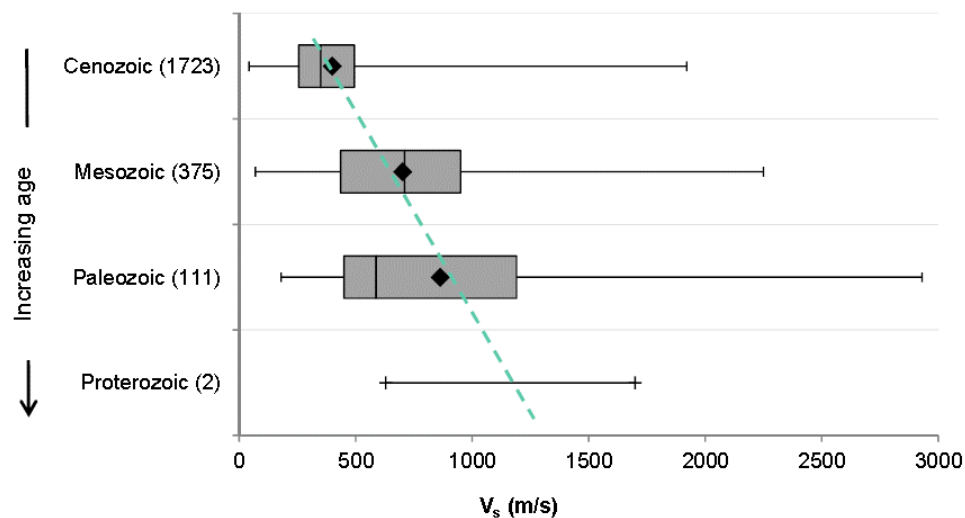


Figure 2-25: Campbell (2014) comparison of age and V_s from all *in situ* results (rock and soil) of Version 1 of the Global V_s Database. (Appendix 2-3). Campbell (2014) indicates the increase in mean V_s with a dashed line drawn by eye.

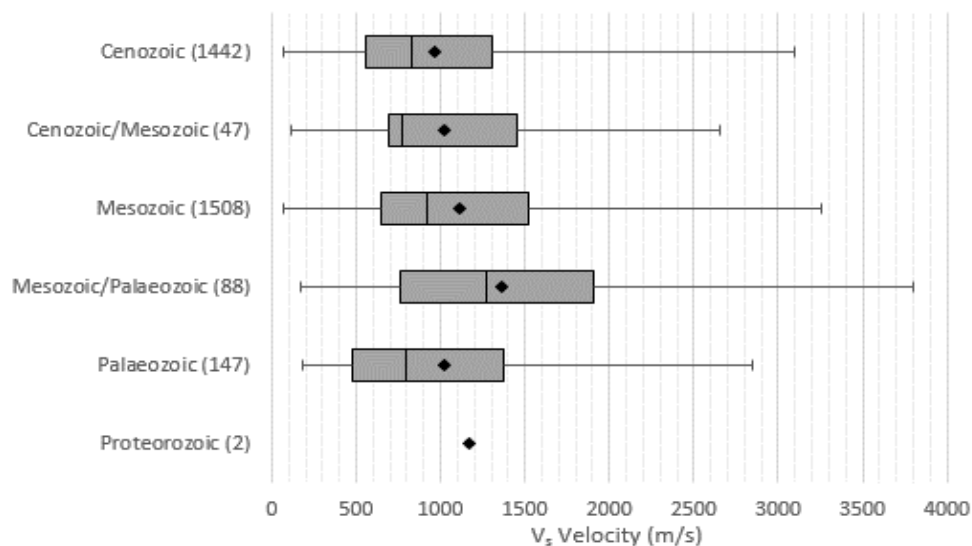


Figure 2-26: Effect of age on V_s velocity of *in situ* rock deposits from records of Version 2 Global V_s Database.

When just *in situ* rock deposits are considered (Figure 2-26), the increase in V_s with age is still visible, particularly when mean of the V_s is considered. The oldest Palaeozoic and Proterozoic eras do not follow this trend, but are similar to the Cenozoic velocities with only 5% difference in the mean. The interquartile range also increases with age until the Palaeozoic era where it again reduces. This is an interesting step change in the records and may represent a change in the controlling factor.

The likely depths of each of the deposits must also be considered. The majority of the Cenozoic rocks are likely to have been measured in the surface, while Mesozoic and Palaeozoic are likely to be at greater depth. However, this assumption is not necessarily true for the KIK-net or Californian datasets. The age of US and Japanese rocks a depth was less than those found in Turkey and Europe. Therefore, depth was also considered.

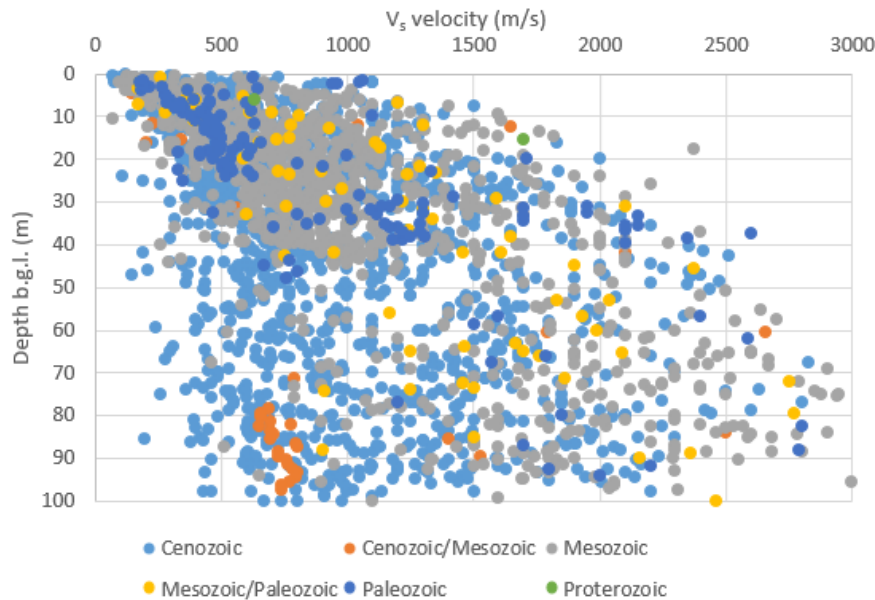


Figure 2-27: Effect of age on relationship of depth and V_s of *in situ* rock deposits from records of Version 2 Global V_s Database.

The rate of change in V_s with depth is variable with age (Figure 2-27). The rate of change is seen to increase from Cenozoic to Mesozoic (Figure 2-28). However, at Palaeozoic, the gradient reverts back to a similar gradient to Cenozoic. The difference between the Cenozoic and Mesozoic eras is particularly noticeable (Figure 2-28) with the Cenozoic rocks over 40m below ground level (b.g.l.) having a weak correlation with depth.

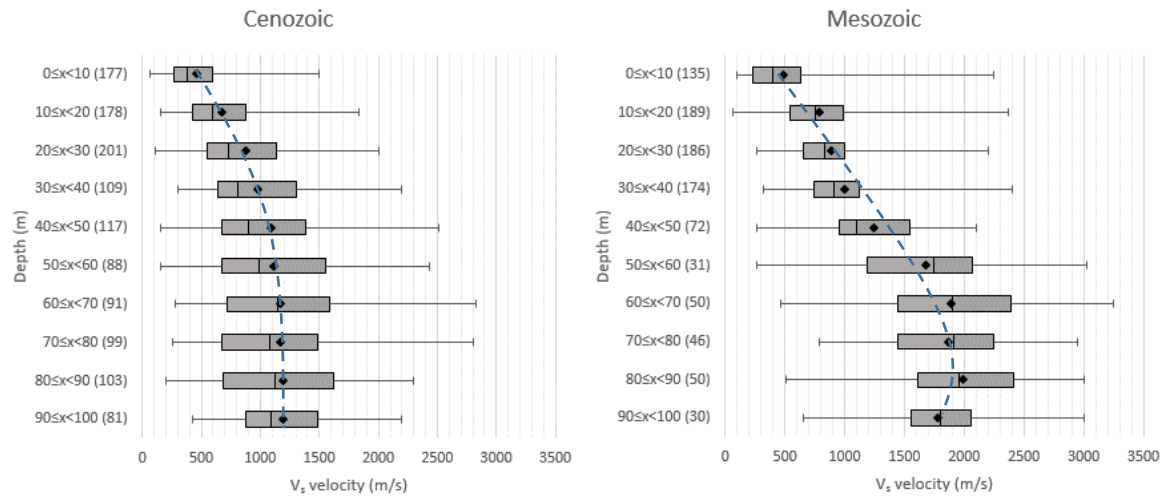


Figure 2-28: Comparison of rate of increase of V_s velocity in rock with depth for (a) Cenozoic era and (b) Mesozoic era.

2.5.7 Influence of rock age: Cenozoic

The effect of the increase of age on V_s is also examined at the time period level (Figure 2-29). The mean V_s is seen to increase between Quaternary and Paleogene time periods by 44%. The interquartile range also increases by 50%, despite more records in the Neogene category and similarly in the Paleogene. This could be caused by another controlling factor such as depth of the deposits.

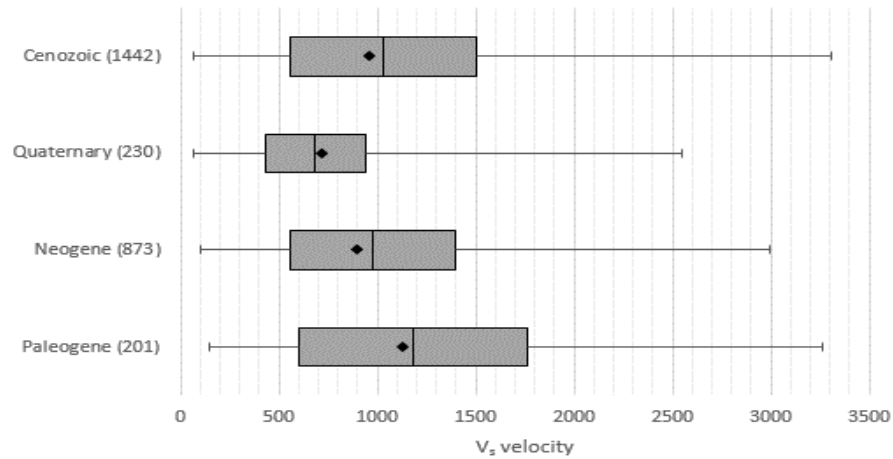


Figure 2-29: Effect of age on V_s for Cenozoic era separated into time periods.

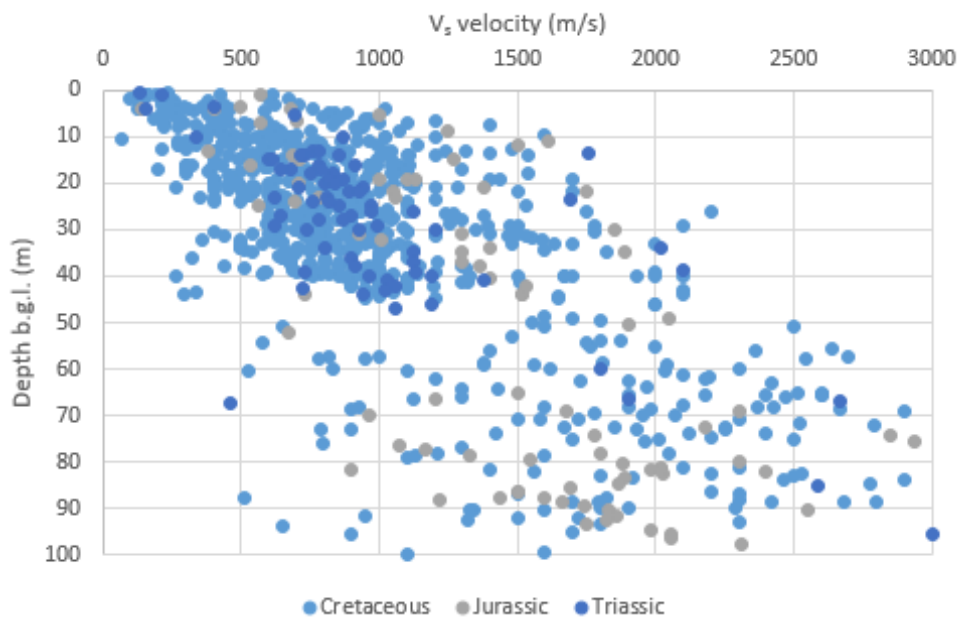


Figure 2-30: V_s of Cenozoic time periods with depth for the *in situ* results of Version 2 of Global V_s Database.

All the time periods have similar rates of increase in V_s with depth (Figure 2-30). However, the Paleogene records are translated higher than both the Quaternary and Neogene. These two have similar variation in records. This is similar to the step change in the Proterozoic results.

2.5.8 Influence of rock age: Mesozoic

In Mesozoic rocks, the trend of increasing V_s with age is less pronounced (Figure 2-31). Although from the Cretaceous to the Jurassic, there is a significant increase, the mean of the Triassic is 335m/s lower than the Jurassic. The interquartile range is also reduced, not following the previous Cenozoic trend. It is also notable that the Paleogene category (Figure 2-31) would be higher in mean and median than the Cretaceous.

There is a slight increase with age in the rate of V_s increase with depth (Figure 2-32). The Triassic rocks have a steeper gradient than Jurassic and the Cretaceous being the shallowest. However, this distinction is weak and no clear trend is visible.

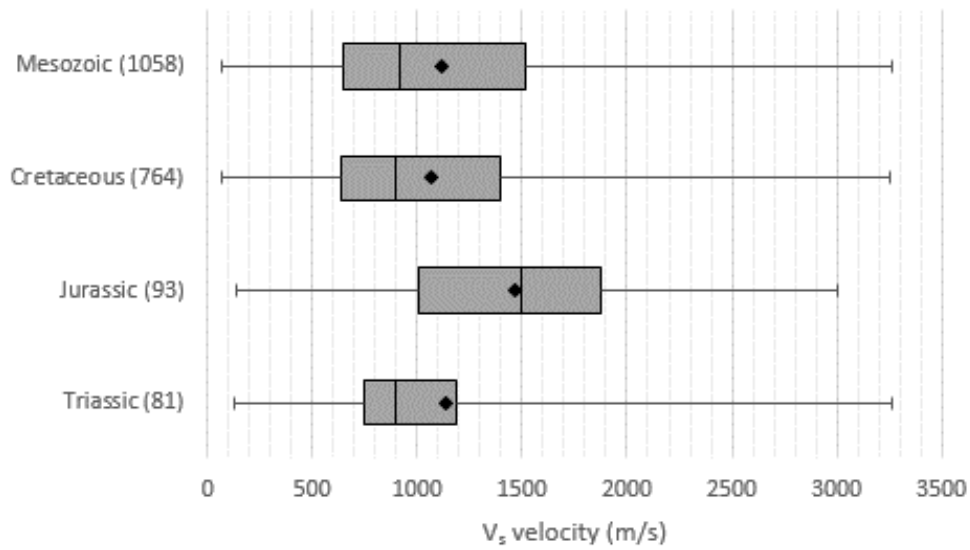


Figure 2-31: Mesozoic era rocks separated into time periods for *in situ* records of Version 2 of the Global V_s Database.

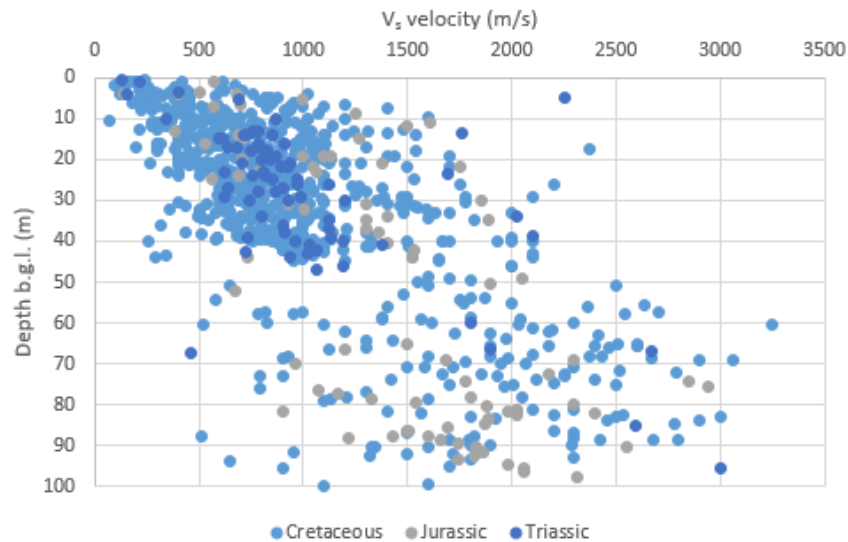


Figure 2-32: Relationship with depth of Mesozoic era rocks classified according to time period for *in situ* records of Version 2 of the Global V_s Database.

2.5.9 Influence of rock age: Palaeozoic

Palaeozoic-age rocks did not follow the general trend observed in other geological eras (Figure 2-33). However, few records were found for materials of this age and not enough to examine the Devonian and Cambrian periods. Therefore, it was not attempted to divide it further.

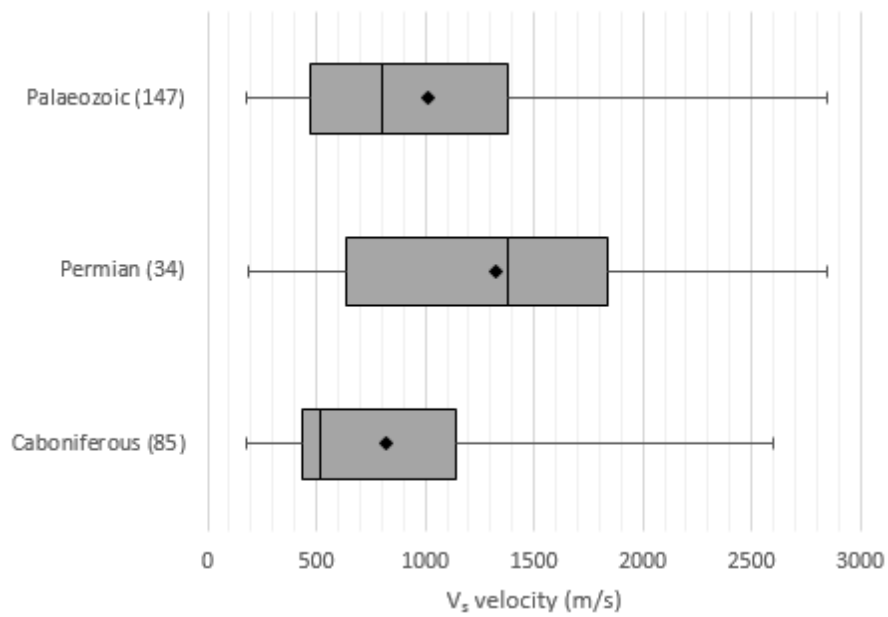


Figure 2-33: Palaeozoic era rocks separated into time period for *in situ* records of Version 2 of the Global V_s Database. Devonian and Cambrian time periods were not included as they had only four results.

2.5.10 Combination of rock origin and age

When age and rock origin are combined, several other characteristics are visible. Both in the Cenozoic (Figure 2-34a) and Mesozoic eras (Figure 2-34b), the shape of the box plots remain similar the overall origin categories (Figure 2-9) *i.e.* the igneous and metamorphic rocks have larger interquartile ranges than the sedimentary rocks. When depth is also considered, the both eras contain significant scatter, particularly at low V_s velocities with increasing depth (Figure 2-34a). In the Cenozoic era, the metamorphic rocks are also seen to be distinctly higher in V_s velocity with depth than the other two classes.

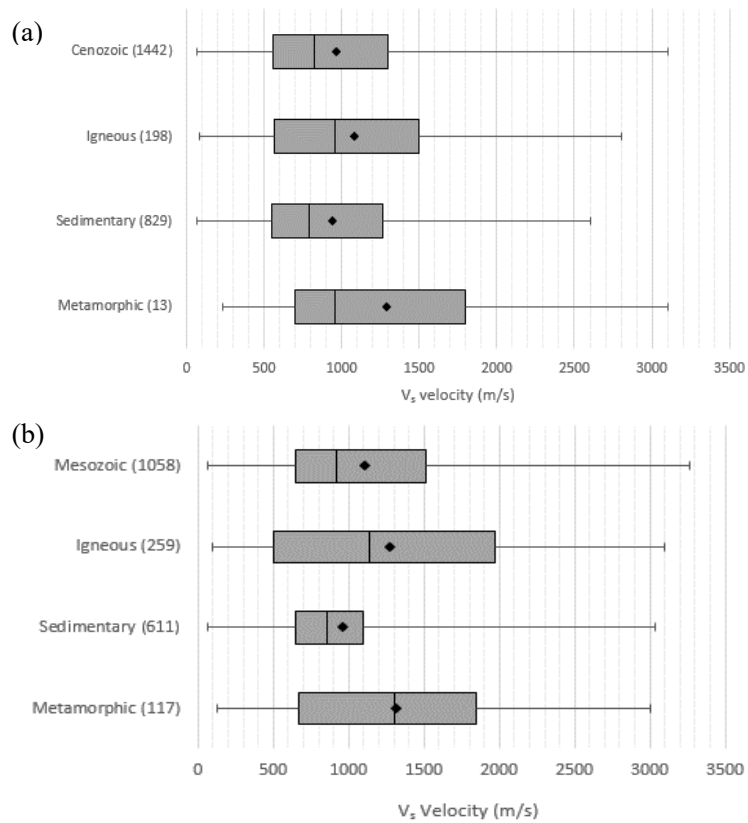


Figure 2-34: Combined consideration of rock origin and age: (a) Cenozoic Era & (b) Mesozoic Era.

There smaller variation in the surface V_s of the Mesozoic rocks (Figure 2-35b) than in the Cenozoic era (Figure 2-35a). Both the igneous and the metamorphic records are spread evenly with depth in the Mesozoic era, but the sedimentary records are grouped from 40m upwards indicating a lack of data below this depth.

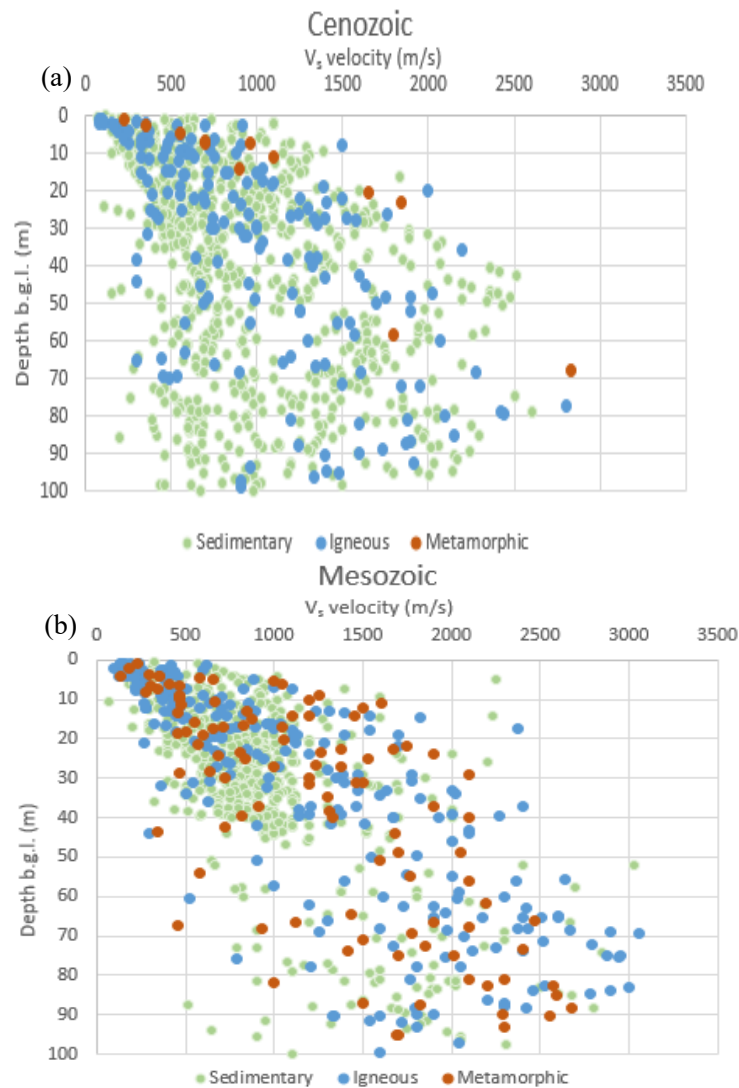


Figure 2-35: Combined consideration of rock origin, depth and age: (a) Cenozoic Era & (b) Mesozoic Era.

From the results of this study, rock type, origin and age only appear to have some influence on the behaviour of the V_s profile, while only depth is considered to be a controlling factor. Certain categories have distinct characteristics; Triassic rocks have lower velocities on average than other Mesozoic rocks. Sedimentary rocks have a narrower average range of V_s than Igneous or Metamorphic. However, these are specific examples of particular types of rocks and while trends are often observed when partitioning the overall data into small classes, the overall level of variability coupled with the large number of potentially influencing factors makes it very difficult to appreciate whether these trends reflect some underlying physical phenomenon or whether they reflect sampling issues inherent

in the data.

2.5.11 Rock weathering and fracturing

In the broader study, Campbell (2014) also considered the influence of the weathering and fracturing of rocks. For the influence of weathering, there was a distinct step in the general trend of increasing V_s with decreasing weathering grade between slightly weathered rocks to moderately weathered rock (Figure 2-36). Campbell (2014) suggests this is the point where mineral grain decomposition begins and the rock becomes more soil-like.

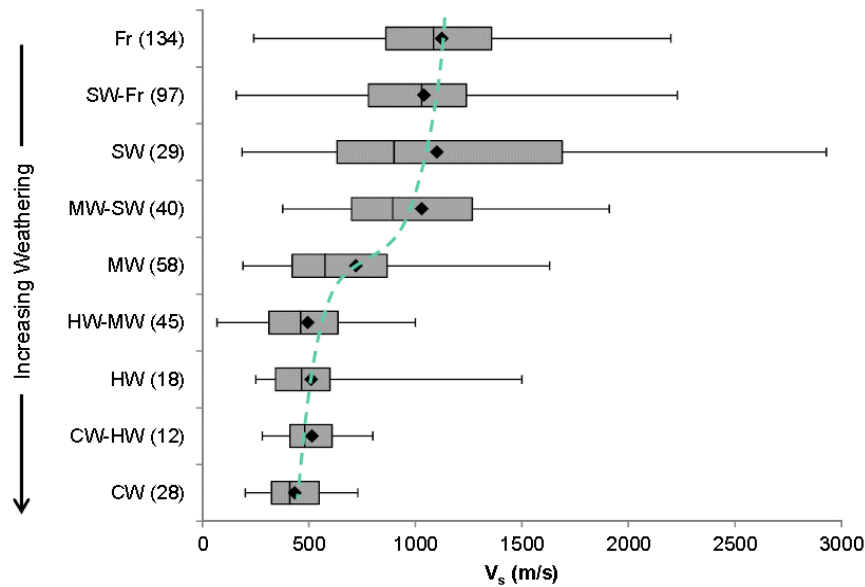


Figure 2-36: Campbell (2014) results from Version 1 Global V_s Database indicating the change in V_s with weathering. Fr is fresh rock, SW is slightly weathered rock, MW is moderately weathered rock, HW is highly weathered rock and CW is completely weathered rock. Campbell (2014) indicates the step change in mean V_s with a dashed line drawn by eye.

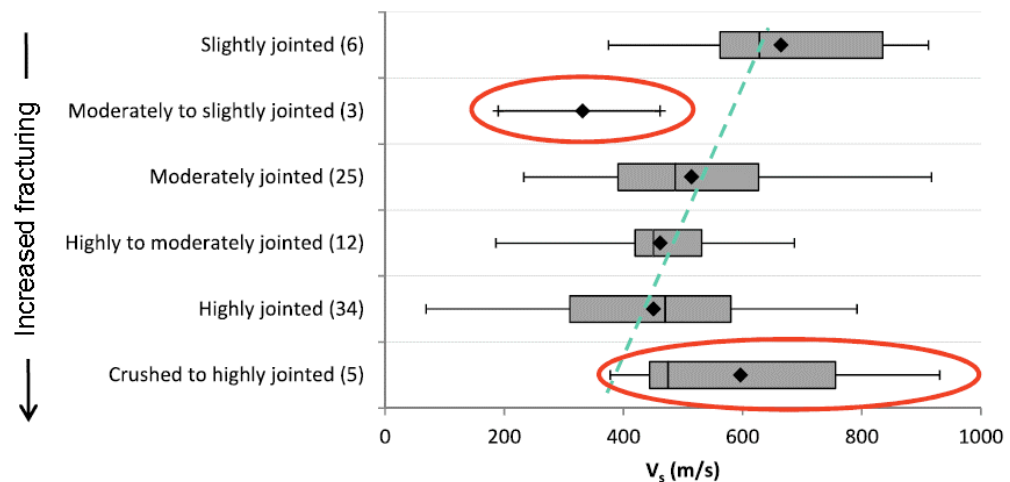


Figure 2-37: Campbell (2014) results of the Turkish Dataset from Version 1 Global V_s Database indicating the change in V_s with fracturing.

For fracturing, a decrease in velocity with depth is also determined from the Turkish dataset (Figure 2-37). This result is less robust as there are few records with this level of detail. The results of the fracturing of the USGS data were more uncertain with a weaker trend (Campbell 2014).

The new datasets used to form the Version 2 of the Global V_s database are suitable for the aims of the next chapters of this study. They include a larger proportion of igneous and metamorphic rocks and so are more representative of UK geology. However, the main limitation of the new data is that there is no formal information on the weathering and fracturing in the records. This means nothing could be added to Campbell (2014) assessment, but fracturing and weathering are considered possible controlling factors and could explain many of the trends seen in the results.

2.5.12 Influence of soil grain size

Campbell (2014) also analysed soils based on origin, examining depositional environment. It was determined that estuarine, alluvial, aeolian and offshore environments generally had a lower V_s velocity than colluvial, glacial or residual deposits (Figure 2-38). This is expected to be caused by grain size (Figure 2-39) (Campbell 2014).

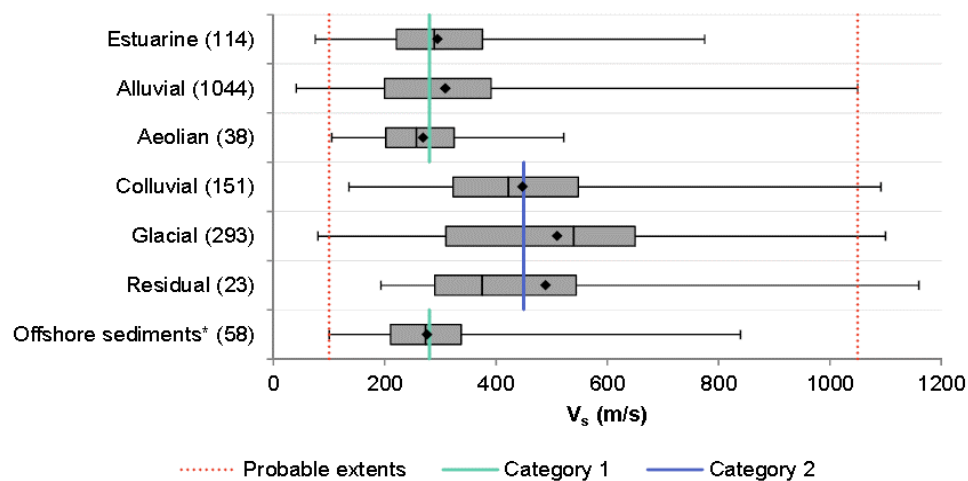


Figure 2-38: Campbell (2014) analysis of depositional environment and V_s velocity for Version 1 of the Global V_s Database. The category lines are drawn by eye.

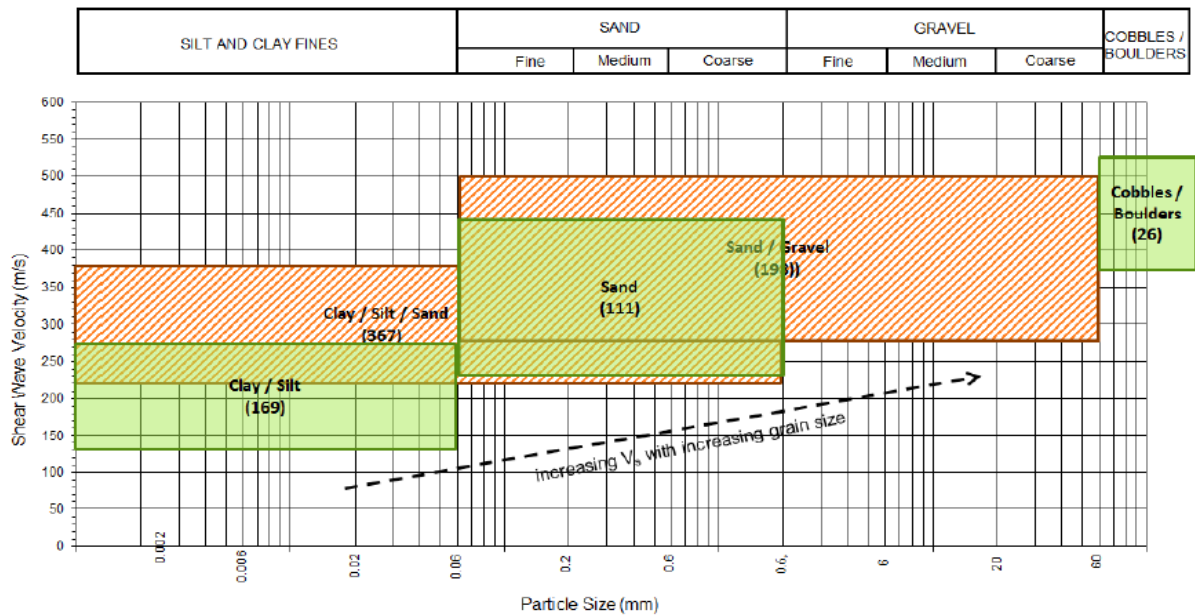


Figure 2-39: Campbell (2014) division of grain size. Typical ranges for particle sizes of the single particle groups are hatched in green while the mixed groups are highlighted in orange.

However, in the Version 1 of the database several of the categories contained few entries as Campbell (2014) limited the results to alluvial environments only. A clear trend with grain size is determined when all results from the extended Version 2 of the database are analysed using Campbell (2014) divisions (Figure 2-40). The interquartile ranges are also small, the largest being gravel of 350 m/s.

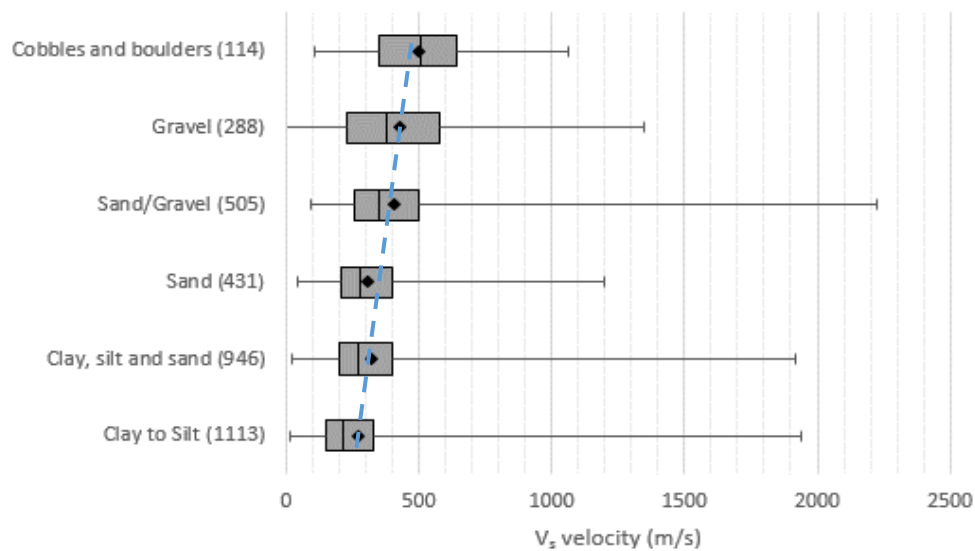


Figure 2-40: *In Situ* soil results from Version 2 of the Global V_s Database, categorised by grain size description as indicated in Figure 2-41. As the groups are classified by description the data is not duplicated between groups. Combining depth and grain size, the rate of increasing V_s depth becomes distinctive (Figure 2-39). V_s increases most rapidly with depth in gravels and sands.

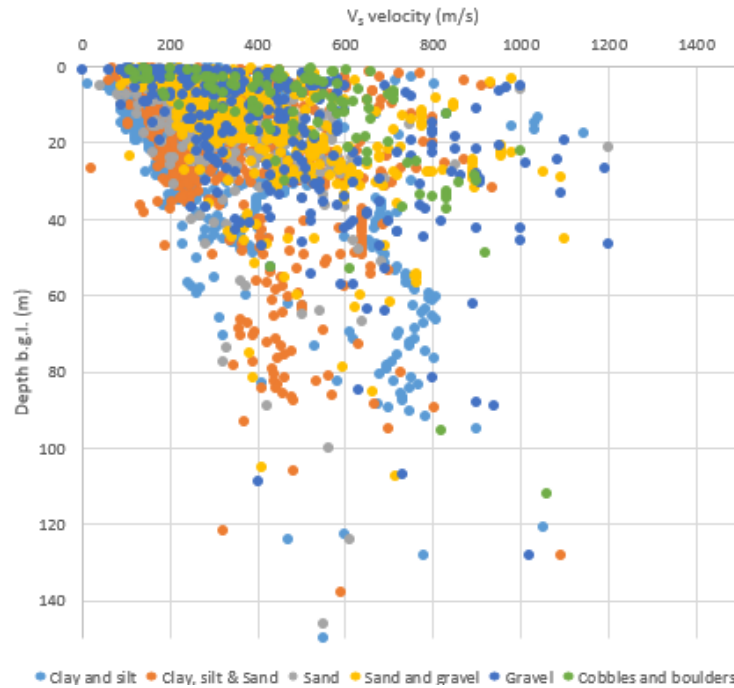


Figure 2-41: *In Situ* soil results from Version 2 of the Global V_s Database, categorised by grain size and depth.

The distribution of each of the grain types is also distinctive and different from the rock distributions (Figure 2-41). All of the clay & silt, the clay, silt & sands, sands and the sands & gravels have a large spread of data in the very near surface, but this is predominately limited to less than 500m/s (Figure 2-42). There is a slight increase in V_s with depth but thus appears less strongly increasing than that of the rock deposits.

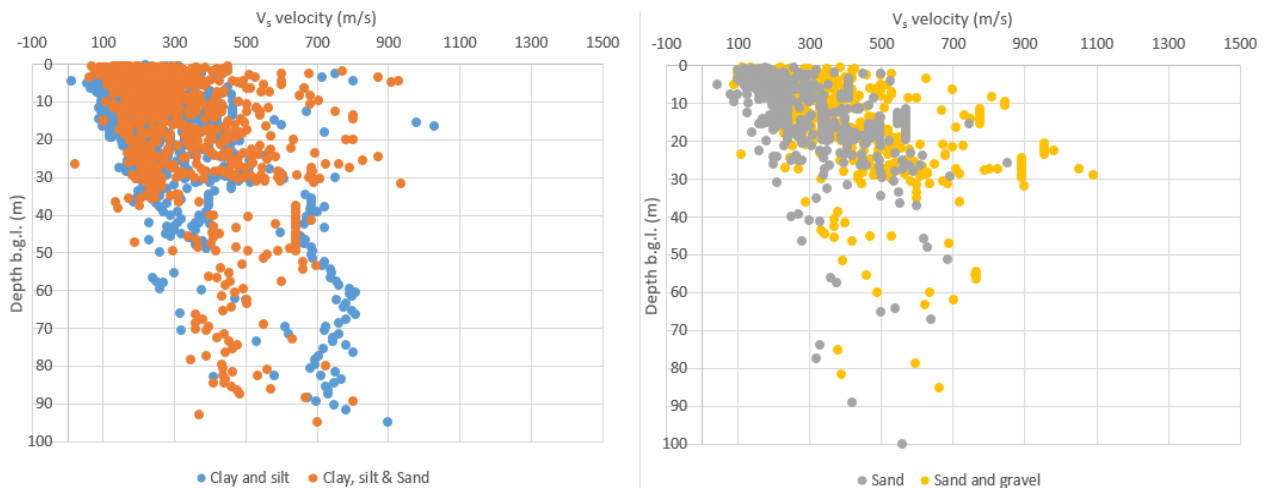


Figure 2-42: Relationship of V_s with small to medium grain size and depth for Version 2 of the Global V_s Database.

The gravels and cobbles have an even wider range in the very near surface, but are generally limited to an upper bound of 600m/s (Figure 2-43). These results are more scattered and do not densely populate the graph. The general variation is also broader than the other soil types.

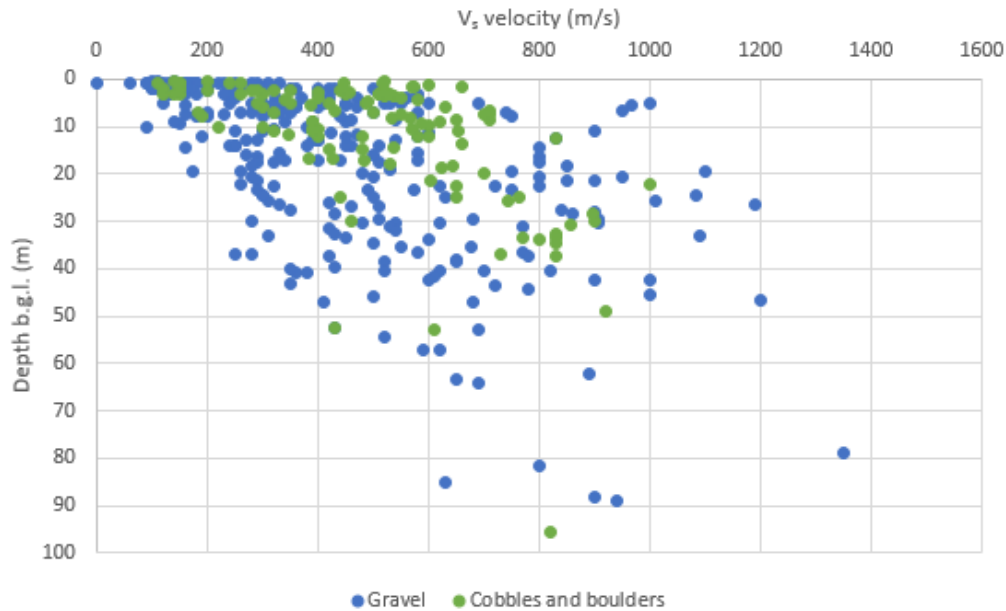


Figure 2-43: Relationship of V_s with large grain sizes and depth for Version 2 of the Global V_s Database.

2.5.13 Effect of increasing depth on V_s in soils

For soils deposits in the Global V_s Database, there is a clear increase in V_s with increasing depth (Figure 2-44). The average V_s velocity doubles over 0 to 50m depth. The interquartile ranges are generally less than the interquartile ranges found in the rock deposits, being on average 150m/s for soil deposits.

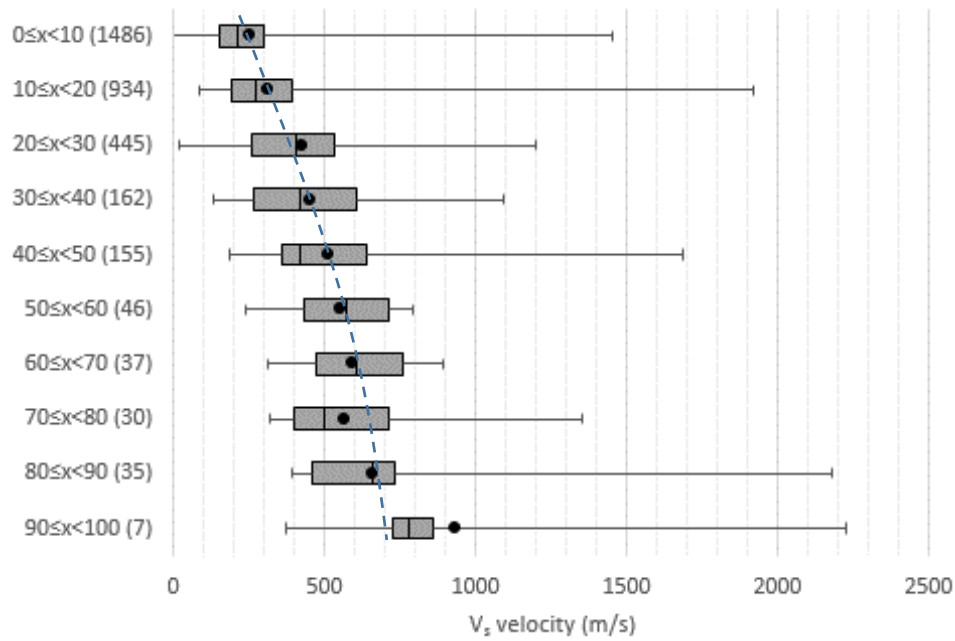


Figure 2-44: V_s with depth for soil results in Version 2 of the Global V_s Database.

2.5.14 Effect of age on V_s in soils

Finally, the effect of age is considered with soil. Soil deposits in the Global V_s Database are generally Cenozoic in age, very few soils tested being recorded as Mesozoic. Therefore, it is considered in time period (Figure 2-45). There is an increase in V_s with age from the Quaternary to the Neogene periods. However, the Paleogene V_s is reduced. This could be caused by similar reasons to the Triassic and Palaeozoic reductions in rocks where it is expected that other controlling factors supersede the age trend.

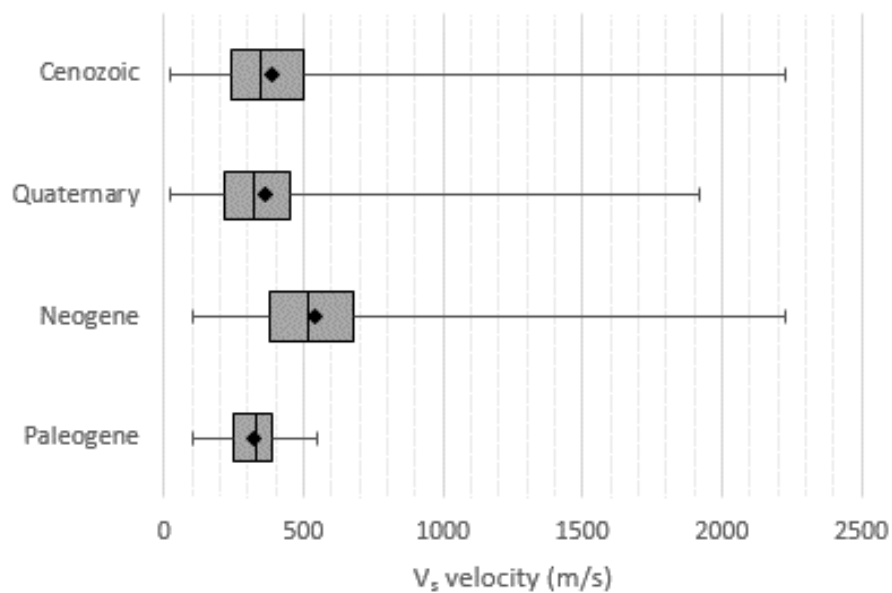


Figure 2-45: V_s velocity with time period for soil results in Version 2 of the Global V_s Database.

2.6 Conclusion

The factors that can be used to characterise site amplification are varied and increasing in number. However, the prevalence of the V_{s30} cannot be overlooked. It does have specific disadvantages, (Mulargia & Castellaro 2009), but, in the absence of a fully characterised site, it continues to be the most successful parameter (Kamai *et al.* 2016) and is used in this research.

The relationships between V_s profiles and geology are not commonly studied. Most advances in this relationship have come through the progression of proxy methods to determine V_{s30} . However, controlling factors are generally assumed in V_s profile modelling, particularly in relationship to origin, age and depth of a deposit.

The Global V_s Database aims to allow a better examination of the relationship between V_s and geology. This has been extended in this study from Campbell (2014) Version 1 co-supervised by the author, by the addition of two large datasets and industry data. It should be noted much more data is available worldwide and Version 2 of the database is by no means all-encompassing (Appendix 2-4). In addition, categories have been defined by description leading to uncharacteristic V_s values of rock being determined (<800m/s). This has been done specifically to show the wide variation caused by geological effects such as weathering in the near surface and to show that a “rock” may not always be defined as a true rock in terms of its stiffness. Strong

From the parameters of rock type, origin, age and depth of rock, depth of the deposit is the only factor examined to have a convincing influence on V_s profile over the top 40-50m b.g.l. This could be further seen in examination of other parameters where trends with depth could be identified. Rock type origin and age parameters have a more tenuous effect, which breaks down on more detailed examination. For example, the expected trend of wider ranges of V_s in igneous and metamorphic rocks than sedimentary is determined as well as increasing V_s with depth and time era. However, when time eras are broken down into periods the trends are altered. Therefore, it is likely that other controlling factors are influencing these relationships. Two further factors expected to impact V_s in rocks are fracturing and

weathering and these are included in the Chapter 3 comparisons.

For soil, grain size is seen to be a controlling factor. This parameter also manifests in the depositional environment and highly influences the trend with depth which highlights the main challenge of determining the controlling geological factors on V_s . Many geological parameters are measures for more fundamental factors or are highly inter-correlated. For example, although grain size appears to be a fundamental parameter, it is also highly related to void ratio and could be a representation of cementation.

This challenge can be overcome with further analysis. However, while searching for further possible datasets, a significant number was found that could have been useful additions, but had little geological data included alongside the estimates. As site conditions become a predominant part of uncertainty in future design, care will have to be taken in standards of reporting to ensure this crucial metadata is not dismissed.

If more time had been available, it would have been beneficial to perform regression analysis on this data, in order to formally test for the trends with depth and for soil grain size. Trends with many of the weaker influencing parameters such as age, may be better defined once these controlling factors had been corrected for. However, this was purposefully not attempted at this stage as the time taken would have prevented a meaningful number of data points from being collected.

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CHAPTER 3

Proxy methods for determining V_{s30}

3.1 Introduction

The inclusion of a site characterisation term can reduce the variance of a GMPE by 80-100% (Thompson & Wald 2015). Therefore, recent GMPEs contain at least one predictor variable that reflects the site conditions, generally V_{s30} . However, in regions of low seismicity, such as the UK, few *in situ* tests determining V_s profiles have been carried out (Lubkowski *et al.* 2004), hindering the development of accurate, region-specific GMPEs.

V_s proxy methods for site characterisation were developed to determine V_{s30} values for regions without previous *in situ* measurements. They are established by correlating V_s to another parameter such as surface geology (Wills *et al.* 2000) or topographical slope (Wald & Allen 2007). These methods are prevalent in projects with large geographical coverage (*e.g.* NGA-West database; Chiou *et al.* 2008) or where rapid assessment is needed (*e.g.* PAGER; Wald *et al.* 2008). However, these approaches are less accurate for specific sites. These methods could also be a departure from the original purpose of V_s as they form a proxy for V_s , which itself is a proxy of site amplification (Yong 2016). Despite this limitation, proxy methods continue to allow GMPEs to be developed for sites without *in situ* testing.

In this chapter, the three predominant proxy methods used in current research are summarised, highlighting their advantages and limitations to applications in low seismicity regions, specifically for characterising the UK Strong Ground Motion Stations (SGMS). Due to the limitations of these methods and the difficulties in their application to individual sites, a new Site-Specific proxy method is developed. The results of the application of the new method to 15 of the UK SGMS are also discussed.

3.2 Current proxy methods

The three V_s proxy methods most commonly used are reviewed to determine their usefulness for characterising the UK SGMS network. Other schemes do exist, but generally no longer fit with the

NEHRP (Building Seismic Safety Council 2009) or EU (2004) frameworks which are the prevailing site classification systems used to establish site amplification for use in generic building design.

3.2.1 Surface Geology method

Wills *et al.* (2000) developed the Surface Geology proxy method, soon after the V_{s30} was introduced as a main parameter for characterising a site. Initially, the method was intended to replace the Petersen *et al.* (1997) classification map for California which bounded areas of hard rock, soft rock and alluvium. Wills *et al.* (2000) altered this to characterise the geological units to the NEHRP V_s classes, as formalised by Boore *et al.* (1993; 1994).

This method uses the fundamental link of V_s with age and type of geological unit (Park & Elrick 1998a). Wills *et al.* (2000) used a series of 1:25 000 geological maps of California which were digitised and then divided into geological units defined by age and type of deposit. The locations of previous *in situ* V_s tests, from the United States Geological Survey (GSC), were plotted onto the map and a V_s range for each geological unit was evaluated. Correlations were established for the age and type of deposit with V_s (Wills *et al.* 2000) and used to characterise geological units without previous *in situ* measurements. These correlations were then included in the generation of a regional site characterisation map. When the previous *in situ* measurements were replotted on the generated map, 75% of the V_s values mapped were within the correct NEHRP class (Wills *et al.* 2000) with many of those incorrectly classed were near the mapped edge of a geological deposit.

Wills and Clahan (2006) refined the method further for the update of the Pacific Earthquake Hazards Reduction Program (PEER) NGA database (Chiou *et al.* 2008). Geological maps with greater detail were used, particularly around the locations of the previous *in situ* measurements (Figures 3.1a). Combined with improved digital discretisation of the geological units, the assessment at the mapped edges of the deposits was improved (Wills & Clahan 2006). In addition, geological units with large numbers of *in situ* tests were standardised and modelled forming 19 generalised profiles for the different kinds of rock in the region. However, uncertainty was created in these generalised profiles as they depended on a small set of deep *in situ* test results (Wills & Clahan 2006).

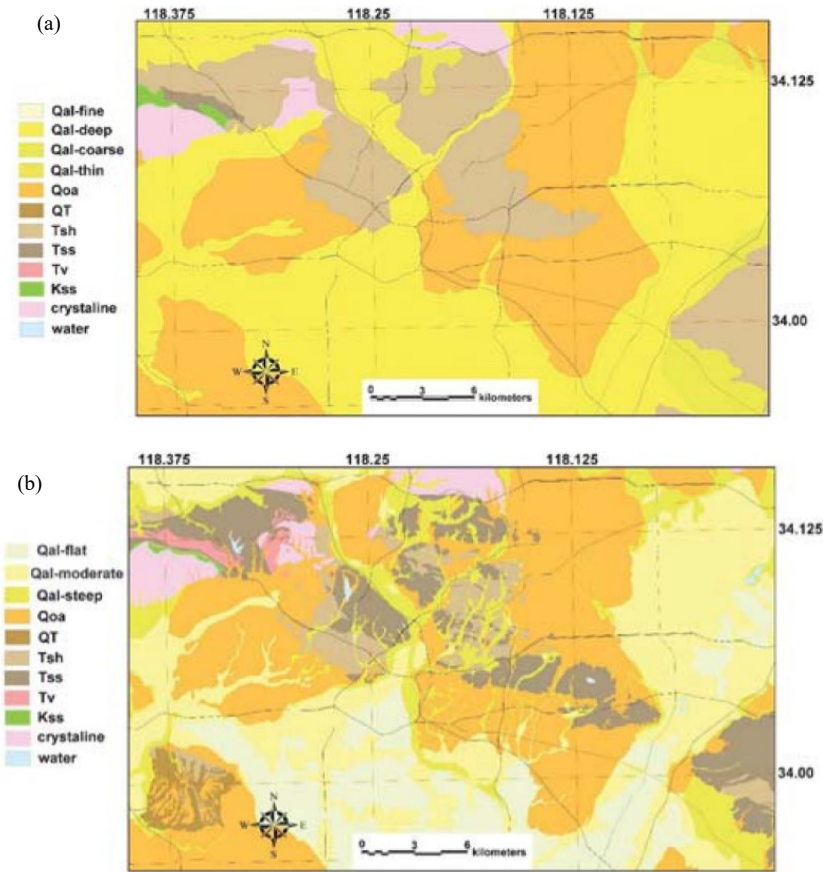


Figure 3-1: Wills *et al.* (2006; 2015) Surface Geology Site classification maps of the Los Angeles Basin (a and b) showing the progression of detail in the method: (a) The map of Los Angeles Basin with surface geology mapped. (a) is improved to (b) by including topographical data. Thus, the alluvium within the river valleys is visible which it is not if only the geological class is examined (Wills *et al.* 2015).

Younger deposits, most specifically alluvium, were the most difficult to characterise, having greater variation in the V_s range particularly within single geological units compared to older units. The introduction of a qualitative topographical factor allowed further site definition among alluvial deposits (Wills & Clahan 2006). Wills & Gutierrez (2011) investigated this further, finding that introducing a slope parameter could improve the estimates of the younger deposits. Deep basin alluvium generally has a lower topographical slope than thinner alluvial deposits in a narrow valley. Wills *et al.* (2015) input these findings into the latest proxy model (Figure 3.1b) and observed that the latest map had improved upon the accuracy of the two previous versions. This was not due to improved map resolution, but rather by improving on the assumptions of the initial method.

This method is generally considered the most accurate of the proxy methods (Yong *et al.* 2012) and is

commonly used in California for classification of untested sites. The NGA-West2 Project includes it as the highest preferred V_s proxy method when assessing V_{s30} value for the strong ground motion stations (Seyhan *et al.* 2014). The method is also being emulated in Taiwan to produce a similar map of the country (Seyhan *et al.* 2014). By combining the ideas of Petersen *et al.* (1997) and Park & Elrick (1998a), this method has much potential for areas with a number of previous *in situ* V_s measurements, where robust correlation between V_s and geological characteristics can be made. In addition, timely improvements of the method have ensured it has increased in use.

However, as geological maps do not necessarily contain sufficient information to determine V_s accurately, with critical parameters not being detailed (Wills *et al.* 2000), this method is not always of practical use. For instance, modes of deposition in soils influencing grain size has been shown to be a significant factor for the younger deposits of Class E (BSSC 2009). This is often not indicated on geological maps nor is the variability within a deposit. Variability at the contacts between deposits is also difficult to define, as the V_s may depend more significantly on the deeper deposits beneath the outcrop (Wills *et al.* 2000). The inclusion of V_s with depth would support this assessment, but it is not yet possible with the current number of *in situ* tests (Wills & Clahan 2006).

A further limitation is that all of the correlations for the proxy method have been developed using West Coast American geological units. When trialled with the Californian measurements, older Italian rocks (more similar to the UK geology) did not conform with the correlations, though the Quaternary categories were found to be unbiased (Scasserra *et al.* 2009). This limits the application of the proxy to regions of older geology, many of which are low seismicity regions, because of the different nature of the deposits. Moreover, there are generally not enough initial *in situ* tests in the low seismicity regions to form separate correlations.

3.2.2 Topographical method

The Topographical method was developed by Wald & Allen (2007) for regions without previous *in situ* V_s measurements. Using precedents from studies in Japan which included geomorphic indicators (Matsuoka *et al.* 2005), where the correlations between elevation and V_s were investigated/derived (Chiou & Youngs 2006), the parameter of slope gradient was chosen. This was selected specifically as satellite digital elevation data can provide uniform quality of topographical data over large

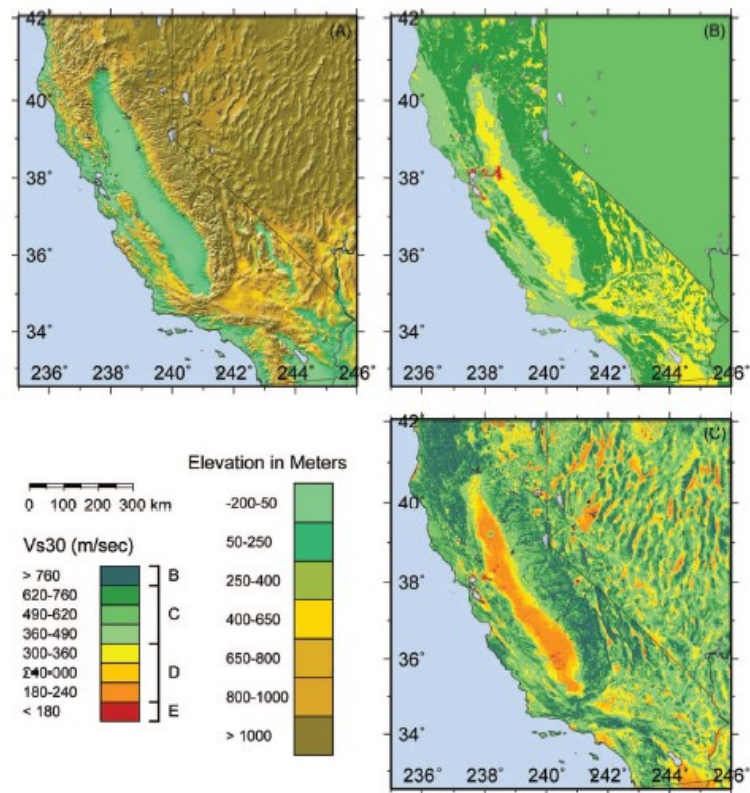


Figure 3-2: Wald & Allen (2007) comparison of (a) Topographical DEM map of California (b) Early Surface Geology Map of California (Wills *et al.* 2000) (c) Topographical Proxy Map for site characterisation.

areas (Wald & Allen 2007).

The method uses the assumption that steeper topography indicates stronger materials, hence higher V_s (Wald & Allen 2007). For example, mountain ranges with steep slopes are generally formed of rocks with high V_s velocities, while flat basin centres are typically formed of soil deposits with low V_s velocities. This also implicitly involves parameters such as effective stress (σ_v') and void ratio (e) which allow the relative angles of the slope to be sustained (Wald & Allen 2007).

In the initial model, Wald & Allen (2007) used Digital Elevation Models (DEM) of 30 arc second resolution, collated through satellite imagery (Figure 3-2a). These were compared to *in situ* measurements from regions including California, Italy, Taiwan, Utah, Memphis and Australia, as well as from other V_s characterisation maps such as the ShakeMaps (Wald *et al.* 1999) (Figure 3-2b). Thus, correlations between slope gradient and V_s were developed. These in turn were refined for tectonically

active and stable regions, as active regions tend to have greater slope angles for lower V_s . Similar to the initial Wills *et al.* (2000) map, the correlations are grouped into ranges for each NEHRP class range (Figure 3-2c).

The method was developed for the PAGER system (Wald *et al.* 2008) which produces rapid estimates of damage to aid the relief effort following large earthquakes. Thus, by design, these topographical characterisation maps can be generated for any region in the world even if no previous *in situ* V_s measurements have been obtained previously. The generation of these maps is fast, repeatable and cheap. As more *in situ* results become available, the correlations can be refined more easily than other methods as the model is not linked to specific geology. However, though possible to generate these maps for any area, they are not necessarily locally calibrated.

Wald & Allen (2007) detail several environments that are more challenging for this technique. These include volcanic plateaus, being regions of subdued topography underlain by strong igneous rock. Glaciated terrain also tends to exhibit low topographic gradients for comparatively higher V_s velocities. In particular, this influences the applicability of the proxy method in many of the low seismicity regions in Northern Europe and Canada. Lemoine *et al.* (2012) found for European sites the proxy method was better than blind chance, but only for EU Class B sites. While Class C sites were characterised more poorly and these locations are arguably more important in assessment for site amplification.

However, the main limitation of this method is the accuracy when applied to specific sites. Due to the rapidness of the assessment needed for PAGER (Wald *et al.* 2008), it is aimed only to be a first order estimate. It is also applied over larger areas possibly without any previous *in situ* results, so when the generated results are investigated at a smaller scale, they are generally not accurate enough for design. Kwak *et al.* (2015) found that regional geotechnical correlations of V_s with Standard Penetration Test (SPT) results improved estimates for V_s compared to geomorphic proxies alone (Section 3.3.1).

To improve the accuracy, the method was tested by Allen & Wald (2009) with a higher resolution map in areas with more *in situ* V_s testing. However, it was found this did not improve the method

significantly. The higher resolution data characterises length scales that are not as consistent with typical length scales of geological/soil deposits. Consequently, advances are expected to come instead from the combination of the Surface Geology method with the Topographical method (Section 3.2.4).

3.2.3 Terrain or geomorphological method

Matsuoka *et al.* (2006) & Yamazaki *et al.*, (2000) investigated the correlation of V_s with both geographical and geological classifications within GIS maps of Japan and the Japan Engineering Geomorphological Classification Maps (JEGM). These studies were similar to the topographical approach of Wald & Allen (2007), comparing V_s to slope gradient. Improved correlation was achieved when V_s was also compared to manually classified terrain units, elevations, and distances from mountains or hills. The inclusion of more than one proxy parameter is beneficial in areas such as Japan where the resources for these correlations are available. In addition, refined terrain maps have recently been found to improve the results (Iwahashi *et al.* 2010). However, to make it applicable worldwide, Yong *et al.* (2012) extended and digitalised the method such that it could be carried out remotely using satellite maps.

The method depends on three parameters: slope gradient, local convexity and surface texture (Yong *et al.* 2012). These are weighted by relative influence on V_s velocities. The primary parameter is slope gradient as it is correlated by the geomorphic processes. Secondly, local convexity or the curvature of the ground surface is considered. This factor assists in the determination of low relief features such as alluvial fans and flood plains. Finally, surface texture which is the frequency of ridges and valleys and so could be described as roughness is measured (Yong *et al.* 2012). These are correlated to V_s through the use of previous *in situ* measurements and V_s proxy classification maps.

Yong *et al.* (2012) used 16 terrain types based on Iwahashi & Pike (2007) with a 1km spatial resolution (30 arcsecs). The Shuttle Radar Topography Mission was used to procure the worldwide DEM maps (Figure 3-3). The maps are then divided into geographical cells which are assessed by each of the parameters, starting with slope gradient (Yong *et al.* 2012).

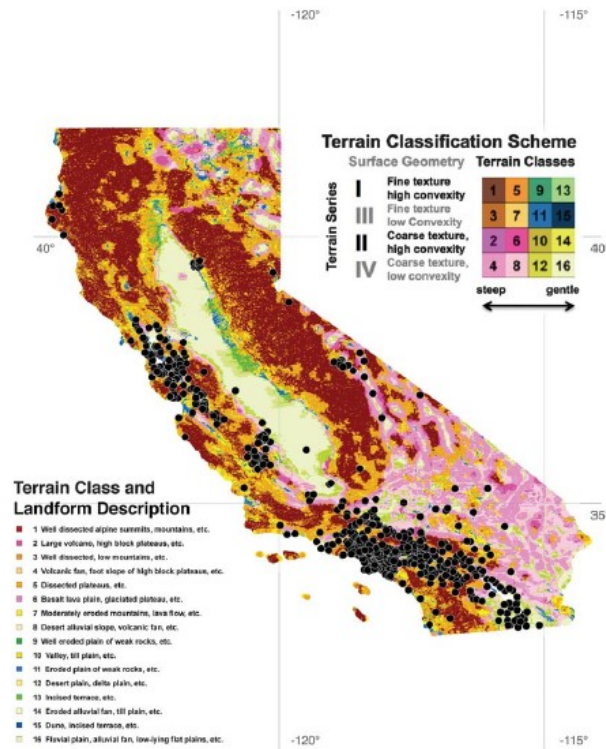


Figure 3-3: Terrain Proxy Map of California (Iwahashi & Pike 2007). The 853 *in situ* V_s measurements used can be seen as black circles. These have a poor spatial distribution over the map leading to concerns of insufficient sampling for each of the terrain units (Wald *et al.* 2011a).

This method is the first which does not depend on a single proxy parameter for V_s alone. Therefore, it gains the advantages of the slope gradient, while the local convexity and surface texture provide further certainty in areas where one correlation alone gives inexact results. The combination of these parameters corresponds well with the rationale that one parameter cannot be enough to describe the likely V_s velocity (Wald *et al.* 2011a). Yong *et al.* (2012) determined that the Terrain method produced improved results from the Topographical method alone when considered over the whole of the US. In a recent comparison of the methods, Stewart *et al.* (2014) considered the Terrain method as having equivalent accuracy to the Wills *et al.* (2015) Surface Geology method (Section 3.2.1).

However, the main limitation of the model is that 76% of the data used in its development is based on V_s velocities inferred from other proxy methods and not necessarily *in situ* measurements (Yong *et al.* 2012). Using multiple correlations requires more V_s measurements in order to assign the new terrain parameters correctly. Therefore, there is a high uncertainty as there is no proof that the method is accurately predicting true V_s values (Yong *et al.* 2012). In addition, there is poor sampling of each of

the terrain units as the few data points that are present are split into groups (Wald *et al.* 2011a). Like the Topographical method, it has problems with some geological environments such as volcanic plateaus and has not fully been tested in glacial environments (Wald *et al.* 2011a).

3.2.4 Combination of Surface Geology and Topographical methods

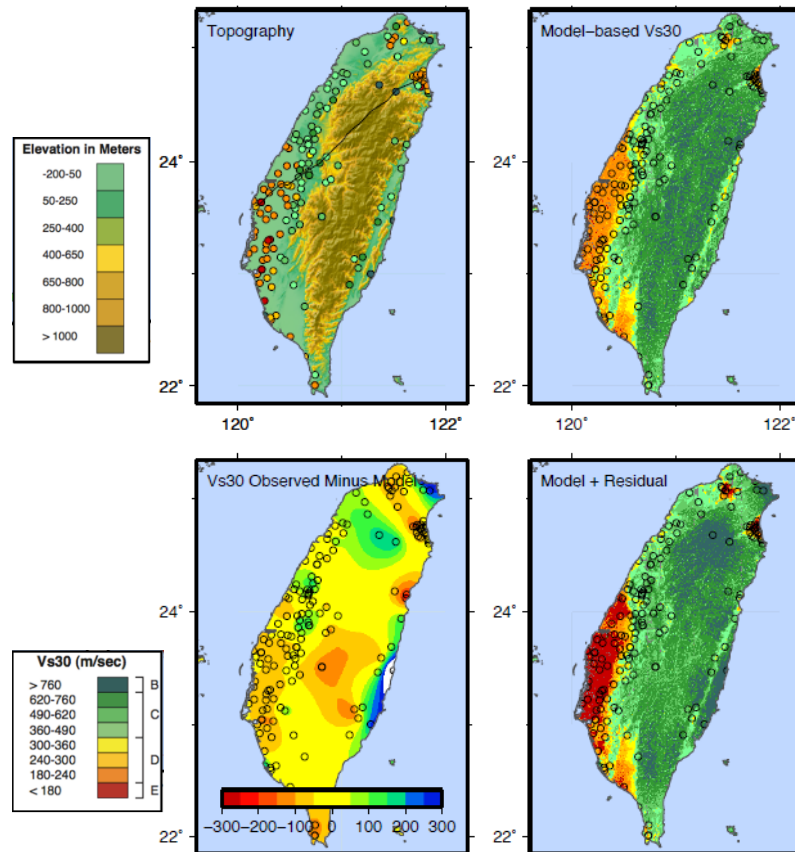


Figure 3-4: Wald *et al.* (2011b) site characterisation maps for Taiwan (a) Topographical DEM map (b) Forward solution of correlation coefficients from the topographical and surface geological models. (c) Kriged residuals from the V_s measurements (d) Final map of combined forward solutions and residuals.

The current research direction for the latest V_s proxy models is the combination of Topographical and Surface Geology V_s proxy methods (Sections 3.2.1 & 3.2.2). Wills & Gutierrez (2011) used this initially to overcome the specific problem of classifying young alluvium (Section 3.2.1). Wald *et al.* (2011a) developed the idea further to combine the models completely, establishing a new hybrid method using the data from Taiwan (Figure 3-4).

The combined method includes kriging in order to account for spatial variation (Wald *et al.* 2011b). Kriging is a generalised least-squares regression algorithm which accounts for spatial dependence between observations (Oliver & Webster 1990) of which numerous variations have been developed. It allows the use of both deterministic results from previous *in situ* measurements, but supports areas with less data using stochastic inferences to correlate between the known measurements (Wald *et al.* 2011b).

Wald *et al.* (2011b) pre-processes correlations in the same region using the Surface Geology and Topographical methods (as described in Sections 3.2.1 & 3.2.2). A forward model is then generated which finds a solution of the two sets of correlation coefficients from the surface geology and topographical results. The residuals for the fit of this solution are formed from comparing the observed values against the solution model and are then kriging is applied to allow for the observed spatial trends in areas of higher uncertainty. This information is then combined with the forward model to produce the final map (Wald *et al.* 2011b).

Wald *et al.* (2011b) designed the method to overcome the previous limitation of failing to reincorporate the measured V_s values once the map is generated. Previous V_s proxy methods only use the *in situ* results to determine the parameter correlations for the generation of the map. They do not re-examine them during the generation of the model nor in post-processing. The use of kriging does, however, allows for incorporation of strong regional trends. The model was recently developed for California resulting in a calculated 40% improvement on the Wills & Clahan (2006) map. The hybrid model also allows for plotting of spatial uncertainty associated with the forward solution and kriging.

However, the resolution of this method is still limited to using higher resolution maps in order to have sufficient numbers of *in situ* testing results, even in high seismicity regions. In addition, having sufficient criteria for determining uncertainty is difficult, particularly as the map for California still depends predominately on proxy-determined V_{s30} values rather than measured profiles (Thompson & Wald 2015). As uncertainties can be taken into account to condition kriging, these issues are expected to be improved.

3.2.5 Limitations of current proxy methods for UK SGMS

If applying any of the discussed proxy methods to the UK, or other low seismic regions, the respective limitations of each method need to be considered. As highlighted by Seyhan *et al.* (2014), each of the proxy methods discussed is region specific. The majority of V_s correlations are based, on Californian ground conditions (Figures 3-1, 3-2, 3-3). Thus, V_s correlations with glacial or older terrains, which includes many of the low seismicity regions, are poorly defined. This could be overcome by updating the correlations with *in situ* tests in these regions, but these are rare and would not yet be sufficient in number to provide statistically significant relationships.

Moreover, the accuracy of the proxy methods can prove insufficient for specific sites as the methods are primarily used for low resolution regional mapping. Despite the refined scales, the maps are not sufficient for small footprint sites such as seismic stations. Furthermore, even though the methods have been reviewed and updated, the current level of dispersion associated with proxy methods by the NGA West2 project (Seyhan *et al.* 2014) is 50%. Comparing three main proxy methods, Yong (2016) determined that they over predict lower V_s values and under predict higher V_s values. In addition, Yong (2016) determined that no single technique of the refined methods is statistically better than any other. Thus, there is a stagnation of development with new advanced maps producing less improvement. This is often due to the dependence of each of the studies on the same parameters or *in situ* results.

Most low seismicity regions, such as the UK, do not have enough previous *in situ* testing to improve the accuracy of the current proxy methods. However, the geology of these regions is generally well characterised. Douglas *et al.* (2009) emphasise the value of using all sources of data to help constrain more generic models to improve accuracy. Currently, there is not a coherent method of incorporating this available geological data into a rigorous evaluation of V_s profile.

3.3 New Site Specific proxy method for characterisation of V_s profile in low seismicity regions

In the absence of sufficient *in situ* testing for use in the discussed proxy methods (Section 3.2), applying these approaches in the UK will only provide first order approximations of V_s . This would be comparable to assuming a Eurocode 8 (EN 2004) site class from the given geological description. Consequently, the methods are not sufficient for characterising the UK SGMS.

A method of characterising V_s is, therefore, considered which is suitable for specific sites. This method will depend on data that is freely available in the UK, such as geological maps and open access, geological *in situ* measurements. This level of information is common among low seismicity regions (Douglas *et al.* 2009), allowing the method to be trialled in areas outside of the UK. The aim of the method is to utilise all available sources to develop a V_s profile for a site and form an estimate of the uncertainty associated with this profile. This is carried out in three stages (Figure 3-5).

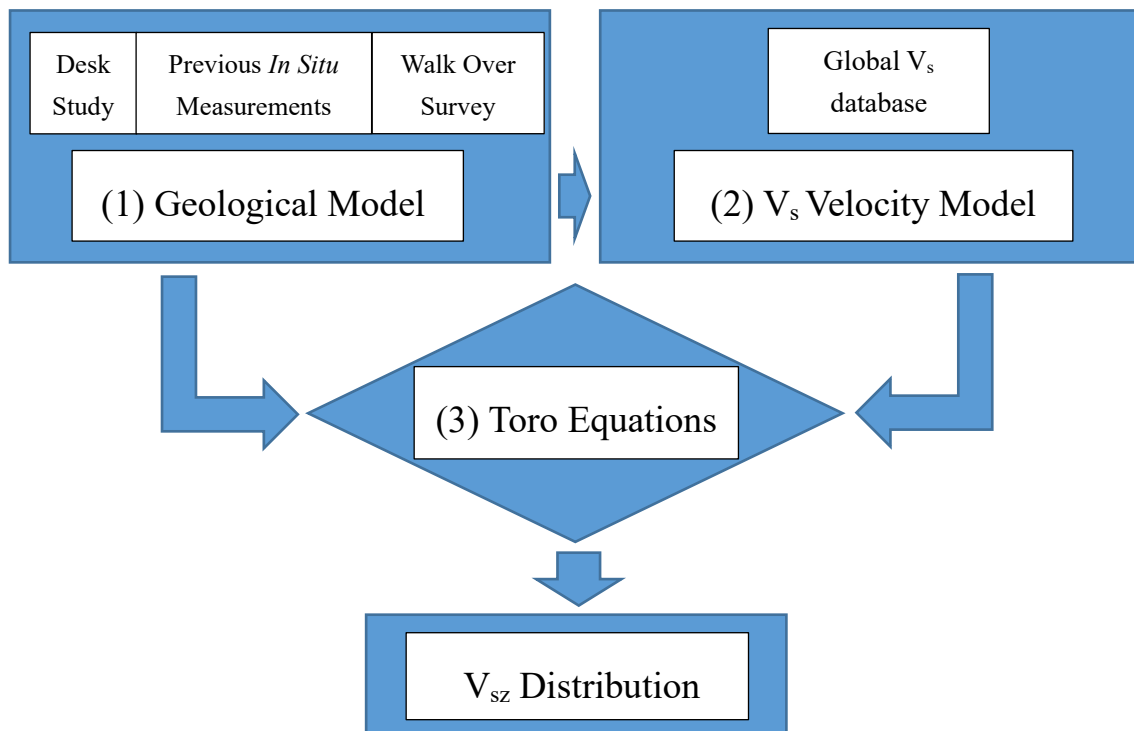


Figure 3-5: Flow chart outline of the Site Specific proxy method: (1) Development of the geological model using a desk study, previous *in situ* measurements and a walk over survey. The strata from this model are compared to the Global V_s database formed in Chapter 2 to develop (2) the V_s Velocity model. Both this and the geological model are input into (3) the Toro Equations and the Monte Carlo simulation is used to determine (4) the V_{sz} Distribution.

The first is to form a geological model of the site. This is critical to forming a site-specific understanding of the nature of the deposits and to constrain each layer thickness in the profile (Section 3.3.1). The second stage is to form a V_s model for the site, determined through comparison with the Global V_s Database *in situ* tests, outlined in Chapter 2 (Section 3.3.2). Finally, Monte Carlo simulations of the Toro Equations (1995) are used to combine the two models to form a distribution of the V_{sz} , generally the V_{s30} (Section 3.3.3). This method is applied to 15 of the UK SGMS (Figure 1-2) and examples determined during the characterisation of the stations are included within the explanation of the method.

3.3.1 Stage 1: Geological model

Park & Elrick (1998b) highlight the importance of the connection between a geological profile at a site and the V_s profile. In the UK, there is often a significant quantity of geological information concerning specific sites. However, although the relationship between geology and V_s velocity is complex, it is generally reduced to a consideration of one parameter in V_s proxy methods. Though no one geological parameter has been found to be the controlling factor (Chapter 2), a geological model or ground profile of a site can constrain the V_s profile, predominantly when the nature and thickness of the deposits are known.

While the relationship between the site geology and V_s velocity may seem self-evident, the detailed geology of a site is frequently not considered during a seismic site investigation. For example, the advanced Italian Strong Ground Motion Database (ITACA) has many examples of borehole logs published alongside the seismic invasive testing results for its recording stations (INGV 2015). However, these have not been used to improve the understanding of the site or correlate between the geology and the V_s profile. Several Multichannel Analysis of Surface Waves (MASW) tests (summarised in Appendix 4.1) have been conducted on the stations, yet in the final report, no indication of the expected geology at the site is given (INGV 2015). As MASW is a non-invasive technique, it is not clear that a conclusive method of determining if the results have any similarity to the site specific conditions has been performed. Yet, layers of different V_s have been assigned and a final V_{s30} value published within the database (INGV 2015). Moreover, the differences between

invasive and non-invasive results have not always been resolved despite some of the non-invasive assessments contradicting the geological results.

In the new Site Specific proxy method, the geological model forms the basis of the method. This is further developed from the initial work carried out by Tallett-Williams (2013). The new proxy has a three staged approach to develop the final geological model. The techniques used to develop the models are standard approaches used by geo-professionals. By using established techniques, but with seismic characterisation as the focus, this model provides a low cost option for obtaining a V_s profile for a site. The geological model can then form the basis for selecting testing techniques, constrain stochastic, numerical and inversion models. In addition, this can identify sites with larger uncertainty; thus, enabling prioritisation of further site-specific *in situ* investigations. This is especially important in low seismicity regions where selective testing will provide more value.

(a) Seismic desk study

The desk study is an almost universally utilised investigative stage in any site investigation. This evaluation of prior information is a required element in many geotechnical codes of practice (*e.g.* Eurocode 8; EN 2000). The site geology is evaluated through initial review of regional maps, memoirs and other sources of prior information (Clayton *et al.* 2005). The aim is to clarify the expected geology and topography at the site and to identify the potential hazards posed to the intended structure. However, specific seismic considerations are often not taken into account.

While some of the techniques used are standard to site investigation practice, it is the evaluation and resolution of data and issues identified by them that are important. Increasing volumes of data are available electronically. Therefore, it is important to distil the key points from these data that are applicable to a particular site such that a geological understanding is formed. The Site Specific proxy method differs from previous proxy methods by the emphasis placed on determining the detailed site-specific, *in situ* nature of the materials present and how these affect the seismic characterisation.

Ranges of scale

Studies for seismic site characterisation should include a full range of seismic information across

several scales. The far-field tectonic structure around the site will influence the frequency of faults or develop discontinuities that influence seismic wave propagation. The tectonic stress history in the region controlled the formation and geometry of specific regional structures. For example, following the Variscan Orogeny in the South-Western UK, the principle stress rotated from horizontal to vertical causing renewal shear fracturing (Green 1992). These shear fractures still shape much of the current geological formations in the region making the likely present day geological structure on site more predictable.

In the far-field, it is important to gather any existing data related to velocity profiles at different depths. The strength and crystallinity of basement rocks may result in more focussed wave-paths and therefore, alter the expected amplification at the surface. Thus, a different reference horizon is required or consideration given to the basement rocks. This was determined during the development of generic amplification functions for the Eastern and Western US (Boore *et al.* 1997). The Eastern US crust is older and more crystalline therefore has a significantly higher V_s profile at depth than the Western rocks, changing the depth of investigation during the desk study.

At the regional scale, geomorphology can indicate trends in the V_s (Figure 3-6). ‘U’ shaped valleys or drumlins indicate previous glaciation of a site. This will cause larger variation to the near-surface V_s profile as is seen around several of the UK SGMS including Station WFL1, Anglesey (Figure 1-2). In addition, current or Quaternary geological processes can have a significant effect. Sites in weathering environments, such as Station LBWR, in the Peak District, can undergo degradation of the near surface deposits. This can considerably reduce the V_s results particularly in harder rocks where the decrease is larger.

At a local scale, the nature of the rockhead, the boundary between soil and unweathered rock becomes extremely important. The depth of this contact and its geometry and definition (sharp or gradational) are critical factors that impact upon the impedance contrasts that drive linear site effects and particularly the amplitudes and locations of resonant peaks within the site transfer function.

The types of buildings on the site and the land use should also be considered. Greenfield or agricultural

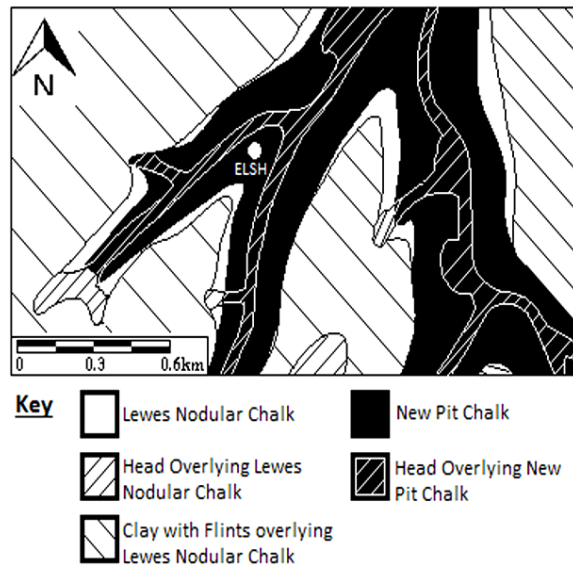


Figure 3-6: Near-field geological map of the region around Station ELSH, 5km north of Folkestone (Adapted from BGS 1982), which is one of the UK SGMS. This shows head deposits which cover much of the high ground and are also present in the bottom of the two dry river valleys that meet to the north-east of the station. During the last Ice Age, this ground was frozen and so may have undergone cryoturbation. Therefore, residual topsoil is expected at the site as it is not mapped with Quaternary head deposits, unlike the other higher elevation slopes.

sites tend to have thicker topsoil. They are less likely to contain crusts of made ground than brownfield or urban sites. Although, topsoil is typically removed for engineering structures, this is not always the case for seismic stations and can be a key consideration.

Topography

At a regional scale, topographical effects may be more critical for the assessment of the site than the possible 1D site amplification. The topography of the site will determine if further 3D analysis may be required for a realistic estimate (FEMA 2015). The local topography can also affect the depth of near-surface soils (Figure 3-7). A structure positioned within a dip or at the base of a hill is likely to have a greater thicknesses of colluvium than a site at a mid-slope location while the crest of a hill may be subject to crest amplification.

Geological structure

The geological structure also should be considered across different scales. In the far-field, the heterogeneity of a rock can affect the ground response (Kramer 1996). Simple structures such as granite plutons, have more consistent V_s velocities, because of low attenuation scattering (energy loss)

in the homogenous rock. This can make the response more dependent on the V_s velocity within the pluton than the near surface deposits. In contrast, heterogeneous or complex structures produce more varied V_s velocities. Numerous reflections and refractions of the seismic waves could occur within the heterogeneous rock and this causes varying attenuation on the wave path. The waves can also reach the surface from a wide area due to refracted wave paths. Therefore, the near-surface deposits may be the predominant factor in the ground response due to scattering rather than site amplification.

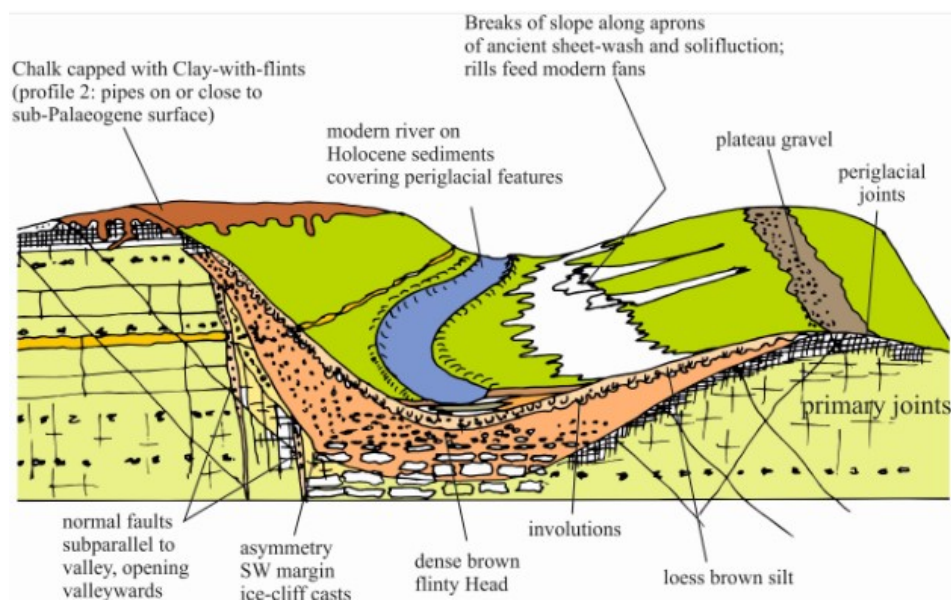


Figure 3-7: Block model illustrating common changes with topography in a chalk landscape (Mortimore 2011), not to scale. This is similar to the ground conditions near Station ELSH. It can be seen that the surface processes can have a profound effect on near surface deposits potentially leading to significant lateral difference in the V_s profiles.

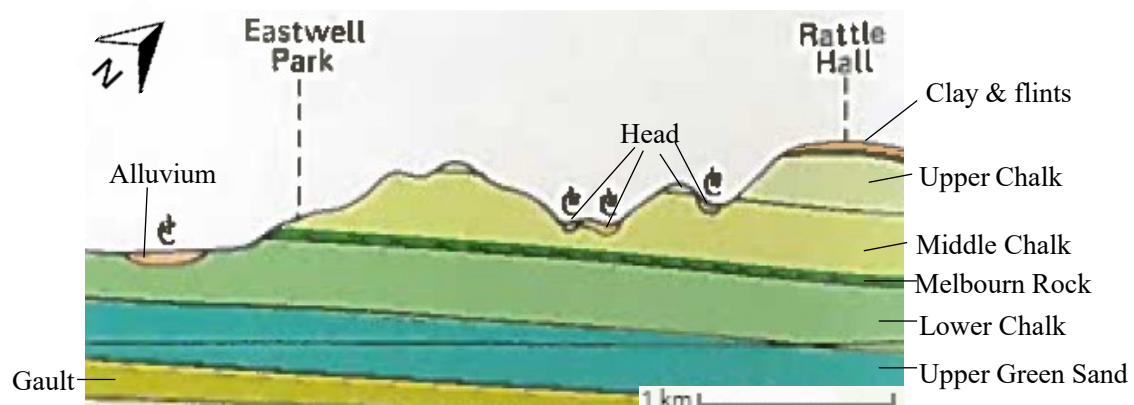


Figure 3-8: Regional cross-section of the geological structure approximately 10km north-west of Station ELSH (BGS 1982). From the cross-section it is clear the extent of the chalk depends on the elevation. The dipping structure is also simple across the region making inferences over larger scales possible.

In the near-field, the layering structure can reveal much about the deposition environment and the alteration since. Significant dip in rock structures may cause challenges with *in situ* testing. Many tests rely on the assumption of horizontally layered 1D profiles. Thus, the identification of the structure beneath a site, particularly the thickness of the layers, is key to the assessment, but this is recognised to be a challenging aspect by Tallett-Williams (2013). However, regional trends within structure can provide a first order estimate (Figure 3-8).

Method of deposition

The environment of deposition also affects the V_s profile of a site (Chapter 2). In the case of aeolian deposits, the V_s is likely to be more consistent, because of the uniformity of the materials in terms of particle size and void ratio. In more varied depositional environments, both stratigraphic and lateral heterogeneity leads to greater variability in V_s velocity, including residual soil profiles or glaciated terrain.

Quaternary deposits

Quaternary terrestrial deposits can be particularly difficult to characterise (Wills & Clahan 2006). Variability in thickness and stiffness of these soils can be significant and will strongly influence the V_s of the site. This heterogeneity needs to be quantified from available regional and site-specific data. Specifically, topography needs to be understood. At the UK SGMS Station ELSH, the regionally-mapped head deposits were not present. The hill on which Station ELSH is situated is lower than the average elevation of those surrounding it (Figure 3-8).

Made ground should also be assessed for human influence on the near surface, such as likely utility voids and velocity reversals from compacted or tarmacked layers. Urban areas present challenging environments as the ground may have been significantly altered. Town records should be consulted as well as placing more dependence on previous *in situ* results which are more likely than in rural environments. It should be ensured the testing does not pre-date any development or earthworks.

Velocity reversals

Velocity reversals occur when a lower V_s layer is situated beneath a higher velocity stratum (Foti *et al.* 2014). The reversals are present commonly in made ground, organic soils and soil with flint bands. At Station OLDB, a low stiffness peat layer is found beneath a relatively thick alluvium (Table 4-2). Indications of likely velocity reversals are particularly important for seismic investigations as they affect not only the ground response, but also the accuracy of testing methods on all layers of the profile (Chapter 4). In later stages of assessment, the reversal can be difficult to identify, so it is critical that the likelihood of these are determined as early as possible. Specific testing and modelling methods need to be chosen if these strata are present (Chapter 4).

In addition, reversals are an important factor in defining the reference horizon for site response analysis. The majority of site response methods do not allow for waves to be reflected back up from beneath the analysis domain. Therefore, the reference horizon should always be placed below any velocity reversals.

Installations and foundations

For seismic considerations, the type of installation of the structure or the location of a seismic station is critical both in terms of horizontal space and depth of the installation. Often Quaternary deposits may have been removed during installation, therefore, do not need to be considered in profile development (Figure 3-9). However, layers at depth may become more prominent depending on the installation depth or type. For heterogeneous sites, high uncertainty can be caused by insufficient accuracy in recording the location of the structure. This is particularly significant for seismic stations as the 1D profile could be completely altered depending on its location within a site boundary.



Figure 3-9: Image of the installation of Station ELSH (Baptie 2015). The thin topsoil can be seen with the typical white of the chalk beneath. However, the station foundations are clearly below the topsoil. The chalk appears rubbly and poor quality and was described as white and clayey (Laughlin 2014).

Methods of investigation for geological profile

Additional methods may be employed in the discovery of supplementary information to increase the observations of a site. Satellite imagery has a wealth of information that is now commonly available through open sources such as Google Maps (2013). This provides geomorphological features, urban outlines and locations of nearby rock outcrops. Speckled landscapes can indicate a large number of boulders, while soil colouration can give an indication of underlying bedrock (Figure 3-10).

Land use should also be considered. Arable farming areas are more likely to have deeper topsoil compared to moorland pasture. In urban environments, the age of the settlement of the area can give an indication of the nature of made ground. Historical topographical maps can aid identification of cut/fill earthworks and prior land use including landfill and quarrying.

The quality of the information should be carefully considered. In particular scale of variance and the application of regional data for site-specific purposes. For example, if the expected rock dip is taken from regional sources, it should be considered if the trend is sufficiently consistent to apply to local measurements. Information that is uncertain or is simply not known should be highlighted. The knowledge of what is lacking can aid the uncertainty classification and focusses the remainder of the

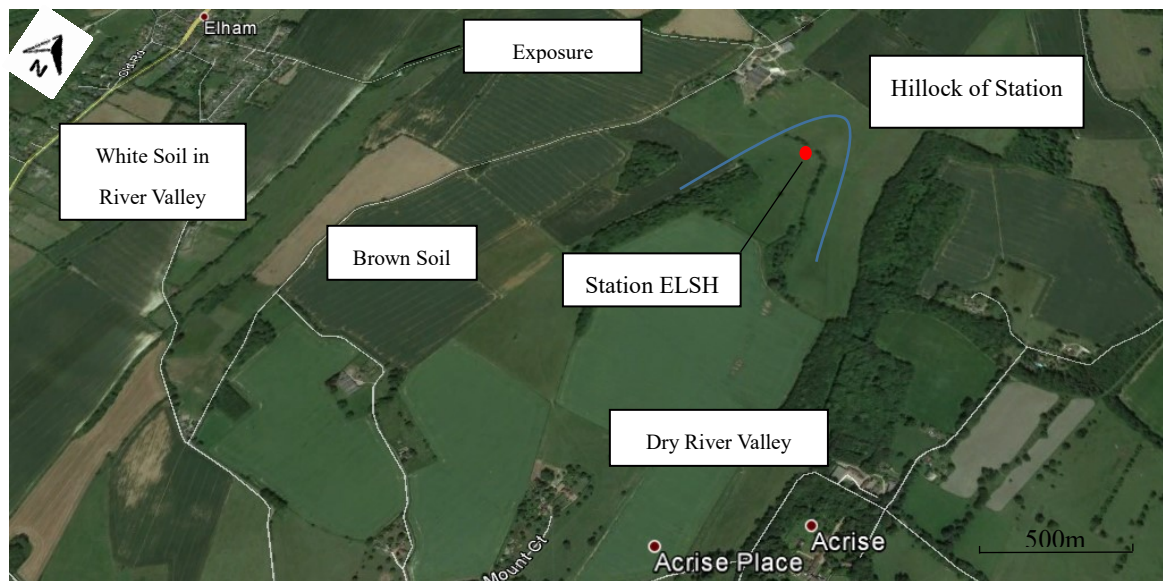


Figure 3-10: Satellite image of the region around Station ELSH (Google Earth 2013). This highlights not only the topography, but also the soil colouration with the ploughed fields on the higher topography, appearing brown showing the extent of the head over the white chalk.

assessment to improving understanding of these aspects.

b) Previous *in situ* results

Standard practice in site investigation desk studies is the acquisition of all relevant prior information. Although these data may be proprietary, open data sources are becoming more common and sufficiently detailed (BGS 2013; Chiou *et al.* 2008). Local government can also be a source of data. Abandoned mining records too are often available online and can be particularly useful for classifying geology at depth. These data can be used to remove uncertainties from the desk study such as the likely thicknesses of strata and the condition of the deposits in terms of weathering. This forms the second part of developing the geological model.

If borehole records are spaced at a sufficiently high spatial resolution, they can be used to develop a cross-section of the region through or close to a site. This can highlight regional structural trends and identify potential local variation. Detailed sections can also be used to determine the thickness variation of Quaternary deposits.

Other tests such as SPTs or shear strength (C_u) and laboratory samples can also give a good indication

of the strength and other properties of the deposits. These are more common at sites than seismic testing and so more readily available. However, in this method, they are considered as indicators rather than using the geotechnical correlations (Chapter 4). Similar to the V_s proxy methods, these correlations depend on sufficient numbers of direct seismic and non-seismic tests. These are not common in low seismic regions.

Sites of similar geology should also be considered even if they are not necessarily within the surrounding area. These can be indicative of parameters such as strength or weathering susceptibility. Therefore, these records can give information where otherwise there may be none within a few kilometres of the site. However, like the geotechnical parameter tests, they should be considered with caution and not necessarily representative. The deposits in the new area may not have undergone the same processes. A full knowledge of the comparative histories of the sites should be considered.

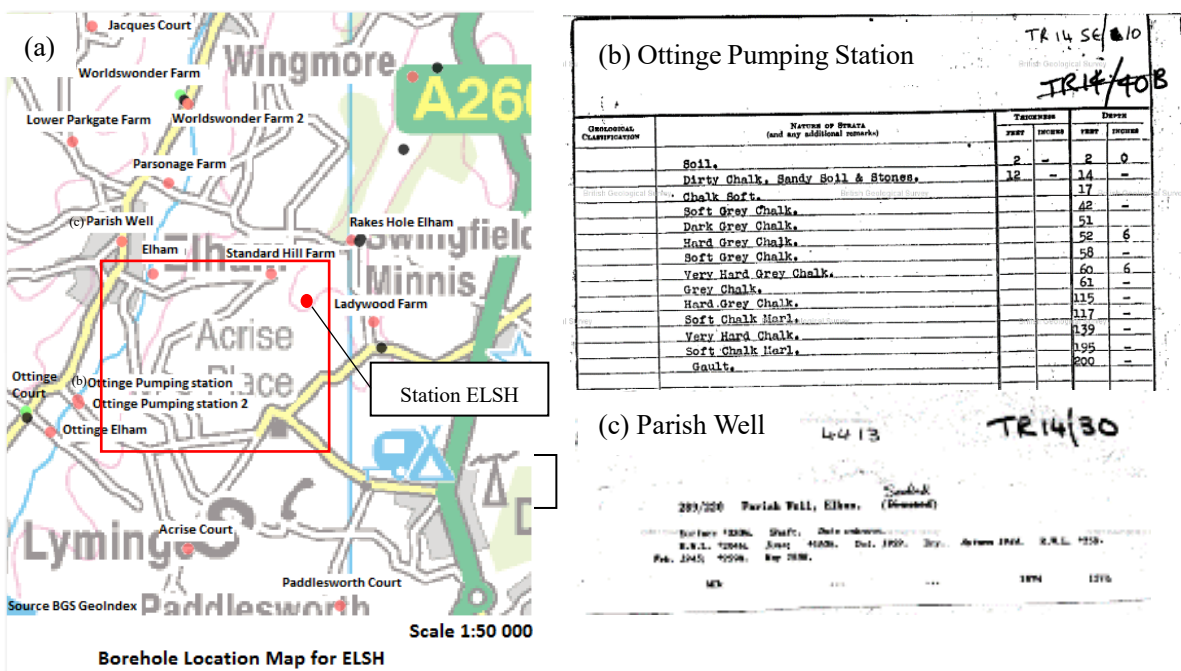


Figure 3-11: (a) Map of borehole locations near to the Station ELSH that were considered in the assessment (Adapted from BGS 2013). (b & c) Two borehole records from the map of differing detail. (b) is relatively detailed for the area while (c) is more typical simply referring to “UCK” or Upper Chalk.

Boreholes of differing quality have been found in close proximity to each other (Figure 3-11). Notably well bores were found to be of consistent low quality. This is, because the hydrology of the site is the

primary concern for these investigations. However, this type of record is more often located in the rural environment of the UK SGMS with few higher quality tests being available. Therefore, the type of record can have significant bearing on its quality which is critical to the assessment. It is also significant that at this stage, there is good correlation between the profile from the desk study and that from the previous *in situ* records. If the two sets of data differ significantly, the desk study stage may need to be reassessed before repeating the *in situ* search.

(c) Walk over survey

The final stage in developing the model involves a visit to the site to conduct a walk over survey. This is again often recommended by codes of practice in site investigations (EN 2000). However, even for well-defined sites, this was found to be beneficial in reducing uncertainty in the geological model. To maximise this reduction in the Site Specific proxy method, the visit is approached with a specific set of goals for each site. This may include investigating areas other than the site itself. Neighbouring outcrops noted in the desk study could be analysed to determine the state of the rock in the region (Figure 3-12).



Figure 3-12: Outcrop of chalk within 1km of the Station ELSH. This shows the quality of the chalk which appears shattered in the near surface, but with increasing blockiness with depth. This is labelled as the exposure in Figure 3-10.

The major advantages of the survey are a visual confirmation of the desk study and ground-truthing of the site. It can be determined whether the assumptions of the desk study are correct and conflicting regional trends can be resolved. This can include simple, but critical information such as confirmation

of the exact location of the site. For the UK SGMS, co-ordinates for their location were only available to the nearest 100m which can be critical for a heterogeneous site. In addition, uncertainty of Quaternary deposits can generally be addressed particularly in determining their depth and nature. Outcrops in the near field too can help identify the condition and thickness of the rock.

During the walk over, the site should be scrutinized as to whether it has been subjected to change and unexpected occurrences also should be noted (Figure 3-13). For the UK SGMS, Station SWN1 was located much closer to the airfield than expected. This site disturbance was found to be significantly more extensive than expected in the desk study or in the assessment of *in situ* measurements.

Engaging with the previous or current site owner can be highly beneficial. Generally, the land owners can give important details about the depth of installation, type of foundations or reasoning behind the placing. The owner of the site for Station MCH1 explained that the site had been chosen specifically because of the thinness of the Quaternary deposits on his land compared to other valleys in the region. He also gave an estimation of the depth of the concrete pad foundation. For Station SWN1, the site manager could give details about the exact nature of the bunker in which the station is situated. Local land owners often have detailed knowledge of land use history that may not be available from other sources.

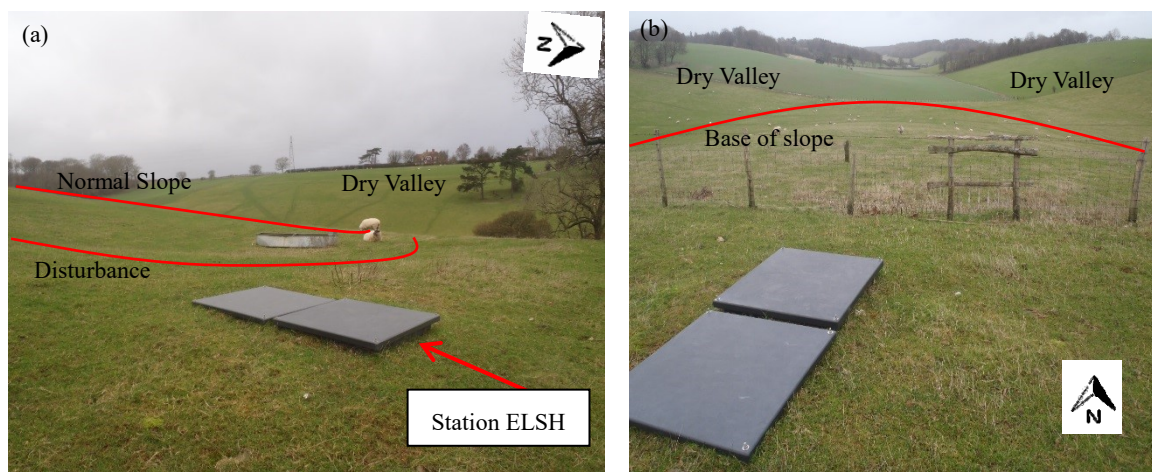


Figure 3-13: Observations of the Station ELSH during the site visit. The station can be seen as the two grey 'drain' covers. (a) There was found to be a change the local slope next to the station which was possibly caused by weathering within the chalk structure. (b) The slightly strange shape of the station hillock, between the two dry valleys was also confirmed.

Ideally, this survey should not be combined with any site testing. The geological model may be significantly altered by the findings and so should be updated given the results before testing. The specification of the testing method or layout may also need to be altered to optimise the test. However, if this is not possible, it is still worthwhile to carry out the survey before testing so that the results can still be used. In this case, several models of the testing should be determined, the final being chosen depending on the outcome of the preliminary survey.

The walk-over survey is considered a key part of the method. Often it was found to be the only source of near-field site-specific information. Exposures often provided invaluable information and rarely confirmed initial estimates, particularly of weathering. In general, weathering horizons were found to be deeper than expected at the UK SGMS sites and would have been under-estimated without the survey. In rare cases, the geology was found in reality not to fully correlate with the geological maps and most critically many of the stations were in different locations than expected (their co-ordinates only being given to 100m) which had the potential to alter the geological profile completely.

Formation of geological model

The data from the desk study, previous *in situ* measurements and walk over survey are combined into a geological model of the site. The aim of the model is to determine as far as possible, the nature of the deposits and the likely depth of the geological strata boundaries. Other considerations may have been determined that have more significance to the site than the geological model. For example, if the site is situated at the top of a ridge, topographical effects may govern the motion rather than 1D site amplification and a different form of study will be needed.

The depth to which the model should be considered must also be carefully chosen. For instance, Station MCH had a thin layer of surface deposits underlain by a homogenous bedrock for over 100m. Consequently, a V_{s30} or even V_{s10} may be a representative estimate for this site. While, for Station OLDB, a conglomerate with a high V_s velocity is expected at 30m with soft rock and alluvium above. Thus, for this station, a V_{s30} may be misleading and a V_{s40} or deeper may be more representative of the site. This highlights the importance of the investigation of scale as, if the model were only

developed to 30m, the hard underlying stratum may not have been considered. Generally, in this study the profiles were expected to be considered to 30m. However, three stations including Station OLDB as well as Station ELSH and GDLE and OLDB were also considered to 40m due to their specific geology (Section 3.4.3 & Station Appendix).

For this study, each of the specific factors for seismic investigation are considered in a qualitative assessment of the quality of the model for a site (Table 3-2). Based on the main desk study, the factors reviewed are most often found to be the main areas of uncertainty associated with the model. This aided in the qualitative assessment of the uncertainty which is determined using the Tallett-Williams (2013) classification system (Table 3-1). This is associated with the nature and condition of the deposits, so is not feasible to assess quantitatively.

The quality of data for the site was ranked classed as 1 to 4: (1) high quality that is site specific. (2) sufficient quality, but interpretation needed from regional records (3) poor quality found or interpretation from far-field sources (4) information about the attribute not found or highly uncertain. This was carried out for ten categories making the lowest score 10 and the highest 40. The categories were chosen from sources of uncertainty found during the formation of the geological model such as depth of weathering or the sources of previous *in situ* testing.

The classification from these quality scores (Table 3-3) associated with the confidence levels (Table 3-2) are slightly skewed. When testing the method with the UK SGMS, values of 20-30 were found to be twice as likely as 10-19 and 31-40. Therefore, 10-19 was more likely reflect a class 1 site while 20-25 would reflect a class 2. However, the rating of the quality table was found to reflect well the maximum uncertainty class in which the model should be placed (Table 3-1).

Initially it was also thought a quantitative measure of uncertainty should be used in relation to the layer boundaries within the geological model. As a result, a profile with boundaries known within 1-2m would be a class 2 site. However, when assessing the site layers, it was found that site boundaries could themselves be variable due to heterogeneity. Several profiles had a stratum that may or may not be present, while other strata were well defined. Thus, to give one classification for every stratum is

misleading. Therefore, the layers are given individual ranges using the developed geological understanding of the site.

Table 3-1: Confidence classification system used to separate the quality of the station models (Adapted from Tallett-Williams 2013). The example reasoning is included to highlight common causes of classification found during the assessment of the UK Strong Ground Motion Stations.

Confidence Class	Description	Example Reasoning
Class 1	As sure as reasonably possible, without additional site-specific invasive ground investigations.	Onsite invasive and detailed geological record and or detailed station installation report. No interpretation required as information already recorded. From 10-19 in the quality assessment.
Class 2	Fairly confident about accuracy of ground profile assessment.	Proximal borehole records in gradually varying geology within $\pm 500\text{m}$ of the station. Some geological interpretation needed, but based on established regional structural trends and/or several proximal boreholes. From 20-25 in the quality assessment.
Class 3	Some uncertainty remains in the ground assessment.	Only far-field borehole records. Assessment relies on geological interpretation. From 26-30 in the quality assessment.
Class 4	The assessment is uncertain and ground investigation should be carried out to confirm evaluation.	No borehole records exist in the vicinity/the geology is highly variable or they are unpredictable. Undetermined/ unknown Quaternary deposits present. 31 and over in the quality assessment.

Table 3-2: Quality is ranked for Station ELSH for the geological model. The ranking system implies that the information is: (1) high quality that is site specific. (2) Sufficient quality but interpretation needed from regional records (3) Poor quality found or interpretation from far-field sources (4) Information about the attribute not found. The overall score is 31 making it at maximum a class 4 profile in terms of the nature of the deposits (Table 3-2).

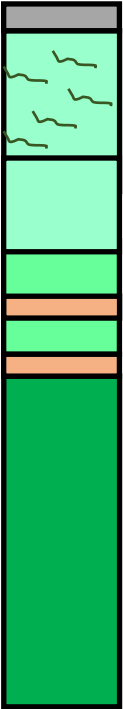
Attribute	Quality	Reasoning
Sources & <i>In Situ</i> testing records	4	The maps and memoirs have not been updated for a while and generally did not have the current chalk nomenclature, but were comprehensive. However, the <i>in situ</i> recordings were poor and had little description or determination between layers.
Discontinuities	3	Generally well defined, however, faulting within the region can be obscured by superficial deposits and results had to be inferred.
Regional Structure	3	Well defined within regional memoirs, but the depth of the chalk strata was generally only plotted for the large classes of chalk rather than the specific groups.
Geomorphology	4	Generally well understood. However, the location of the station is unusual between two dry river valleys. The knoll is rare in the surrounding region, particularly as it does not have Quaternary deposits. Its origin and condition are unclear.
Topography	2	Well defined within the region but only to a 1:10 000 scale.
History & Deposition	2	Well defined within the literature, but regional only.
Quaternary Deposits	4	No Quaternary deposits were found on the site nor expected by the desk study, but residual soil does remain for which the likely depth is uncertain.
Weathering	4	The extent of the weathering was unclear and inferred from low quality <i>in situ</i> testing records.
Reversals	3	These may well be present in the Middle Chalk, but more rarely than would be expected in the upper chalk. Piping in chalk is a common form of weathering, so hard and soft layers may alternate.
Installation	2	Installation method and dimensions were discussed with those who constructed the foundations.
Overall Score	31	

Thus, from the initial assessment a descriptive geological model constraining layer thickness with associated uncertainty estimate and 3D considerations is formed for the UK SGMS (Table 3-3). All of the assessments for each of the stations have been included in the Station Appendix.

It is noted that the geological model will not only be dependent on the quantity and quality of data, but also on the user of the method. The experience and judgment of the user given the information available will alter the final profile. However, though a significant constraint on the method, it is also its main benefit when compared to other proxy methods. If the assumptions of the user are presented

and justified, it allows repeatability and a defensible final V_s profile estimate, rather than the ‘black box’ calculations of the other proxies.

Table 3-3: Summary of 1D ground model for Station ELSH. This station was classified as class 4 as the state of the upper layers of the deposits was unclear and only far-field boreholes could be found which were of generally poor quality. The boundary between the New Pit Chalk and Holywell Nodular is also not defined. In this profile ridge effects may be possible, but the topography is relatively shallow and the crest wide.



Stratum	Depth to base of layer (m b.g.l.)	Description
Station Housing	~0.5	Instrument foundation of thin concrete pad with embedded housing box.
Weathered New Pit Chalk (Middle Chalk)	1-10	At the surface, stony structureless chalk (almost like topsoil). Upper surface meters expected to resemble white clay, progressing to fractured weak chalk, increasing in strength. Likely to be a residual chalk profile with dissolution features.
Unweathered New Pit Chalk (Middle Chalk)	5-15	Mainly blocky strong chalk with few but thick marl seams (100-200mm). Several soft layers likely to include putty chalk. Rare flint and nodular chalk seams may be present. Boundary with Holywell chalk is expected to be poorly defined.
Holywell Nodular Chalk (Middle Chalk)	15 to 30	Generally hard nodular chalk with only thin marl bands and significant portions of shell debris. The Melbourne Rock just above the base has a lack of shell deposits. The base is marked by interbedded chalk and coloured marl.
Zig-Zag Chalk (Lower Chalk)	To the end of profile	Massive grey and white marly chalk becoming more thinly bedded.

3.3.2 Stage 2: V_s Profile through the Global V_s Database

With the layer thickness and nature of the deposits constrained, the geological model is compared to the Global V_s database (Chapter 2) to establish the likely V_s velocities for each stratum. Accurate material descriptions allow V_s values and uncertainty estimates to be selected for similar materials in a similar condition from anywhere else in the world. This method is analogous to the ergodic principle used in PSHA (Fenton *et al.* 2006).

This differs from previous V_s proxy methods as all of the current knowledge about the site is used in determining the V_s velocity for each stratum. A series of parameters is compared, rather than one alone. It is also not essential to have the same number of parameters for every site. The Site Specific proxy method aims to increase similarities between the database values and the site in consideration by improving the comparison. Only *in situ* tests results were considered as laboratory results have been shown to be unrepresentative of *in situ* properties (Chapter 2). However, it may be possible to consider laboratory results if the necessary adjustments were made, particularly where the testing is conducted under *in situ* loading conditions.

V_s of geomaterials is a function not only of composition and primary structure, but also factors including fracturing and weathering (Chapter 2). The following system of refinement is used in determining similarity of geological facies: initially, only the type of rock or soil is compared with the Global V_s Database records. This is further filtered by matching the depth of the stratum to the depth of the tests. The records are then compared by age. At first, generally, era and period are considered, but, in the cases of the younger deposits, epoch could also be significant.

The next comparison, geological nature, was the most qualitative measure and open to subjectivity. This is based on the group similarity. For example, a sandstone interbedded with mudstone and shale would be compared to all three rock types separately in the type comparison, but at the nature stage a similarly interbedded rock would be required. The sensitivity of this grouping was tested by repeated selection 6 months apart and two engineers categorising the same site. The means of repeated tests were found to be within 5% of each other, while the two engineers were found to be 5-10% different.

Given the scale of the uncertainty related to the results in the UK SGMS (Section 3.2), the sensitivity was considered sufficient. However, both were taken from the same interpretation of the geological profile.

Finally fracturing, weathering and method of deposition were all compared equivalently, as results for these parameters in particular groups were relatively rare. Using this comparison, the standard deviation of the V_s velocity for each stratum determines a measure of uncertainty for the V_s velocity of that layer. Minimum and maximum values associated with deposits are determined which aided in the determination of the likely site class. Distributions of the results can be taken into account, for example, many rock deposits are positively skewed for V_s with the low possibility of very high velocities.

Trends between the parameters as the comparison progresses are worth monitoring during the processing. For example, the mean V_s of a weathered, Cenozoic sandstone would be expected to decrease as the comparisons increase in similarity from sandstone, to a Cenozoic sandstone and finally a weathered Cenozoic sandstone. If there is a sharp increase in mean V_s velocity from the sandstone to a Cenozoic sandstone this could be caused by a reduction in the number of records remaining in the comparison. Equally this can show the importance of the influence that parameter on the deposit.

Table 3-4: Typical values from the Global V_s database when compared to chalk.

Description	Location	V_s (m/s)
Structureless Chalk	UK offshore	300-600
Chalk	UK offshore	500-900
Lower Chalk	UK onshore	750-1000

For example, the profile for Station ELSH was compared on the basis of similarity of geological facies with a database of compiled V_s records (Table 3-4). When the type of rock was separated from the main database, the series of comparisons outlined above were carried out for each stratum, Figure 3-14 (Full calculations are included in the Station Appendix ELSH 08: V_s modelling calculations). This began with a depth assigned to each of the layers. These ranges overlapped to account for the uncertainty associated with the geological model. However, in this case the layers in the profile are relatively thinly bedded. This caused fewer results to be relevant from the database because of the

narrow depth for comparison. This meant that the depth & age or the depth & nature comparisons had few results. Consequently, these were not considered statistically valid and not used for any following preceding section.

To improve this, geological nature correlations were introduced instead of the more normal depth correlations as this caused the main reduction in the number of results. In the nature comparison, the weathered chalk was compared to structureless deposits, while the Holywell deposits were compared to more competent chalk. The lower chalk stratum was compared to only lower chalk deposits from the Global V_s Database, even though this reduced the number of results for this stratum slightly. These comparisons were particularly restricted, because of the common rock type for all layers. However, the geological nature comparison follows the trend seen in the other strata which appears to be common in the chalk (Figure 3-14).

As can be seen at Station ELSH, although the database contains a significant number of records, with each parameter introduced, fewer results are available for comparison. Therefore, there was not necessarily a sufficient number for a statistically viable comparison. The minimum number that was considered a good comparison was around 80 records or 1% of the total number of database records. However, this value was not based on statistical analysis and in certain cases, this was relaxed due to the scarcity of results or if the comparison was thought to be more likely to be representative than any previous comparison.

Without current validation of the method, the probability for the likelihood of each comparison stage is considered equal, unless they had significantly more or fewer records than the other stages. Thus, each stage of the comparison develops a V_s distribution for each layer. Consequently, a series of equal probability velocity models is produced. For each of the UK SGMS in this study, the developed geological model (Section 3.3.1) is related to V_s distributions for each stratum from the Global V_s Database. All of the assessments are included in the Station Appendix.

The sensitivity to the user of the method is again noted. Though this was briefly tested for the ‘geological nature’ class in the V_s profile, the bias or assumptions made during the formation of the

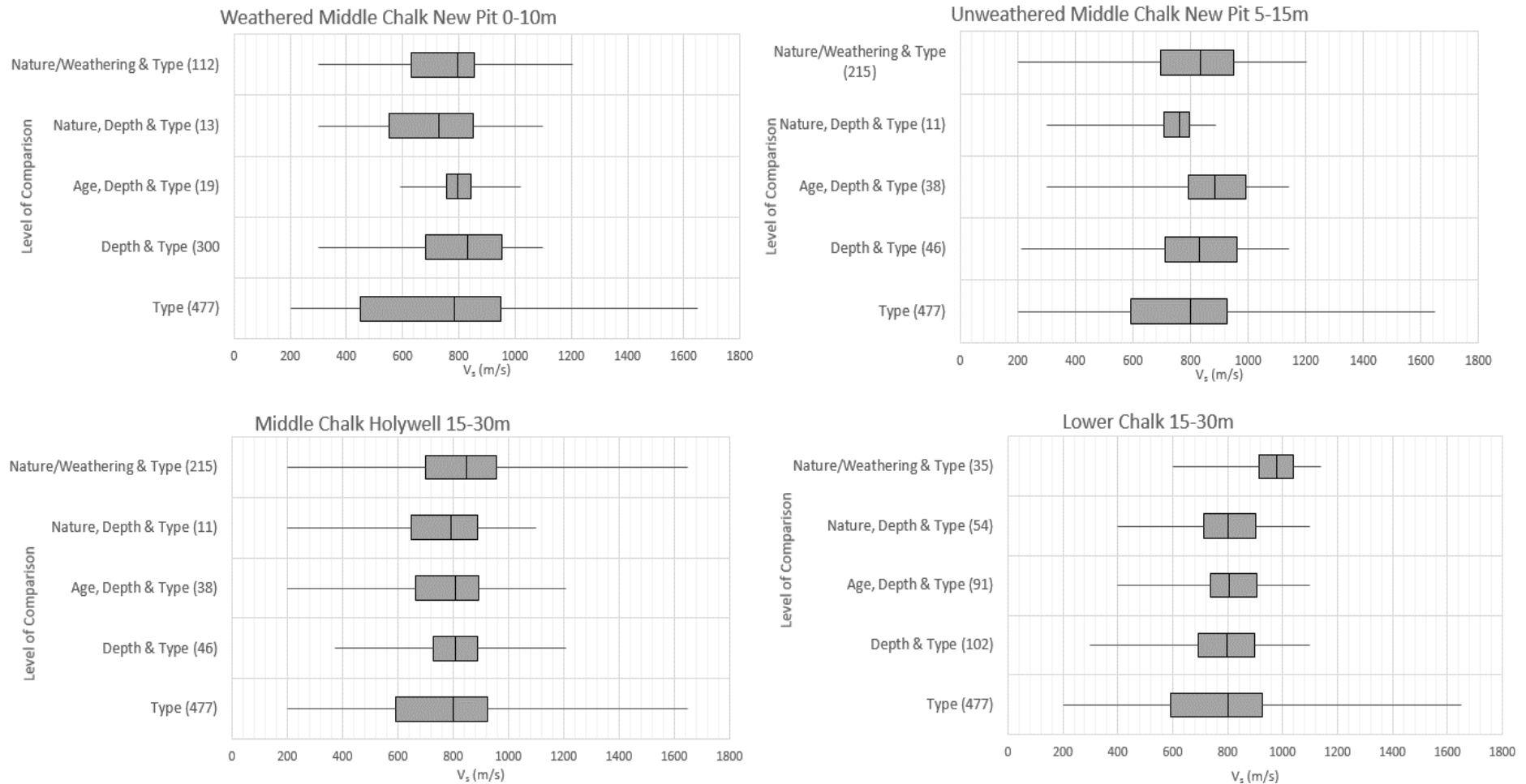


Figure 3-14: Results from the comparison with the Global V_s Database for each of the four rock types. The trends in the comparison seems fairly consistent, however, the depth & age and depth & nature comparison should not be used as there are not enough results to be considered statistically significant.

geological profile have been carried through to the selection of the V_s ranges for each of the layers. Therefore, the geological profile and V_s profiles are combined probabilistically aiming to remove the user as much as possible from the final stage.

3.3.3 Stage 3: Toro Equations & Monte Carlo Model

Having developed a geological model with V_s values for each stratum, the aim is to combine both models and form a representative V_{sz} value. This can then be used for the site profile. In the Site Specific proxy method, the combination is achieved using an adaptation of the Toro (1995) method. This develops a probability distribution for the V_{sz} including an expected time averaged velocity and an estimate of the uncertainty associated with that velocity.

Developed through *in situ* tests, the Toro (1995) method is the most common approach for stochastic V_s profile randomisation (Cox *et al.* 2015). This is used within STRATA (Rathje & Kottke 2010), in combination with the Monte Carlo method (Jones *et al.* 2002). Toro (1995) describes a soil profile as a series of interlinked soil layers with inter-correlated, but varied, V_s velocities. This is currently the most advanced system of equations to describe V_s velocities in soil profiles as it improves on previous models through the interlayer V_s correlations. These were previously either assumed perfectly correlated V_s velocities (McGuire *et al.* 1989) or independent velocities (Field & Jacob 1993), both of which represent extreme cases.

The Monte Carlo method aims to determine the statistical properties of a complex system response (Jones *et al.* 2002). This is achieved by generating a series of randomised responses which are combined into a probabilistic distribution of the expected overall response (Kottke & Rathje 2008). For use in determining V_s site profiles, this requires the full description of the layer properties, specifically expected layer thickness and V_s velocities for each stratum. Following stage 2, there is a layering model for each site under investigation, with approximate distributions associated with V_s in each layer. The distribution of V_{sz} is determined by computing this metric for profiles that are consistent with this layered model. Monte Carlo simulation is used to generate hypothetical profiles that are consistent with the layered model. The method depends on a series of equations outlined below

and the implementation is included in Appendix 3 in MATLAB (Mathworks 2014) code.

The Toro (1995) model is separated into (a) soil thickness and (b) V_s profile in the following explanation. However, in order to demonstrate the development method, the results of Station ELSH model are used. Thus, variation is seen in both the soil thickness and V_s profile in the figures. The parameters of the Station ELSH model are outlined in the Station Appendix which includes the all UK SGMS models.

(A) Adapted Toro thickness model equations

Toro (1995) describes the strata thicknesses with depth as a non-homogeneous Poisson model. This is a statistical distribution generally describing the rate of occurrence of an event with time (Kottke & Rathje 2008). However, for site profiles, instead of depending on time, the model depends on the rate of occurrence of layers with depth. The model is non-homogenous so the rate of layers is considered to decrease with depth (Figure 3-15a). This implies that thin layers are more likely at the surface, but, as the depth increases, they are more likely to be thicker. This aims to ensure that the likely thickness of the layers increases with depth despite the randomisation (Figure 3-15b).

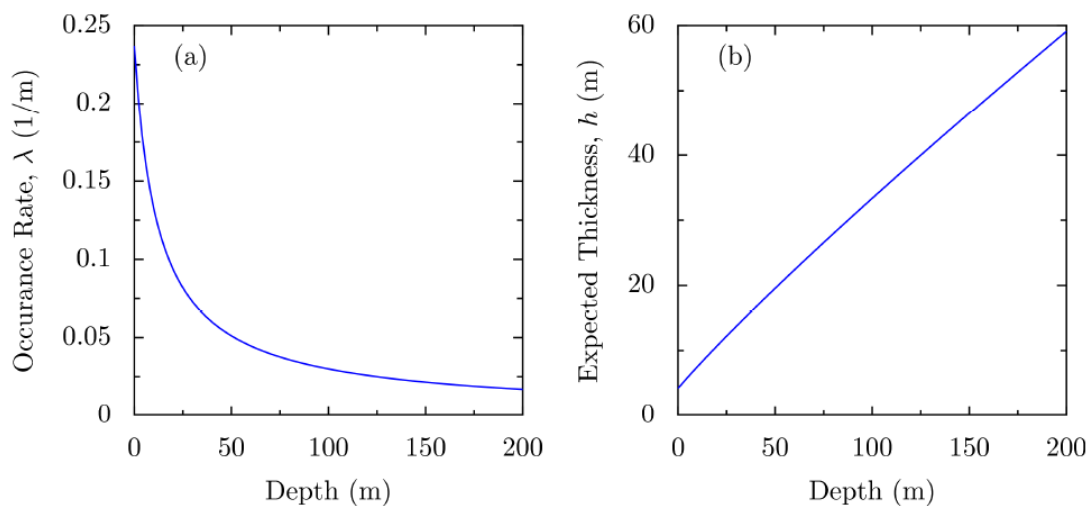


Figure 3-15: Toro (1995) model for layering of a geological profile (Kottke & Rathje 2008). (a) The non-homogenous occurrence rate of strata against depth which can be seen to decrease exponentially with depth. (b) Expected thickness with depth forming the inverse of (a).

Toro (1995) empirically determined an expression for the rate of layering with depth (Equation 3.1).

$$\lambda(d) = a_1(d + a_2)^{a_3} \quad [3.1]$$

Where the rate λ is dependent on the depth d and a_1 , a_2 and a_3 are all empirically derived coefficients obtained using maximum likelihood procedures. The empirical data used to constrain these coefficients comprise *in situ* testing results from 557 sites mainly within California (Toro 1995). This resulted in values of $a_1=1.98$, $a_2=10.86$ and $a_3=-0.89$. As the rate is non-homogeneous, this is integrated to give the cumulative rate over the depth:

$$\Lambda(d) = \int_0^d a_1 (s + a_2)^{a_3} ds = a_1 \cdot \left[\frac{(d+a_2)^{a_3+1}}{a_3+1} - \frac{a_2^{a_3+1}}{a_3+1} \right] \quad [3.2]$$

Where $\Lambda(d)$ is the cumulative rate function and s is a depth within the profile.

However, when inputting a geological model, it is not generally the rate of occurrence of layers that is known, but the expected thickness of each layer. Similar to the time between events being the inverse of the rate of occurrence of events with time, the expected thickness is the inverse of the rate of occurrence of layers. Thus, Equation 3.3 is converted into terms of expected thickness (h).

$$\Lambda^{-1}(h) = \left[\frac{a_3 h}{a_1} + \frac{h}{a_1} + a_2^{a_3+1} \right]^{\frac{1}{a_3+1}} - a_2 \quad [3.3]$$

To produce a series of randomised profiles, Toro (1995) generally inputs a randomised thickness interval based on an exponential distribution. For each randomised profile, these are incrementally added and input into Equation 3.3 to determine an overall depth model. The aim of this method is to produce a series of randomised layering profiles that will increase in thickness with depth.

However, from the geological model in the Site Specific proxy method, the general layering profile is known. Consequently, randomly generating intervals from an exponential distribution would not make any use of that knowledge. In addition, the site profile will not necessarily correlate with the maximum likelihood coefficients determined by Toro (1995) during the empirical testing. Using the cumulative rate in Equation 3.3 may force the developed layering models not to reflect the site itself.

Therefore, an alternative method is used for this section of the code that does not enforce the increase of thickness with depth. The layers in the geological model are described as normal distributions with a mean equal to the most likely strata thickness. A normal distribution is chosen as, although the mean layer thickness is considered most likely, each layer could be equally thicker or thinner than expected. Similar to Toro (1995), the layer thickness is assumed independent. Thus, if the first layer is considered thicker than expected then none of the subsequent layers are impacted. This is developed by randomly generating a variable within a normal distribution for the layer. This distribution has a mean of the expected layer thickness and a standard deviation of the layer uncertainty.

The layers were initially truncated to values equal to or greater than zero to ensure no “negative thicknesses” are produced. However, when testing the method with the UK SGMS, it is found that this light level of truncation is not sufficient to produce a representative result for the site layering. The profiles produced had unfeasibly high standard deviations and the majority could not be deemed useful to represent the site.

Therefore, using the understanding of the site determined in the geological modelling, truncation inputs are introduced by the user. The values used for these were the maximum or minimum value for each layer credible. For example, in a specific weathered layer of rock, the boundary with hard rock is expected to be anywhere from the surface to 5m depth. Thus, the minimum truncation value is easily determined as 0.

The maximum truncation limit is often more challenging and subjective to define. This was chosen as the upper bound of feasibility at the site. However, in several of the UK SMGS, when the truncated distribution was plotted, the upper bound was found to interfere with the main body of probability rather than prevent extremes being included. This was not the aim and so these boundaries were increased. The truncation was carried out in MATLAB (Mathworks 2014), and thus, the probability was redistributed after the truncation. This was taken into account when extracting the mean and standard deviations from the final solution.

Station ELSH is modelled with the normal distributions for the four layers (Table 3-6), outlined in the geological profile (Table 3-3) and in the V_s comparisons (Figure 3-16). The mean of the distribution is modelled by the expected thickness and the standard deviation. Truncation limits are provided for each of the layers.

Table 3-5: Geological layering model for Station ELSH for input into the Toro Equations.

Layer	Weathered New Pit Chalk	Unweathered New Pit Chalk	Holywell Chalk	Lower Chalk (Zig-Zag)
Expected thickness (m)	5	5	20	50
Standard deviation of thickness (m)	5	5	10	10
Thickness truncation limits (m)	0-20	5-30	10-30	30-Inf

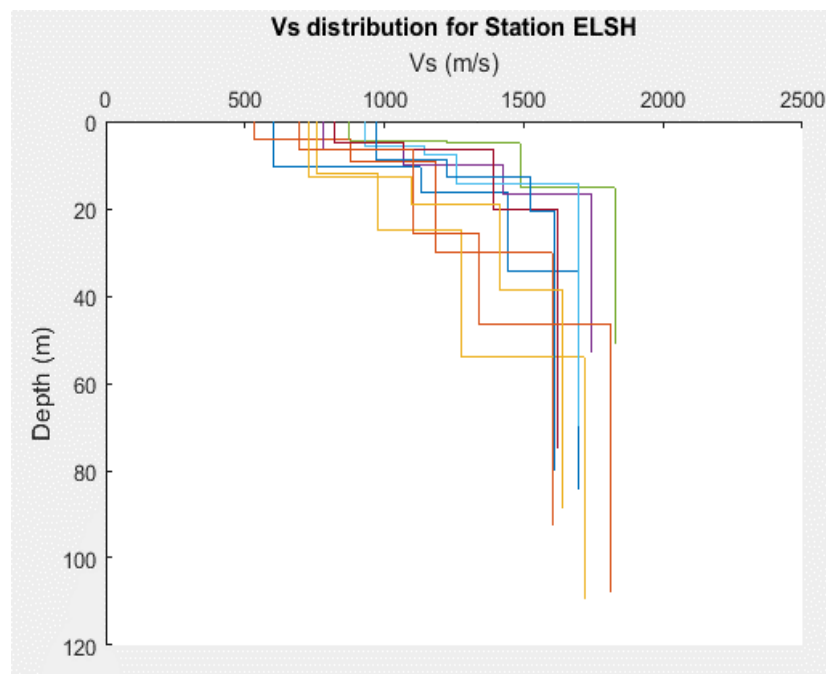


Figure 3-16: A sample of ten randomised profiles for Station ELSH output from the Toro Equations with varied depths and also velocities which is discussed in (B) Adapted Toro (1995) V_s models.

This method of modelling the layering of a geological profile allows the result of the randomisation to correlate more closely with the current knowledge of the site. In addition, the effects of the uncertainty of the layering associated with a site, can be fully explored, particularly if a site is at the boundary between two site classification classes. However, the results of this modelling depend on the accuracy of the initial geological profile (formed in Section 3.3.1). If there are false assumptions or unknown layers within the profile, the complete randomisation of Toro (1995) may produce a better

result if calibrated to fit the regional geology.

Adapted Toro (1995) model depth to end of profile

The Toro (1995) model is generally used with a depth to bedrock parameter at which depth the profile is concluded. For the Site Specific proxy method, the required parameter is instead the specific depth to the end of the profile (Figure 3-17). Therefore, this is specified in place of the depth to bedrock. However, the general process was unaltered: the last stratum is reduced to the correct depth if determined to extend beyond the end of the profile. If the required depth was reached before the last stratum, the profile generation is stopped with fewer layers. Therefore, it is critical the strata are known to several metres below the required profile depth. This is in case the upper strata are modelled at the lower boundaries of thickness expected in the geological model.

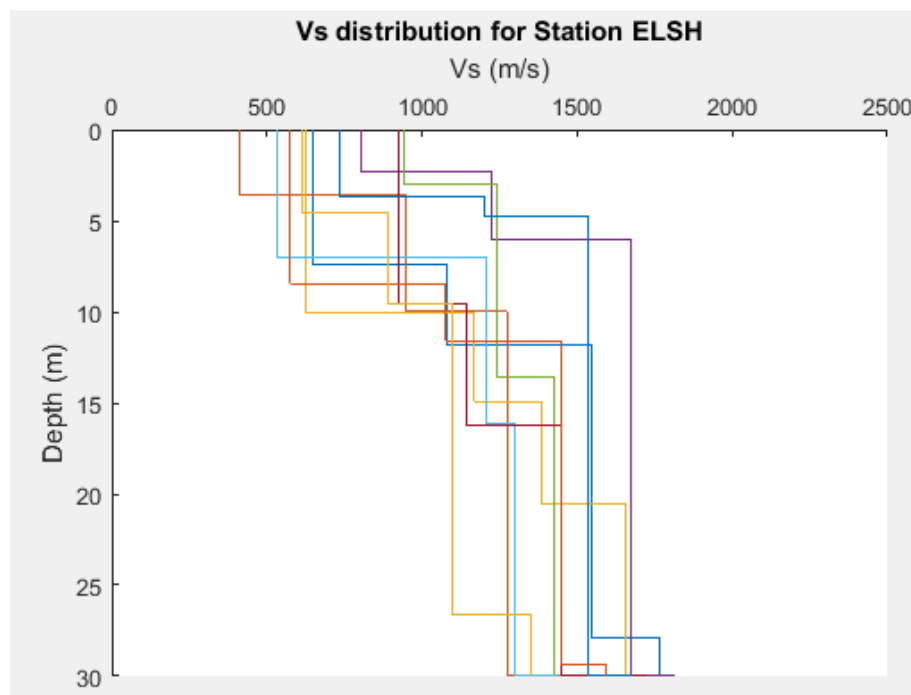


Figure 3-17: A sample ten randomised profiles for Station ELSH output from the Toro (1995) method cut to the desired profile depth of 30m with varied velocities.

Inclusion of layer probability

In several of the UK SGMS geological models, it was not always clear whether or not a stratum would be present. For example, in the geological model for Station LMK, several layers such as the thinly bedded Tealby Limestone are variable in the region of the station as a result of previous erosion. Thus, this stratum may or may not be present within the geological profile. More commonly, the introduction

of a weathered layer in the near surface of rock sites could not always be verified as outcropping rock was not present in the walk over survey. Consequently, the possibility is considered that the layer may not in fact be present in order to develop a representative upper limit for the V_{sz} distribution.

One of the inputs, associated with the geological model, is a qualitative assessment of the likelihood of each layer being present, not included in the Toro (1995) method. This matrix is compared to a series of randomly generated variables of uniform distribution between 0 and 1, one for each layer. If the random variable is greater than the probability of the strata being present, it is assumed to have no thickness or V_s velocity and the model would proceed to the next layer.

Currently, the probability of the layer not being present is chosen by the user. Thus, this assessment depends on the experience of the site, gained through the development of the geological profile. However, this does add further subjectivity to the method. In addition, the choice must be carefully considered given the probabilities of all the layers. It is possible that unfeasible profiles containing too few layers could be considered if more than one layer does not exist simultaneously.

The four-layer model for Station ELSH had a layer probability matrix of [0.9 0.9 0.9 1], with the certainty of the weathered layer being less than one. The equations would generate a series of random variables one for each layer such as [0.8 0.45 0.7 1] or [0.92 0.36 0.1 0.65]. In the first case, all the strata would be considered present as all of the random variables are less than or equal to the layer probabilities. However, in the second case the first stratum would be assumed not to present and not be assigned a thickness or depth as 0.92 is greater than the probability of the first layer. Therefore, a new set of 10 profiles appear to have layers missing (Figure 3-18).

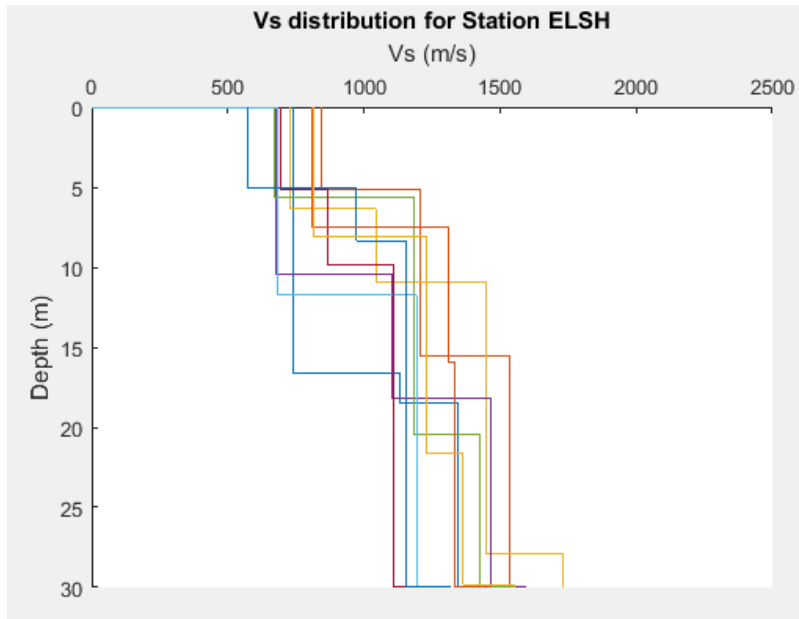


Figure 3-18: A sample ten randomised profiles for Station ELSH output from the Toro Equations with inclusion of layer probability with varied velocities.

This modelling, focusses on the thickness of layers, as these were the main outputs from the geological models. However, when using this model, depth horizons are not ensured. For example, if there a horizon or stratum boundary at 10m depth, the approach could simulate lower than average thicknesses for layers above this and result in the depth of this horizon being much shallower than the expected 10m. This generally did not affect the simpler sites where the main concern was the weathering boundary and little change in strata occurred. However, on more complex sites, the maximum and minimum layer thicknesses were carefully considered with respect to any specific known boundaries so that they could not vary beyond the uncertainty of the boundary itself.

Finally, the possibility of the presence of thin layers of extremely stiff materials was considered such as flint within chalk. These layers can cause strong high frequency peaks in the response spectra and so alter the site response significantly. However, it was determined they had little effect on the averaged V_{s30} value for each site, being so thin and so this is included in Appendix 3-2.

(B) Adapted Toro (1995) V_s model

Toro (1995) assigns velocities to each layer, centred at the mid-depth. The distribution of V_s within a given layer is assumed to follow a lognormal distribution. Toro (1995) expresses this distribution as:

$$V_i = \exp(\sigma_{\ln V_s} \cdot z_i + \ln[V_{smedian}(d_i)]) \quad [3.4]$$

Where V_i is the V_s velocity in the i^{th} layer, $\sigma_{\ln V_s}$ is the standard deviation of the natural logarithm of the V_s (Table 3-4), z_i the standard normal variate of the i^{th} layer, $V_{smedian}(d_i)$ is the median V_s velocity at mid-depth of the i^{th} layer.

Originally, the parameters in Equation 3.4 were proposed by Toro (1995) as generic V_s profiles with standard $V_{smedian}$ for each site class of the NEHRP classification system (Building Seismic Safety Council 2009). However, this is adapted in the Site Specific proxy method to take into account the input median and approximated standard deviation of the V_s profiles formed in Section 3.3.2 instead of the generic values.

The standard normal variate, z , are generated as a result of the inter-correlation model between each layer (Kottke & Rathje 2008). It is based on a Markov Chain which is a stochastic sequence in which the next step is conditioned only upon the value of the previous step (Ibe 2009). This is the Markovian property, that given the current state of the process, the immediate future state is independent of any past states before the current time (Ibe 2009).

The velocity of first layer in each profile is generated from a random variate from the standard normal distribution (Toro 1995). In the subsequent layers the z_i is dependent on the correlation with the thickness and depth layers, Equation 3.5 (Toro 1995).

$$z_i = \beta z_{i-1} + \varepsilon_i \sqrt{1 - \beta^2} \quad [3.5]$$

Where z_{i-1} is the standard normal variate of the previous layer, ε_i is generally a new standard normal random variate and β is the interlayer correlation.

According to the empirical testing carried out by Toro (1995), the interlayer correlation depends on both the thickness (Equations 3.6) and depth (Equation 3.7) :

$$\beta_h(h) = \beta_0 \exp\left(\frac{-h}{\Delta}\right) \quad [3.6]$$

Where β_h is the thickness correlation dependent on the thickness of the layer h . β_0 is the initial correlation and Δ is a model fitting parameter (Table 3-6).

$$\beta_d(d) = \begin{cases} \beta_{200} \left[\frac{(d+d_0)}{200+d_0} \right]^{b_0}, & d \leq 200 \\ \beta_{200}, & d > 200 \end{cases} \quad [3.7]$$

Where β_d is the depth correlation dependent on the mid-depth of the layer, β_{200} is the correlation coefficient at 200m, d_0 is the initial depth parameter and b is a regression coefficient (Table 3-6).

These correlations ensure that, as the thickness and depth of the layers increase, so does the associated correlation of the V_s values. These are then combined into the correlation coefficient defined by Toro (1995):

$$\beta(h, d) = [1 - \beta_d(d)] \beta_h(h) + \beta_d(d) \quad [3.8]$$

The correlation parameters ($\sigma_{\ln V_s}$, β_0 , Δ , β_{200} , d_0 , b_0) used in the Site Specific proxy were determined by Toro (1995) during the site testing of 557 Californian sites and depend on the V_{s30} class (Table 3-6). This included a combination of the site classes which is particularly useful for sites expected to lie on the boundary of a class. Estimates using the first and third quartiles for each of the layers to produce maximum and minimum estimates for a site from the V_s model allowed the correct coefficients to be used.

Table 3-6: Empirically calculated parameter values for Equations 3-4 to 3-8 (Toro 1995).

Property	V_{s30} (m/s)				NEHRP V_s Classes	
	(A) >750	(B) 360-750	(C) 180-360	(D) <180	A&B	C&D
$\sigma_{\ln V_s}$	0.36	0.27	0.31	0.37	0.35	0.36
β_0	0.95	0.97	0.99	0.00	0.95	0.99
Δ	3.40	3.80	3.90	5.00	4.20	3.90
β_{200}	0.42	1.00	0.98	0.50	1.00	1.00
d_0	0.00	0.00	0.00	0.00	0.00	0.00
b_0	0.063	0.293	0.344	0.744	0.138	0.293
Number of Profiles	35	169	226	27	204	253

Without *in situ* V_s profiles in the UK to calculate equivalent correlation parameters, currently the original Toro (1995) parameters had to be used for this method. This will limit the accuracy of the randomised profiles as the constants are derived from a different regional environment and from a small number of tests. However, this can be improved as more tests become available in the future and better correlation parameters can be derived.

Inclusion of series of V_s models

However, the Site Specific proxy method model of V_s (Section 3.3.2) includes several comparisons of increasing similarity for the V_s layer structure. There is currently no evidence that a comparison based on type of rock is improved by considering weathering or geological nature. Thus, each level of comparison was generally assumed to have equal probability with up to five different V_s structures. Therefore, the code (Appendix 3-1) is altered from the Toro (1995) method to include each comparison.

The probability of each comparison is included as an input parameter, with the requirement that probabilities must sum to one. This is then altered into cumulative probability. For a model with four V_s profiles of equal probability, the initial input matrix would appear as [0.25 0.25 0.25 0.25]. This is summed to change into cumulative probability within the code. The code would modify the matrix above to [0.25 0.5 0.75 1].

A random uniform variable between 0 and 1 is then generated for each randomised profile and compared to the cumulative matrix to determine which will be used (Figure 3-19). For example, if a random variable of 0.1 is generated for the example matrix above, the first model is used for that profile. While, if 0.3 is generated the second model is used. This effectively acts as a switch such that the proportion of generated profiles with each V_s model is equal to the likely probability of the model.

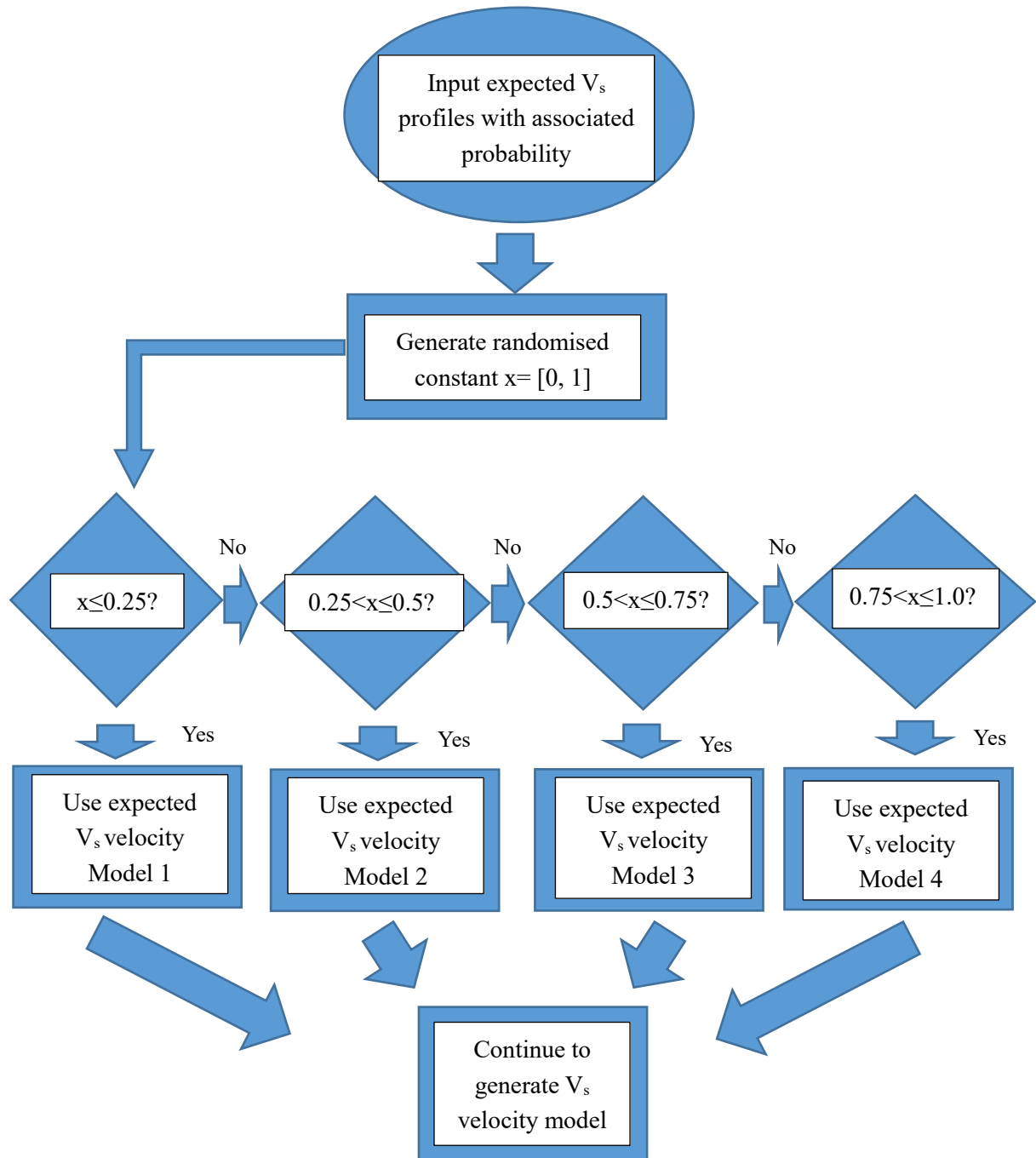


Figure 3-19: Flow chart illustrating how the adapted method switches between velocity models for generation of profile. This specific example has four V_s velocity models with equal probability.

Distribution of V_{sz}

When all of the random profiles have been generated by assigning layer thicknesses and V_s velocities, the time averaged V_s profile over the required depth (V_{sz}) is calculated for each profile (Equation 2.2). Using Monte Carlo simulation, these values are assumed to represent a sample of results from the

overall distribution of V_{sz} . Therefore, the mean V_{sz} value and its standard distribution are computed from the randomly generated profiles. In this way, a clear valuation of the uncertainty associated with the model is given. For Station ELSH, 100 profiles with the inputs as above had a distribution of $858\text{m/s} \pm 190$. This categorises the site by placing it between the A and B classifications for the Eurocode (EN 2000).

Convergence of V_{sz} model

Initially the model was run for a number of profiles that were specified by the user. However, it became clear that, although 100 models could produce an estimate of the V_{sz} distribution, because the inputs were randomised, this may differ if the model was run again for a new set of 100 profiles. Therefore, the code was constrained to run until the model converged on a V_{sz} distribution such that adding another random profile did not alter the mean from the previous two by 1%. This allowed a final converged V_{sz} distribution to be formed. Station ELSH required 3363 profiles to produce a mean for V_{s30} of $838\text{m/s} \pm 204$ (Figure 3-20).

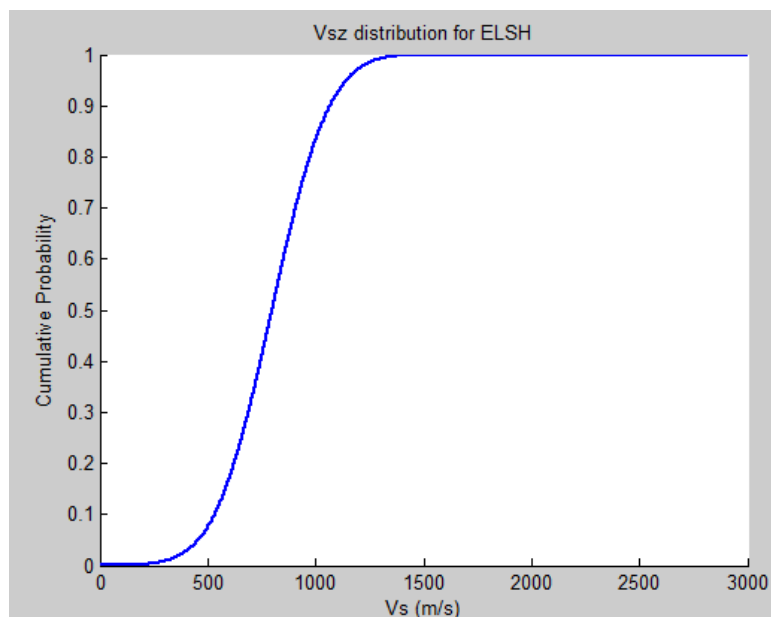


Figure 3-20: Converged cumulative probability distribution for V_{s30} Station ELSH from the sample of randomised profiles.

Discussion of the adaptation of the Toro (1995) methods

The main motivation to formulate this model was to highlight the uncertainty associated with each estimate. From consultation with industry, this is rarely carried out and there is little appreciation for

its significance, even when using the other proxy methods (Section 3.2). By including the uncertainty, this can be taken into account throughout the PSHA design. This can be particularly important if a site overlaps several classification classes.

When used to characterise the UK SGMS, the method is found to be particularly successful in showing unexpected combinations within a profile behaviour. For example, several profiles expected to be hard rock with weathered surface were found to be closer to a B classification than previously thought as the weathering had a large effect. In addition, by including the large number of generated profiles, a robustness in the estimate is created given all of the data available. This model is also less subjective than simply picking maximum or minimum values from the Global V_s Database.

Cox *et al.* (2015) has questioned the Toro (1995) method for use with dispersion curves from testing such as MASW surveys (Chapter 4). The method is often used to randomise a profile determined from a dispersion curve to provide a better indication of the aleatory uncertainty associated with the ground model. When Cox *et al.* (2015) back processed several sets of profiles for different dispersion curves, the resulting fit was poor. The profiles would not initially have been considered for the dispersion curve.

Cox *et al.* (2015) concluded that the Toro (1995) method introduces greater randomisation than necessary if there is previous knowledge of the site. Therefore, by specifically adapting the thickness profiles Toro (1995) method to fit the site, the profile is modelled within the uncertainty from the original parameters. Nevertheless, the number of profiles used to form the V_s model correlations in the Toro (1995) method was not large particularly in the Class A and D sites (Table 3-4). The correlations may also be biased by the location focus in California. However, the Toro (1995) model remains the most advanced method for soil profile generation (Kottke & Rathje 2008).

3.4 Example of application of Site Specific Proxy method to Station FOEL

In order to fully demonstrate the Site Specific Proxy method, the application to Station FOEL is included. This station was chosen as it is typical of the majority of UK SGMS consisting of a residual soil layer over rock. However, the profile contained significant uncertainties, having few near field boreholes and consisting of an older rock uncommon in the Global V_s database. Thus, in this example, it is established how these uncertainties are incorporated into the model. It should be noted that the same level of detail is available in the Station Appendix for all of the other UK SGMS analysed.

3.4.1 Development of geological profile

Location

Station FOEL is located less than 5km west of Oswestry and 20km east of Snowdonia Nation Park (Figure 3-21). The station is situated on a steep hill, Foel Wylfa, above the village Tregeiriog, around 5km south of Llangollen. The site is farmland and currently designated as pasture. The area's topography is characterised by steep, large hills and narrow valleys.

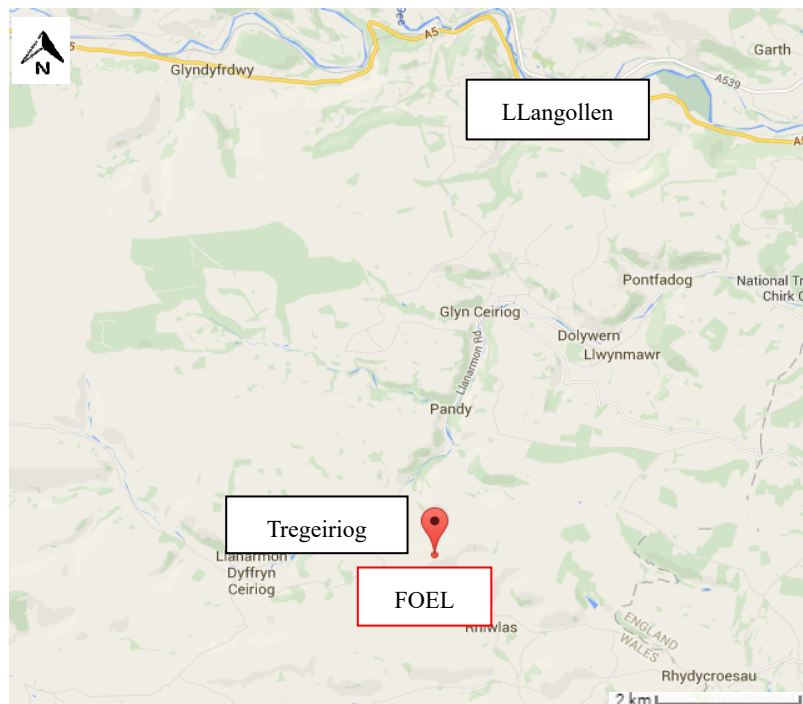


Figure 3-21: Location of Station FOEL. It is situated near the crest of a steep hill, Foel Wylfa, approximately 2km from the Welsh-English Border (Google Maps, 2016).

The Berwyn Anticline forms the main geological structure in the region (Wedd *et al* 1929). Station FOEL lies approximately 1.75km north of the apex of the anticline which is complex with no defined axis of folding. The topography in the district is raised due to this structure, but there is little to no faulting in the region of the station. Faults are instead present around the edges of the anticline forming the Berwyn Dome (BGS 2000). However, all the rocks of the region are typically described as deformed, folded, faulted and cleaved due to deformation in the Silurian period, with a general east-west alignment (Challinor & Bates 1973).

Geology

The station is located on the Caradoc stratum (Figure 3-22). This is Ordovician in age and specifically part of the LLangynog Formation. This formation consists of mudstone, sandy shales with intercalated tuff, felsic lava and limestones (BGS 2016). This formation can be up to 1750m thick, but it is expected to be approximately 1000m thick in the region of the station (BGS 2000). The formation lies unconformably over the Craig-y-gln Group mudstones of the Llanvirm Formation (Figure 3-23) (BGS 2016).

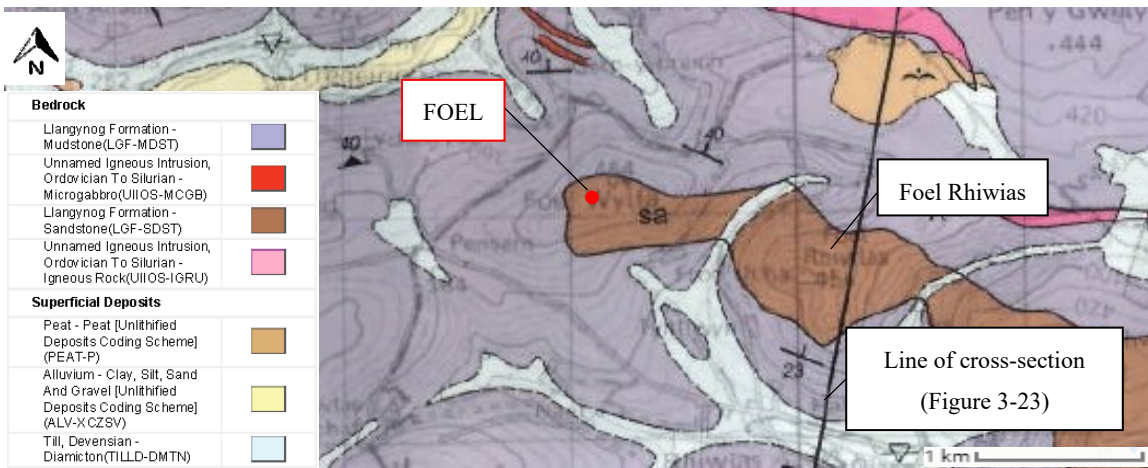


Figure 3-22: Geological map Station FOEL in the Ostwestry district (BGS 2000.) The line of the cross-section running in black (Figure 3-23).

Northern Wales is projected to be over 850m (Glasser *et al.* 2012). Therefore, it is likely the entirety of the hill, on which the station is located, will have been covered in ice. This indicates that the bedrock may be relatively intact at the surface and the extent of weathering will be less.

There are Quaternary deposits within the valleys including alluvium, till and peat (BGS 2000). The peat is variably present on the hill crests. There seems to be no particular trend to this, except that it becomes more frequent to the west. In this region, several true peat bogs are present (Wedd *et al.* 1929). However, in the east near the station, the peat occurs predominantly in the low ground. Thus, due to the exposure of the rock there is expected to be some weathered material present, but no significant Quaternary deposits are expected. It should be noted that Wedd *et al.* (1929) highlight landslides within the area, indicating some slope instability.

There are very few boreholes in the area. None are present within 2km of the station and none in the far-field within the specific sandstone deposit. In addition, the records that are present have little geological information concerning the deposits encountered (Station Appendix FOEL 4).

Thus, the initial expected geology of the station is outlined in two cross-sections (Station Appendix FOEL 3) and summarised below (Table 3-7). There were some inconsistencies found when determining the sandstone dip in the cross-sections. In the north-south section the dip was calculated from the BGS map (2000) and found to concur with that on the BGS cross-section (2000). Yet this could not be correlated with the outcroppings on recorded on the Wlyfa hill during the walk-over survey. This was also difficult in the E-W sections. However, these discrepancies occurred below the 30m range and so were not considered critical.

Table 3-7: Expected Geology for Station FOEL after initial assessment

Stratum	Expected extent of strata b.g.l. (m)	Description
Topsoil and LLangynog Sandstone (Weathered)	0.5-2	Weathered sandstone with some soil overlay. Expected to be gravelly soil at surface, becoming more amalgamated with depth until intact rock.
Llangynog Sandstone (Unweathered)	90-110	Thick, but not massive, sandstones banded with sandy mudstones and shales. Grades into mudstone at base.
Llangynog Formation (Unweathered)	Extent unproved	Mudstone, sandy shales with intercalated tuff, felsic lava and limestones.

Profile

The top 30m of ground is expected to consist of topsoil and weathered deposits, underlain by sandstone Llangynog Formation. Only four borehole logs within the same elevation were found and all in the BGS GeoIndex (2015). These were located from 2.7km to 9.3km away and none within the sandstone (Station Appendix FOEL 4).

In addition, the borehole records were of poor descriptive quality being well bores and so had little geological information. However, it was clear some topsoil is present in the region around 0.3-0.6m thick. There were also broken rock deposits, gravels and clay in the near surface. These were in the order of 5-15m. However, in the record closest to the station (Llanarmon Estate) these deposits were not recorded. This could be because the other recordings are at lower elevations than the Llanarmon Estate and some were within river valleys. At Moel-Y-Gwentyn, at high elevation mudstone is recorded to 6.1m of broken rock. All records determined grey shale/slate to over 60m depth, but there is only one record of a tuff outcrop.

As so few records could be retrieved, seven more were taken from the surrounding area to try to determine trends in the region including the weathering in the rock. These were all within 10km, however, they were also at lower elevation. The highest had 3m of clay and gravel followed by 27m of mudstone.

As site specific information was spared other sources were consulted. However, the area is largely rural with little development. Mining has been present in the region and has been the subject of a number of reports including Cooper *et al* (1984.). These focus on possible gold seams within the rocks and are generally taken from outcrop observations.

The site is located near the crest of a steep hill. The crest of the hill is formed of the sandstone from the Llangynog series. The station is located on the steeper north-west face of the hill which descends rapidly into a river valley. The south-eastern slope is slightly less steep, but is more “U” shaped. Satellite imagery shows the steep slopes clearly (Figure 3-24) (Google maps 2016). These are intact around the station and no hollows or depressions are shown. On the southern side of the hill there is evidence of land movement with a possible scarp visible. This could be a landslide however there is no obvious toe or debris heap. Therefore, it may also be a small quarry. There is scarring above this with possible terrasetts. There is also a linear feature down the western side of the hill which could be a small stream.

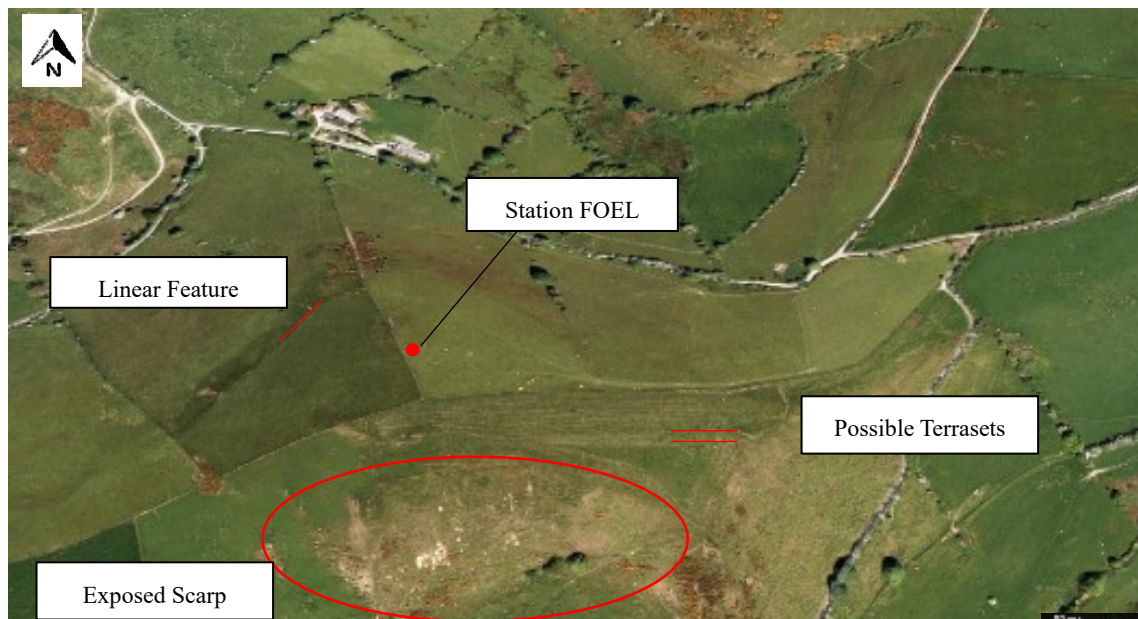


Figure 3-24: Satellite image of Foel Wlfya with unusual landforms highlighted (Google maps 2016). The outcrop appears to have a yellow colouration possibly indicating the presence of sandstone.

The expected profile from the desk study and previous *in situ* results is outlined (Table 3-8). Although, there is significant regional information, little site-specific data has been found. This leads to large

uncertainty about this site particularly in terms of the weathering or thickness of residual material over the bedrock.

Table 3-8: Expected Profile for station after desk study and previous *in situ* results.

Stratum	Expected extent of stratum b.g.l. (m)	Description
Topsoil	0.3-1	Thin topsoil overlay, expected to have rootlets and be gravelling.
Llangynog Sandstone (Weathered)	5-10	Weathered sandstone, possibly like a sandy clayey gravel with little cohesion. Expected to be gravelly soil at surface, becoming more amalgamated with depth until intact rock.
Llangynog Sandstone (Unweathered)	To end of Profile	Fairly thick but not massive sandstones banded with sandy mudstones and shales.

Site walk over survey

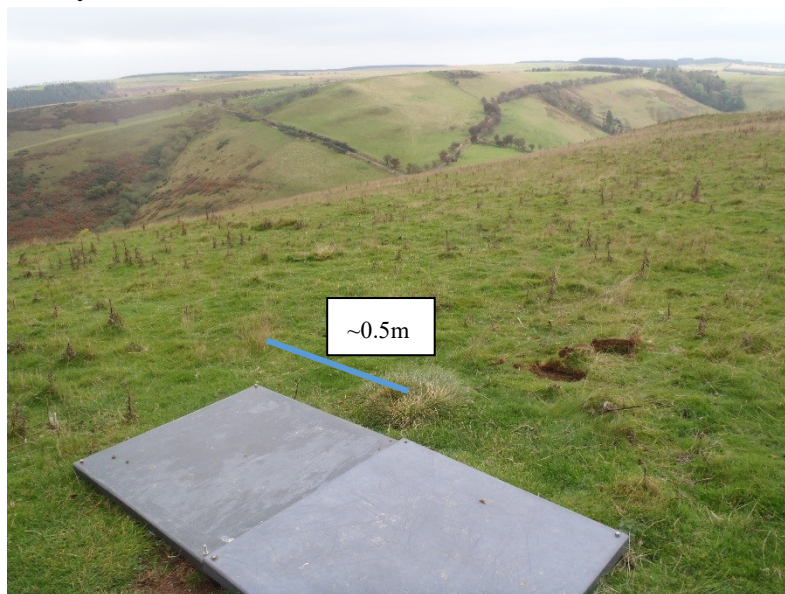


Figure 3-25: Station in foreground overlooking the steep river valley. Each station cover is around 0.5-1m across

The station was visited on 14/10/14. It is positioned near to the crest of the hill overlooking the steep river valley (Figure 3-25). The ground was well covered with grass and terrasetts were not observed.

The topsoil seemed to be thin, resisting digging with a spade after less than 15cm. The soil was a silty clay matrix with some gravel, but was mainly rootlets. At the top of the hill near the station the gravel/shards had a white colouration, as did the soil with increasing depth (Figure 3-26).



Figure 3-26: Lighter yellow cobbles indicative of the gravel near the station, found near to the fence line.

The fence line at the ridge of the hill was unusual as it had stone inserts between the normal barbed wire fencing (Figure 3-27). These appeared to be rough repairs to the fence where the wire was in poor condition and were not regularly spaced. It is also unlikely they were brought from another site. The land owner indicated that they could not use any form of mechanical transportation in the region of the station. Thus, it is likely to be taken from the site itself.

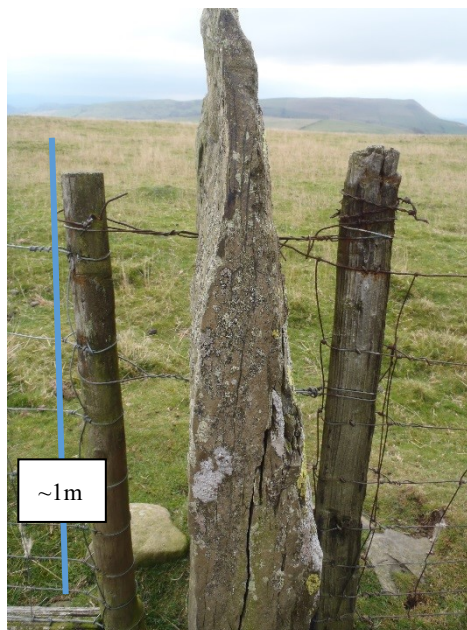


Figure 3-27: Stone insert into barbed wire fence approximately 1.25m high. Image facing south west toward Foel Rhiwas which can be seen as the hill in the distance.

The rock had fine, but visible particles and was sedimentary of origin (Figure 3-27). It was yellow-green in colour and had distinct bedding, approximately 50 mm spaced. The rock had been exposed and was weathered but still largely intact with no flaking. There was a large crack at its base possibly caused by weathering or its extraction and positioning. Several other boulders of the same rock were seen around the base.

An outcrop was observed on the track to the station, 230m north-east of the station and 80m downhill (Figure 3-28). This was of dark blue colouration than the rocks on the crest of the hill. It appeared to be shale like rock with little cohesion and could be pulled away from the rock face by hand. The layers were extremely thin, the thickest being in the order of 20mm. Weathering was seen to have a strong affect with a large number of thinly flaked scree of shards up to 200mm long. Though the matrix was not strong and quite sandy the rock itself was hard with particles too small to see. One piece was removed from the rock face. After time, this had a red colouration in layers along one face indicating the presence of iron. The topsoil had a high sand content and had a higher gravel content than that on the crest of the hill. It was also variable in thickness from 10-30cm.

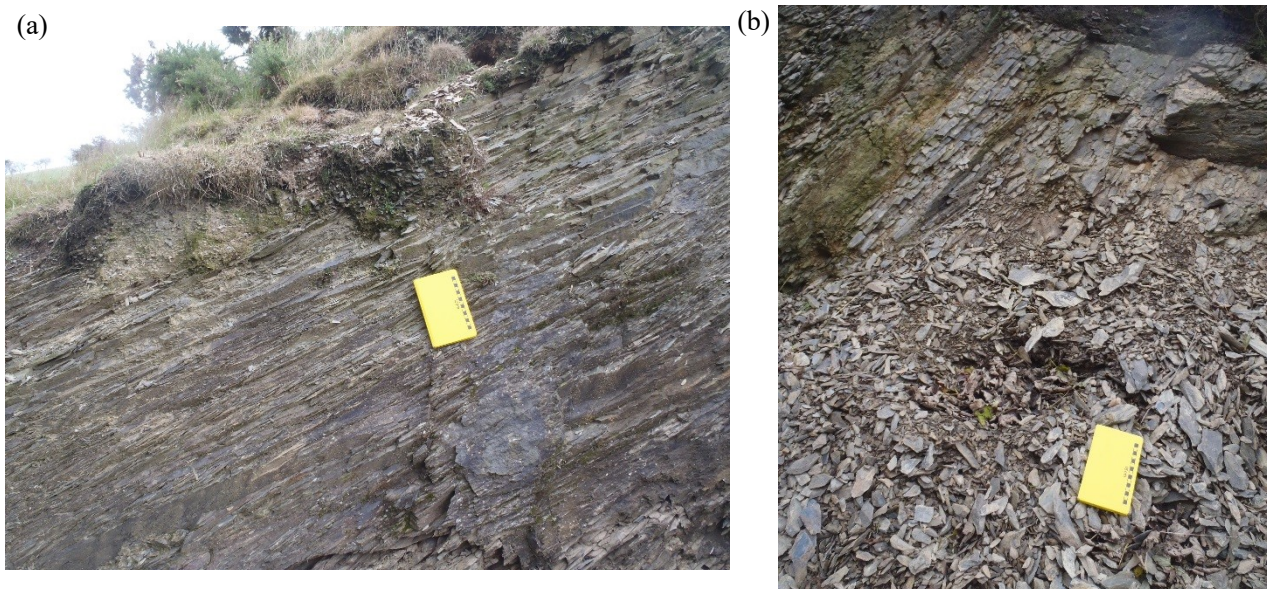


Figure 3-28: Semi-circular exposure in the northern side of Foel Wylfa. (a) Facing south-east, the layering in the rock as well as the thinness of the bedding is visible. (b) Facing-south west into the hill, there is a scree pile with shard of rock having fallen/slid of the face.

Further Work Suggested

Access could not be gained to the southern side of the hill so the exposure seen in the desk study could

not be investigated. This might reveal the level of the division of the sandstone and the shale as well as the extent of the weathering in the sandstone. The profile would benefit from more site-specific data. This could be obtained from contractors who have worked in this area. However, as this location is remote few buildings have been built particularly on the higher ground, limiting both the amount of new data possible to find.

Quality assessment

Quality is ranked for Station FOEL for the geological model (Table 3-9). The ranking system: (1) implies the high quality information that is site specific. (2) Sufficient quality, but interpretation needed from regional records (3) Poor quality information found or interpretation from far-field sources (4) Information about the attribute not found. The overall score is 26 making it at maximum a class 3 profile in terms of nature of the deposits.

Table 3-9: Quality assessment for Station FOEL

Attribute	Quality	Reasoning
Sources & <i>In Situ</i> testing records	4	The maps and memoirs are not current, but are comprehensive. However, the <i>in situ</i> recordings are poor and none could be found within the sandstone deposit.
Discontinuities	2	Generally, well defined, but no site specific information.
Regional Structure	3	Well defined within regional memoirs, but no site specific information and some confusion about the dipping of the sandstone
Geomorphology	2	Generally, well understood with the resistant sandstone forming the higher topography
Topography	2	Well defined within the region, but only to a 1:10 000 scale.
History & Deposition	2	Well defined within the literature, but regional only.
Quaternary Deposits	3	No Quaternary deposits were found on the site or are expected by the desk study. However, the likelihood of residual soil on site to unknown depth makes the assessment uncertain.
Weathering	4	The extent of the weathering was unclear and inferred from poor previous <i>in situ</i> testing records.
Reversals	2	These are not thought to be present within the residual profile, but without the site specific boreholes, uncertainty remains.
Installation	2	Installation method and dimensions were discussed with those who constructed the foundations, but evidence was not seen.
Overall Score	26	

3.4.2 Development of V_s profile

Confidence class for geological profile

The confidence class for this profile after the desk study is a Class 3. There is a significant amount of regional information. However, apart from the walk over survey there was little site-specific data determined particularly in terms of borehole records. From the walk-over survey, the topsoil is thought to be thin, but the likely extent weathering line is still unknown. A residual rock deposit could dramatically reduce the velocity of the strata in the near surface.

Comparison with the Global V_s Database

The profile was compared on a basis of similarity of geological facies with the Global V_s database (Chapter 2). The profile is considered to 30m depth as the sandstone extends more than 5m below this level and the intact shale/mudstone at depth is not anticipated to be dissimilar in stiffness to the sandstone. The profile is split into two layers: the weathered sandstone and the unweathered sandstone (as in Table 3-8), as the topsoil is expected to have been removed in the station installation.

The first comparison with the Global V_s database is type which is sandstone for both of the strata. Thus, the results are identical for the two layers for the first comparison (Figure 3-29). The first type model is then refined by depth: 0 to 10m for the weathered sandstone and 5 to 30m for the unweathered. The overlap in the depth is included due to the uncertainty associated with the depth of the weathered layer.

The third comparison as outlined (Section 3.3.3) is age. However, this parameter reduced the number results from the type and depth comparison dramatically in each of the comparisons as rocks of Ordovician age are unusual and so rare in the Global V_s database. Thus, the number of results are unlikely to be statistically significant as weathered sandstone layer contains 35 results and unweathered 45 results. In addition, inclusion of age in the comparison reduced the mean V_s value for the unweathered sandstone. This would not be expected. Thus, neither of the comparisons including age are considered.

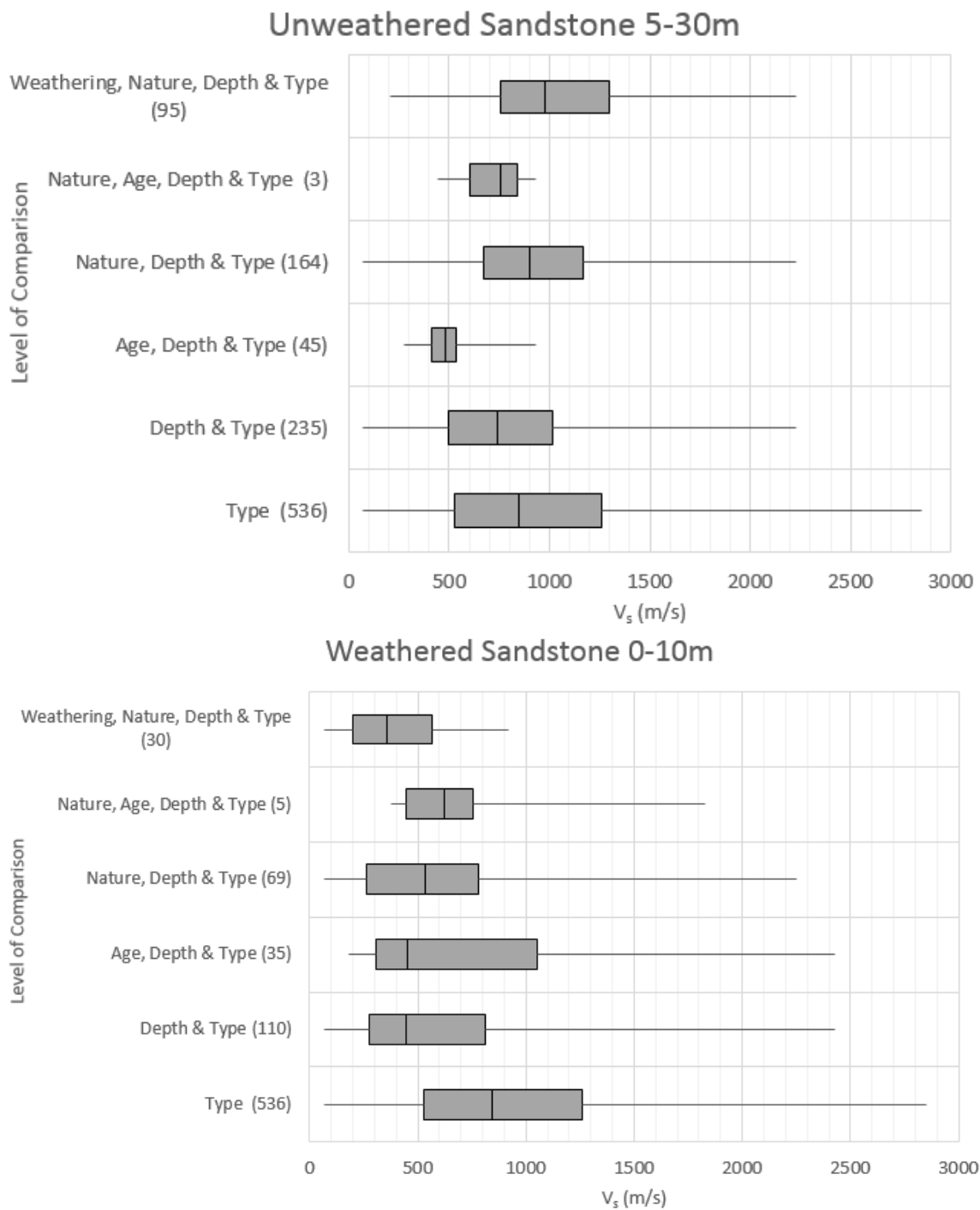


Figure 3-29: Results from the comparison with the V_s Global database for each of the two layers in the profile.

The type and depth comparison for the strata are then refined by geological nature. As discussed this is the most subjective of the categories, but it enables the pure sandstone and interbedded shale of the sandstone to be included and less representative deposits such as sandstone interbedded with claystone

to be removed. Age was also considered in this comparison, but its inclusion again reduced the number of results too dramatically to be included.

Finally, weathering is considered to allow the upper layer to be refined and weathered results removed from the lower stratum. Inclusion of this comparison did reduce the number of results within the weathered layer to below 1% of the number of results in the Global V_s Database. However, as this comparison is a major distinction between the two layers and the trend for the median and quartile results remained consistent to that expected so this comparison was included. Thus, the following V_s models for the two layers are formed (Table 3-10).

Table 3-10: V_s models for the two strata within the Station FOEL profile

Comparison	Weathered Sandstone mean V_s (STD) (m/s)	Unweathered sandstone mean V_s (STD) (m/s)
Type (Sandstone, cemented sandstone, sandstone with claystone/mudstone/shale/slate interbedded, weathered sandstone & sandstone with flysch)	847 (559)	847 (559)
Depth (0-10m for weathered; 5-30m for unweathered)	447 (437)	740 (424)
Nature (Sandstone or interbedded sandstone and shale)	536 (395)	903 (432)
Weathering (weathered; not recorded as weathered/fresh/intact)	359 (252)	980 (445)

3.4.3 V_{sz} Distribution using the Toro equations

Using the four V_s models which had sufficient results and followed the general trends of the deposits (Table 3-10). The following parameters were placed into the adapted Toro Equations (Station Appendix FOEL 8) in order to produce an estimate for the V_{sz} distribution (Tables 3-11, 12). It was assumed that thin layers of hard rock were not present within the residual layer. The convergence expected was 0.0001% between 3 consecutive profiles.

Table 3-11: Geological Model Inputs for Station FOEL

Layer	Weathered Sandstone	Unweathered Sandstone
Expected thickness (m)	5	100
Certainty of thickness ($\pm$ m)	5	10
Thickness truncation limits (m)	0-10	30-Inf
Probability of layer presence	0.9	1
Extra Layers	No	

Table 3-12: V_s model inputs for Station FOEL

Layer	Weathered Sandstone	Unweathered Sandstone
Expected V_s Models 1-4 (m/s)	847;447;536;359	847;740;903;980
Expected standard deviation Models 1-4 ($\pm$ m/s)	559;437;395;252	559;424;432;445
Probability of each V_s model	0.25	
NEHRP model	A (3)	

When completed as a Class A classification the result is a mean V_{s30} 893m/s $\pm$ 525 from 8434 profiles (Figure 3-30). This is a high standard deviation caused by the larger ranges for the rock profile, but also indicated the model may be an A/B site. Therefore, the profile is also with an A/B classification, this resulted in a mean V_{s30} of 864m/s $\pm$ 488 from 9324 profiles. The difference between the two models is 3% suggesting a relatively stable solution despite the high standard deviation. Therefore, the A/B classification is used as both calculations result in the site being between the two classes.

It is noted that the standard deviation associated with the final estimate for this station is high, being 56% of the mean. This station had one of the highest uncertainties and yet the value is not dissimilar to those of other proxy methods. However, when tested (Chapter 5) the final result is only 10% different from the predicted mean and the standard deviation is reduced to 13%. Thus, if the Global V_s Database could be expanded and more records included, it is expected this initial large standard deviation could be improved.

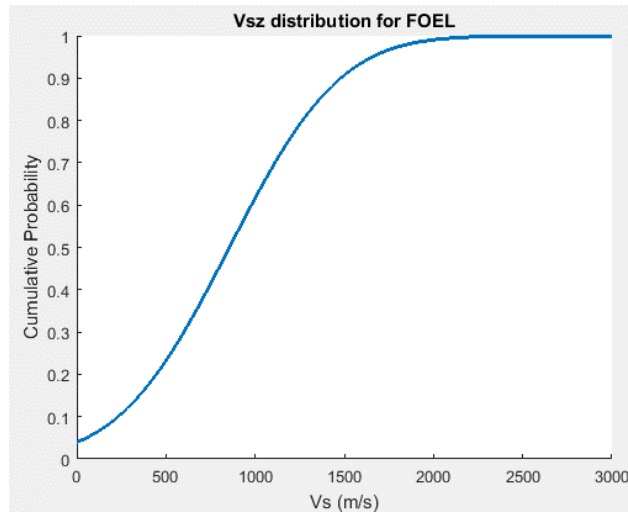


Figure 3-30: Cumulative probability distribution for V_{s30} Station FOEL

3.4.4 Geological profile and V_{s30} distribution

Table 3-13: Expected geological profile for Station FOEL, which has an expected V_{s30} of 864m/s ± 488 and a confidence class 3. It should be noted this station is located at the crest of a significant hill and therefore, may include topographical amplification in its site response.

	Stratum	Depth b.g.l. (m)	Description
	Station box and foundation	0.3-0.5	Thin pad foundation of poured concrete and station housing box.
	Llangynog Sandstone (Weathered) V_s compared to weathered sandstone, interbedded sandstone with shales.	5-10	Weathered sandstone, possibly like a sandy clayey gravel with little cohesion. Expected to be gravelly soil at surface, becoming more amalgamated with depth until intact rock.
	Llangynog Sandstone (Unweathered) V_s compared to unweathered sandstone, interbedded sandstone and shales.	To End Of Profile	Fairly thick but not massive sandstones banded with sandy mudstones and shales.

3.5 Results from application of the new proxy method the UK Strong Ground Motion stations

In order to test the Site Specific proxy method (Section 3.3), it is applied to 15 of the UK SGMS. These have been previously classified by the regional surface geology alone compared to the Eurocode 8 (2004) site classifications. Little more is known about their detailed geological profiles. Therefore, the aim is that the stations are representative of other low seismicity regions. It is common in these areas, that seismic stations have been installed, but there is little funding to retest the V_s profile beneath them. All assessments are included in the Station Appendix, but the results are outlined in Table 3-14.

3.5.1 Geological models

For each of the 15 stations, a geological model is formed through synthesis of data from the desk study, previous *in situ* investigations and walk over surveys. For the UK, the desk study had good sources of information such as data from the British Geological Survey (BGS) and Geologists Association. Therefore, for this stage of the assessment, the quality of information is generally high. Geological maps are detailed; regional structural trends are well defined; and material properties are provided with clear explanations.

The greatest uncertainty in the desk study, common to all stations, is the exact location of the stations. The available co-ordinates for each were accurate only to $\pm 100\text{m}$. In several of the sites located in regions of complex geology this made determining an accurate profile challenging. The walk-over surveys greatly aided the resolution of this problem, but in several cases, the desk-studies had to be repeated.

However, availability of prior *in situ* data poses the greatest challenge. The stations are sited in order to reduced interference from human noise and consequently are remote, or in non-urban areas. This means sufficiently detailed boring logs are generally not available for the stations or the immediate surroundings ($<1\text{km}$). Station WLF1 has no accessible borehole records within 5km of the site. Water well boreholes are the most commonly available sources of subsurface information. However, these contain little or no information on the quality of the strata present. Additionally, these are “drillers’

records” that often describe geological materials in a non-standard manner.

The BGS GeoIndex (BGS 2013) is found to be the most consistent source of data. Additional data were obtained from published site investigation reports (Station Appendix). Mineralisation reports and mining records were also useful for some locations (*e.g.* Stations CCA1 & LMK). In general, prior data from *in situ* investigations were rare.

Large sources of uncertainty for most sites is the degree of weathering within the rock, likely depths of strata contacts and the presences and nature of Quaternary deposits onsite. The walk-over survey addressed two of the main uncertainties: the location of the stations and the presence and nature Quaternary deposits onsite. In several cases (*e.g.* Station GDLE), there was also sufficient exposure to confirm the likely levels of the strata boundaries. For the majority, this was not the case. However, the walk over survey successfully addressed others uncertainties such as the depth of human interference.

The quality of the profiles the values ranged from 19-31, with an average of 26 (Table 3-14). The poorest quality rating was for the degree of weathering expected. The second poorest rating, quality of *in situ* testing, often predetermined the degree of weathering quality rating as finding sufficiently detailed records was challenging and these rarely described the condition of the rock. Unexpectedly the regional structure also had a fairly poor result, most likely because of layers not always being present.

There are no profiles examined to have an uncertainty rating of confidence class 1 (Table 3-14). Although, the profile for Station JDG was developed from high quality data, the amount of site disturbance since the *in situ* records was unclear. Hence the station was rated as confidence class 2. Class 3 was the most commonly assessed model quality. Half of these sites were developed from high quality data, potentially class 2. However, these data were not site-specific. The profiles followed well constrained regional trends, but there was an absence of site-specific data to prove this conclusively. The remaining Class 3 sites had more varied uncertainties. Stations CCA1 and FOEL had concerns

about the depth of weathering, while Station OLDB had the possibility of a high V_s velocity basal conglomerate at 30m in its profile. Station WPS had little site specific information and variable Quaternary deposits.

The final five stations were determined to have the greatest uncertainty, *i.e.*, class 4 (Table 3-14). Complexity of the geology was the main reason for sites being assigned this confidence class. Station LMK was downgraded from a quality rating equivalent to class 3, because of its complex geology. This site had at least five thin geological strata with the possibility of others being present. The region around Station HPK is highly faulted making any regional extrapolation challenging. Station WACR has heterogeneous Quaternary and Upper Chalk deposits, while Station WLF1 is located at the edge of a granite pluton in the baked complex surrounding it. Both Stations WLF1 and WACR had little site specific information. The uncertainty in the ground profile at Station ELSH is the degree of weathering within the chalk. This is expected to be high and possibly includes dissolution making velocity reversals likely in the near surface.

However, despite the uncertainties associated with the profiles, the geological modelling represents a large improvement in the understanding of the ground profile for each of the sites. The uncertainty associated with this is equally important as it identifies areas that should be targeted for testing or future research.

3.5.2 Comparisons with the Global V_s Database

For the comparisons with the Global V_s database, the majority of the profiles were compared to type, depth and depth & geological nature with the average number of layers of comparison being three. The depth comparison is generally considered the most successful as it improves upon any comparisons of rock type by including the known correlation for V_s . This is again improved by narrowing the results in order that the geological nature of the deposits was more similarly compared. An interbedded sandstone and shale layer is modelled better than considering only sandstone and shale deposits, instead of sandstone with subordinate shale.

Fewer results could be found in the database when the depth range of the stratum is narrow or when the layers were over 30m in depth. In these cases, most comparisons had to revert to a pure geological nature comparison. This is not ideal as the nature comparison is more qualitative. However, the geological nature comparison obtained more representative results at sites where the depth comparison yielded too few to be statistically significant.

When using this method, comparison by age is rarely used for the UK SGMS, particularly if combined with any other parameter. This is in part, because all of the records for the database have depth and a geological description, while age was not mandatory to the input for the database results. Therefore, only the chalk profiles consistently considered age due to its consistency in the UK. Other comparisons of era could be successful, particularly in the younger deposits, but rarely were period or epochs considered. This will also have been caused by the ages of the UK bedrock being greater than many other high seismicity regions from which the database results originated. Therefore, results for Palaeozoic rocks was rare in the database, but relatively common among the profiles.

Comparison by weathering is also relatively common. This was useful for differentiating hard from soft rocks and splitting deposits of a similar nature. For example, the Tealby Limestone in the Station LMK profile was exposed at the crest of a scarp slope and so likely weathered. In its geological nature comparison, it is related to hard limestones at some depth which are similarly sandy, but could not be representative. However, when the weathering comparison is introduced, the intact limestone is removed from the comparison.

Method of deposition is also used in the soil deposits. However, these were relatively rare among the station profiles so this comparison was not used often. Fracturing too, was more rarely used as often the previous *in situ* records gave no significant information about the state of the rock.

The main sets of data used were from the USGS and Turkey SGMS. This was augmented by UK industry results for chalk. The USGS and Turkey SGMS results were the most detailed, with the majority of the categories in the Global V_s Database included, while sets from the Japanese Kik-Net

and the Italian ITACA were less consistent with these data. The deposit that had the poorest comparison was the mudstone. In the database this was generally interbedded with other deposits and pure mudstone was found to be relatively rare.

3.5.3 Modelling with the adapted Toro (1995) Equations

The geological and V_s profiles are combined in the Toro (1995) method to produce V_{sz} distributions for the UK SGMS. All the stations were trialled to 30m, but several were also profiled to 40m. The latter included Stations ELSH, GDLE and OLDB. These stations had a change in deposit to a higher V_s rock at approximately 30m. Therefore, it is unclear from the current understanding of the sites where this layer would be present or not in the profile. The inclusion of such a larger V_s velocity could change the V_{sz} result significantly. Consequently, 40m depth may be more representative of the site, though V_{s30} will be more useful for further calculation. Station SWN is also taken to 35m b.g.l. This is because the station is located on the bunker floor at 5m depth so technically 30m is still considered.

Four stations were Eurocode Class sites from the Eurocode Class A sites (EN 2004), *i.e.*, hard rock (Table 3-14). This included the sites on Anglesey (WPS and WLF1), Station JDG in Jersey Dam on Pre-Cambrian Ignimbrite and Station MCH1 situated on Old Red Sandstone. All of rock types are geologically old and therefore, challenging to find suitable comparisons in with the Global V_s Database. This led to significant standard deviation for each profile. However, none are expected to fall into the class B site due to external records or knowledge of the rock. Thus, the lower classification being unfeasible and going against all current knowledge of the sites, the standard deviation was reduced so the expected V_{s30} for these sites did not overlap the Class A boundary.

Nine further stations are classed as between the A & B classifications, termed A/B by Wills *et al.* (2000). These were either side of the 800m/s boundary between the classes, but the associated standard deviation of the estimate allows the site to be allocated either site class, with no external evidence to prefer either classification (Table 3-14). The profiles included in this class often included the softer rocks such as the interbedded mudstone and sandstones. The majority of these are expected to be severely weathered or have significant Quaternary deposits, possibly moving the profiles into the B

Table 3-14: Summarised results from the application of the Site Specific proxy method to the UK SGMS. Full results are included in the Station Appendix. V_{s40} estimates are included alongside V_{s30} for stations where the V_{s40} profile is expected to be more representative of the station response.

Station	Mean V_{s30} (V_{s40})	Standard Deviation (V_{s40})	EU Site Class from model	Geological Model Confidence Class	Data Quality	Ridge Or Basin Flag	General Profile Description	Main Uncertainty
CCA1	811	611	A/B	3	27	N/A	Thick layer of residual granite, overlying weathered Carnmenellis granite.	Depth of weathering and superficial deposits.
ELSH	838 (842)	204 (199)	A/B	4	31	Ridge	Highly weathered Newpit Chalk (even to putty chalk) over Holywell Nodular Chalk and Lower Chalk	Depth of weathering and strata elevations.
FOEL	864	488	A/B	3	26	Crest	Weathered rock, overlying thick sandstone, followed by shale near crest of isolated hill.	Depth of weathering and far field <i>in situ</i> results.
GDLE	912 (912)	511 (487)	A/B	3	24	Change in slope angle	Highly heterogeneous sandstone, siltstone and mudstone/shale on steep scarp slope. Underlain by sandstone and mudstone.	Heterogeneity of deposits and likelihood of weathering.
HPK	911	337	A/B	4	31	N/A	Thin layer of glacial till underlain by interbedded sandstone, mudstone and shales.	Complex faulting in the region with heterogeneous Quaternary deposits.
HTL	948	503	A/B	3	24	N/A	Residual, weathered deposits with turbiditic sandstone and shale underneath.	Far field <i>in situ</i> results.
JDG	1083	710	A	2	19	Valley but no alluvial deposits	Concrete base of the dam, grouted Ignimbrite, weathered to intact Ignimbrite.	Final depth of grout and quality of rock beneath.
LBWR	809	439	A/B	3	26	N/A	Thick layer of weathered rock followed by shale grit bedrock.	Depth of weathering and far field <i>in situ</i> results.
LMK	599	201	B	4	29	Unstable scarp slope	Series of thinly layered limestone, mudstone, ironstone and sandstone underlain by thick Kimmeridge Clay.	Depth of weathering and instability in the slope.

Table 3-14 (continued): Summarised results for the UK SGMS

Station	Mean V _{s30} (V _{s40})	Standard Deviation	EU Site Class from model	Geological Model Confidence Class	Data Quality	Ridge Or Basin Flag	General Profile Description	Main Uncertainty
MCH1	898	462	A	3	22	N/A	A cyclic progression of sand/siltstones, with weathered shales.	Far field <i>in situ</i> results and depth of weathering.
OLDB	379 (456)	201 (223)	B/C	3	26	N/A	Thick alluvial deposits, with around 1m peat at the base, Mercia Mudstone & a thin basal conglomerate underlain by sandstone.	Variable depths of layers, particularly the basal conglomerate and the presence of peat.
SWN1	867	197	A/B	2	22	N/A	Man-made bunker, underlain by Lower Chalk, with Greensand underneath	Depth of human interference
WACR	798	215	A/B	4	31	N/A	Relatively thin layer of glacial till, overlying a series of weathered chalk, Upper Chalk and Middle Chalk.	Strata elevations, heterogeneous Quaternary deposits and flint banding.
WLF1	1093	636	A	4	31	Local valley effects	Hornfels to an unknown depth, underlain by similar metamorphic rocks.	Complex geology, strata elevations and far field <i>in situ</i> results.
WPS	1115	650	A	3	23	N/A	Weathered mixed metamorphic rock consisting of schists, tuffaceous siltstone and sandstone with subordinate conglomerate banding.	Far field <i>in situ</i> results and depth of weathering.

classification.

This reduction in classification of expected hard rock sites not only illustrates the importance of the near surface deposits on the profile classification, but also highlights the condition superficial deposits in the UK. This is often assumed to be hard rock to the surface. However, the detailed proxy assessment indicates this may not always be the case. This would have implications for the UK GMPEs which are based on the recordings from the SGMS.

Unlike these reduced V_{s30} rock stations, two of the chalk stations, Stations ELSH and SWN1 are classed more highly than expected in the A/B classification. Both of these sites are expected to be formed of relatively soft chalk and so form class B sites, particularly if weathered in the near surface. This higher A/B classification is expected to be caused by the limited number of chalk deposits in the Global V_s Database, the majority of which come from strong chalk rock. Thus, this may be an over-estimation of these two sites V_{s30} .

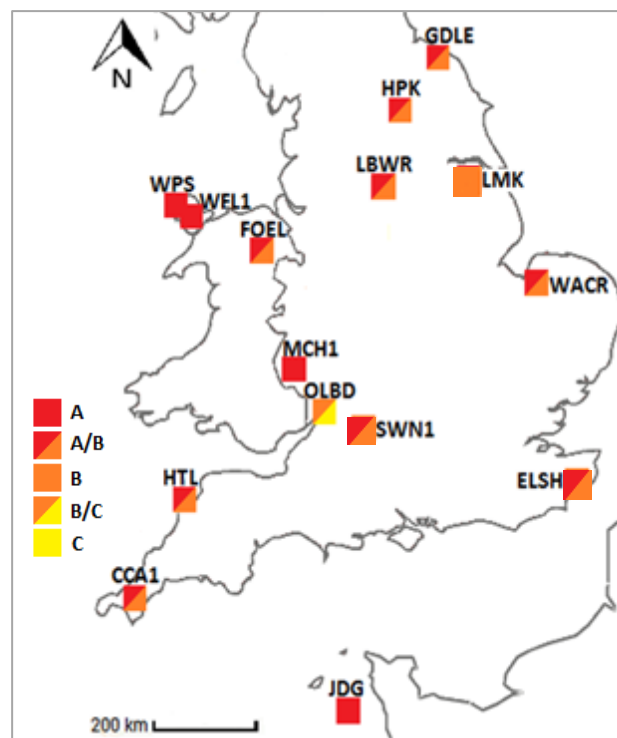


Figure 3-31: Site Specific proxy method assessment for the UK SGMS. Two unexpected results of Stations SWN1 and EL SH being higher results, possibly relying on limited results of chalk from the Global V_s Database.

Only two stations were found to be in the lower classifications (Figure 3-31). Station LMK was determined to be a class B site. Although this station was initially classed as an A/B station, its mean V_{s30} result is close to the lower bound of this class and the standard deviation overlap with class A was not large. Therefore, given the likely weathered nature of the site and the soft sedimentary geology, a class B is expected to be a more accurate representation. The second station, Station OLDB, is classed as a B/C site which is located on alluvium. The station assessment fell just on the boundary between the two classes at 360m/s. This station should be further investigated for site amplification.

3.6 Limitations of the proposed method

During the assessment of the UK SGMS, the main limitations for the development of geological profiles was the lack and quality of site-specific data. The sites are remote in order to decrease anthropogenic noise. Therefore, they are situated in areas with little to no invasive testing at or near (<1km) the site. Without site-specific data for the nature and condition of the deposits, the uncertainty associated with these sites increased. The walk-over survey was a key element to resolving main uncertainties, particularly if the nature and condition of the deposits could be confirmed visually.

The Global V_s Database was collated from a series of different independent sources based on high quality data. However, due to the varied and complex nature of V_s , there may not be sufficient results to be representative for all environments/deposits types. This is in part because of the significant time required in collecting and harmonising the records. There is also a lack of availability of records which is in part caused by the way it is generally collected over small regions by individual teams for a variety of purposes (discussed further in Chapter 2). In addition, the data are biased as the tests are generally located in seismically active regions leading to a lack of data particularly in glacial deposits. However, for countries such as the UK, the database provides a large data source where no other is yet available and is a significant improvement on correlating with UK *in situ* tests alone.

The Site Specific proxy method depends on the understanding of a site which introduces interpretative subjectivity from the user of the method. For example, if it is believed that the rock on the site is fresh when in fact the first few metres at the surface are residual deposits, both the geological model and

the later V_s estimates for this stratum will likely be incorrect. More subtly, in the comparison of the database and the inclusion of deposit types, the similarity of deposits increases the subjectivity. To reduce this user subjectivity, the Toro Equations were introduced.

However, although this did reduce the dependence of the final estimate on interpretation, the Toro (1995) equations did introduce randomised profiles not necessarily representative of the “site signature”, as described by Cox *et al.* (2015). This was less distinct in the thickness profiles which depended only on the geological model, but for the V_s velocity, the dependence on the Toro (1995) correlations was noticeable. Improving the datasets for these correlations or calibrating them to the UK environment would be expected to make an improvement to this model.

From the UK SGMS results, there is still significant uncertainty in the assessment. The standard deviation for each result was high and limited the usefulness of the classification. This is particularly true in the rock sites which have large uncertainties relating to the expected extent of weathering and by too few results in the Global V_s Database. Many of the sites were located on unusual rock types limiting the comparisons further.

Finally, as yet there are no results to support the models. The comparison of similar geological facies has previously not been attempted, so there is no evidence that introducing the extra parameters improves the correlations of the method. Thus, testing will be required to validate this method (Chapters 4 and 5).

3.7 Conclusions

There are numerous methods of calculating a V_{s30} value from a proxy method. However, these methods are generally better suited to high seismicity regions, because they have been primarily derived for use in such areas. In addition, they depend on sufficiently numerous previous *in situ* measurements to be able to correlate with one parameter which is mapped over a larger region. Thus, these are not suitable for the UK SGMS as there is little or no regional V_s testing.

Therefore, a Site Specific proxy method is created, based on a series of formation of a geological model, comparison of the model through similarity of geological facies to the Global V_s Database to produce a likely V_s profile and combining these using an adapted version of the Toro equations. This method had some limitations, particularly in terms of finding sufficient previous *in situ* invasive testing and the final uncertainty associated with the results.

The application of the new method, without validation, to 15 of the UK SGMS suggests important differences in the inferred V_{s30} values to the expected hard rock values ($>750\text{m/s}$) generally assumed for the UK environment. However, the method requires validation. As no previous testing has been carried out at these stations it is currently not possible to determine the accuracy of the method. Therefore, a method of testing must be chosen and carried out to corroborate the current expected V_s profiles.

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CHAPTER 4

In situ testing methods for V_s characterisation

4.1 Introduction

In low seismicity regions, obtaining sufficient numbers of *in situ* test results for calibrating or testing a proxy method for determining a reliable evaluation for V_s velocity is a significant problem. Even in relatively high seismic regions, a significant proportion of seismic stations remain unclassified (Figure 4-1). In low seismic regions, the probability of an earthquake that causes ground motions of engineering significance is too low to require modified design for most structures (EN 2004). However, critical structures, including nuclear facilities, are generally required to be able to cope with ground motions of probabilities of 10^{-4} to 10^{-6} per annum (Atkinson & Martens 2007). Subsequently, only these sites have had detailed seismic testing programs.

The high cost of new geological and geotechnical testing does not assist improvement of site data coverage over a region (Wald & Allen 2007). Specific expertise and specialised equipment are needed to carry out the *in situ* techniques both in the field and in analysis (Foti *et al.* 2014). Subsequently,

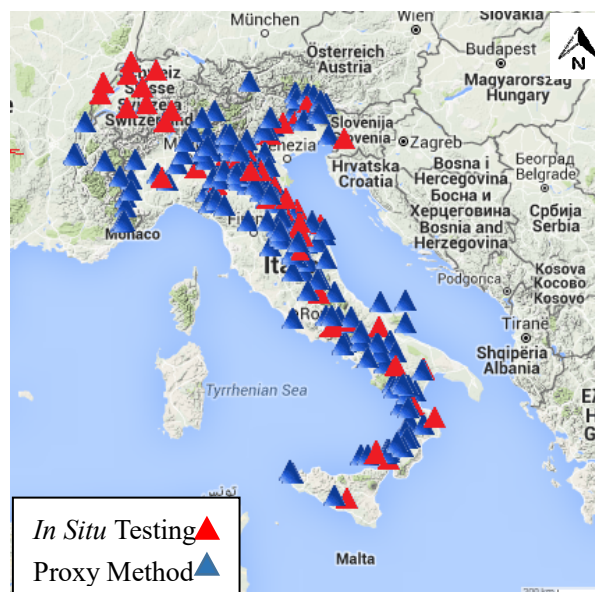


Figure 4-1: Strong Ground Motion Stations of EU Class C ground conditions in the ITACA Network (INGV 2015) in the high seismicity region of Italy. Only 56 stations have *in situ* measurements at time of writing. The remaining 251 stations have been estimated.

testing is generally only carried out only when obligatory. Thus, results from private companies have a high proprietorial value or are generally not obtainable due to their sensitive nature.

Lack of previous *in situ* measurements can have serious consequences for the seismic design of both small and large developments. Although possible to resolve for single sites, the site-specific seismic testing can add considerable cost to a ground investigation (Wald & Allen 2007). Without previous V_s measurements, this cost cannot yet be reduced by experience from previous results or from expected relationships for known rock types. For larger projects, such as the creation of national GMPEs, the cost of performing the number of tests required from the outset makes the work economically unfeasible (Stafford *et al.* 2008). This has led to considerable uncertainties in expected ground motion models in countries where the seismic activity is relatively low. This includes the UK where considerations for site specific amplification have not yet been performed (Lubkowski *et al.* 2004).

V_{s30} estimates can be obtained using proxy methods; this was initially intended to be the aim of this research (Chapter 3). However, during the investigations of the UK SGMS it became clear that having *in situ* validation of the ground models has significant additional benefit by reducing the uncertainty associated with the V_s profile. Without this, parts of each model cannot be satisfactorily determined, often leading to larger ranges of V_{s30} velocity than would be ideal and which would increase the parametric uncertainty in an amplification function. This is reflected in the coefficient of variation assigned to each method by the USGS: 20-35% for proxy methods based on surface geology (Figure 4-2) and 1-20% for *in situ* testing, dependent on the method (Moss 2008). As reducing bias and uncertainty is particularly important for low seismicity regions with small datasets, introducing *in situ* testing into the method is desirable.

In this chapter, the current state of investigative practice in low seismicity regions is reviewed. Potential methods that could be used to determine V_s for the UK SGMS are evaluated. As the main testing method, the HVSr testing is outlined in detail. Similar detail for the SCPT and MASW methods is included in Appendix 4-3. Finally, validation testing is carried out on the HVSr method in order to fully capture its limitations.

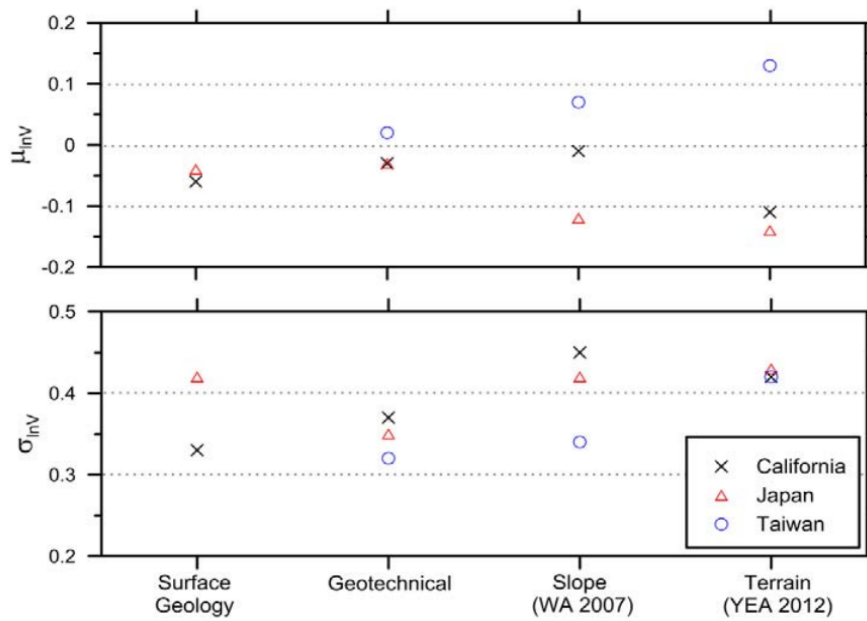


Figure 4-2: Comparison of the four main proxy methods (Chapter 3) used to classify the stations in the NGA West database (Seyhan *et al.* 2014). The top graph shows the median difference between the V_{s30} expected from the proxy method and the actual *in situ* results, while the bottom panel shows the dispersion of the expected V_{s30} . It should be noted the slope and terrain methods used in the comparison are not the most recent. Further studies have shown these methods to have equivalent accuracy at least in the USA, but still a significant dispersion (Thompson 2015).

4.2 Current practice of *in situ* investigation for site characterisation in low seismicity regions

Similar to most low seismicity regions, investigation in the UK of seismic hazard has been driven by the nuclear industry. The UK nuclear regulatory body places the responsibility to show that a hazard has been adequately characterised on the operator (Health & Safety Executive 2014). This has led the industry to instigate the installation of much of the UK seismic monitoring network in the 1970s (Browitt 1991) and the development of the first response spectra for the UK (Figure 4-3a).

However, as these spectra were developed using only 49 earthquake recordings which are further separated into three site classes (Bommer *et al.* 2011), it is noted the response from the spectra are significantly altered by adding or removing a single one of these records (Bommer *et al.* 2011). With the current large databases of earthquake recordings which can be used for regression analysis more robustly, these spectra are no longer considered sufficient (Bommer *et al.* 2011). The spectra have been used in industry since the 1980s (Musson 2014), but it was recommend to revise this methodology to

include the latest practises in recent regulatory reports for new nuclear power plants (Weightman 2012).

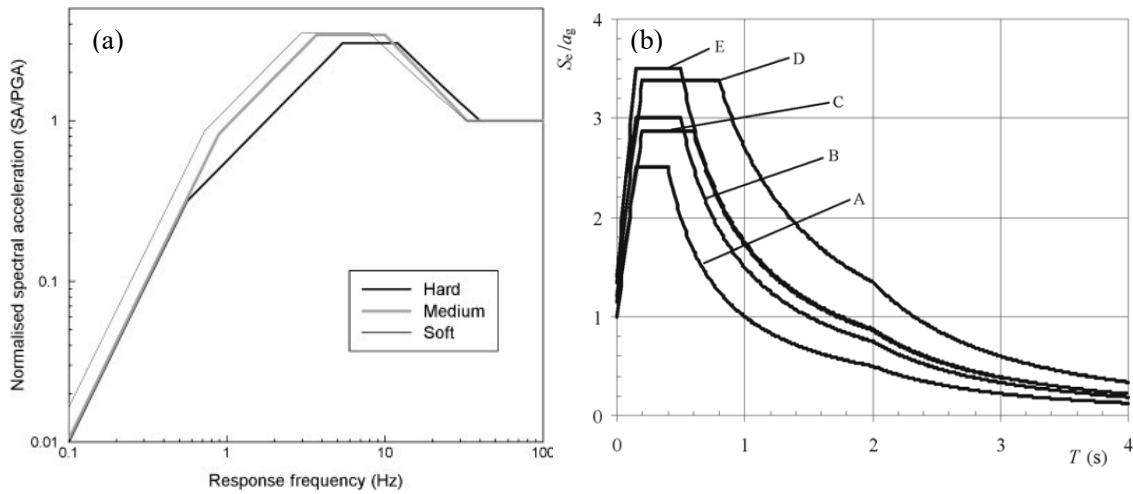


Figure 4-3: (a) Principia Mechanical Limited (PML) spectra for spectral acceleration in the UK (Bommer *et al.* 2011). These were the first response spectra developed for the UK in 1981. Though now outdated, the spectra are still widely used in practice. This is despite relying on a small dataset. (b) EN (2004) graph of spectral acceleration (S_e) against period (T (s)) of 5% damped Type 1 sites. This current code of practice depends on five quantitative classifications.

Eurocode 8 is currently used for design of general buildings and bridges throughout Europe, including low seismicity regions. The code accounts for linear site amplification with several site classes defined in terms of V_{s30} (Figure 4-3b). These site classes are used to determine the shape and amplitude of the response spectrum, in combination with several other factors, including the importance of the structure (EN 2004). Eurocode (2004) requires geotechnical or geological data in “sufficient quantity” are used to determine the relevant site class. This may include existing microzonation maps or information integrated from areas of similar geology. *In situ* V_s testing for sites of importance or sensitive/soft soil site classes is recommended, as well as laboratory testing, to determine the shear modulus (EN 2004). The aim is to obtain basic data for a normal ground investigation, but also to find any marked irregularities in the near-surface which may cause site amplification (Fardis *et al.* 1998).

The case of careful treatment of soft soils (EN classes D-S2) is highlighted in Oslo, Norway. Norway is generally considered a region of low to medium seismicity. However, its capital city is located on a deep basin of clay located relatively close to a known discrete seismic source (Ronnquist *et al.* 2012).

The proximity of this source indicates that the city has the potential to experience strong seismic shaking, even if the event itself is small (Ronnquist *et al.* 2012). The uniform hazard spectra used in the Eurocode (EN 2004) results in a relatively flat spectral shape (Figure 4-4) due to its high idealisation. This is aimed to reflect generalised behaviours and cannot model individual cases such as the peaked response spectra in Oslo (Ronnquist *et al.* 2012). For cases such as these the code highlights in the importance of the ground investigation (EN 2004) and taking the further action when required.

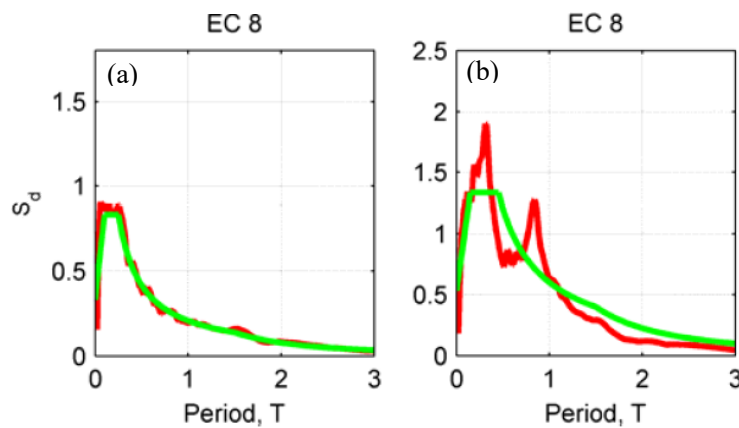


Figure 4-4: Ronnquist *et al.* (2012) comparison of (a) bedrock response input motion and (b) the surface response from site response analysis in the Oslo clay basin (red lines) to the EN uniform hazard spectra (green lines). This is a modelled response from a generated **M**6.5 earthquake which has a return period of 475 years.

The use of seismic spectra is the currently accepted method of design worldwide. The code endorsed by US Federal Emergency Management Agency (FEMA 2015) is the National Earthquake Hazards Reduction Programme (NEHRP) recommended provisions for seismic hazard (BSSC 2009). This uses similar site classes to Eurocode 8 for determining a response spectrum for a site. However, more guidance is given on the importance of the geotechnical investigation data and its interpretation. A highlighted case is an isolated soft soil layer beneath a building foundation surrounded by a homogenous layer of soil (BSSC 2009). This could be dismissed in a normal investigation as the homogenous soil properties dominate, but the soft layer could have a large effect on the site amplification.

The importance of the type of foundation used is emphasised. For piled foundations the deep geology

may be of more interest than the material at the near surface (BSSC 2009). In addition, BSSC (2009) recommends the use of 2D or 3D models in the case of site with complex variable geology. The minimum number of tests needed for these models is outlined. This includes boreholes or other invasive investigative methods to obtain pertinent geotechnical parameters such as Standard Penetration (SPT) or Cone Penetration (CPT) resistance. It also outlines the required laboratory testing of the soils encountered.

Direct measurement of V_s velocity is rarely the only considered method. Instead correlations between SPT and undrained shear strength (S_u) have also been used site characterisation (Fardis *et al.* 1998). These correlated methods are found to give better results in younger soil conditions (Fardis *et al.* 1998). BSSC (2009) recommends direct V_s measurements should be used wherever possible and clarifies that SPT N-values and the derived S_u cannot be used directly to imply the V_{s30} value. It is suggested the existing correlations are conservative and have higher uncertainty (BSSC 2009). It is also noted that non-invasive geophysical methods are rarely mentioned in either Eurocode 8 or the NEHRP recommendations. Eurocode 8 (2004) recommends invasive geophysical methods only for important structures.

Other low seismicity intraplate regions have started to increase the extent of their *in situ* seismic investigations. The Australian Government has been developing a site class map of the country using the topographical proxy method, discussed in Chapter 3 (Mcpherson & Allen 2007). However, site-specific V_s velocity measurement is recommended for the investigation of the hazard on site. This has been highlighted through the recent investigation of 50 of their strong ground motion stations using Spectral Analysis of Surface Waves, SASW, (Kayen *et al.* 2014).

The Geological Survey of Canada (GSC) has recently advanced not only the investigation of the Canadian sites, but also the methods of investigation themselves. GSC believes that seismic hazard has a significant impact on all residents. Therefore they have produced a set of guidelines on each of the predominant geophysical *in situ* testing methods (Hunter & Crow 2012). The aim was to educate all those involved in construction about the common geophysical techniques, standardize reporting practices among practitioners and give better awareness of the limitations of each of the methods

(Hunter & Crow 2012). This idea is being further developed by COSMOS (2016), who aim to raise the awareness of seismic hazards and to produce best codes of practice globally. The organisation is currently producing an international set of guidelines on all non-invasive *in situ* techniques (Yong *et al.* 2017).

Switzerland also considers earthquakes as the largest natural hazard with the most significant potential impact on the local population (ETH Zurich 2006). The Swiss seismic network has been upgraded by introducing more instruments and this network expansion has included *in situ* testing at each of the station sites. The sites are characterised through a series of tests including non-invasive geophysical testing (Edwards *et al.* 2013).

In situ testing at each strong ground motion station is the current the state of the art, equivalent to the Japanese Kik-net (Aoi *et al.* 2004). However, to date this has been poorly executed with even seismically active countries failing, to carry out work to update these parameters for their stations through *in situ* testing. To ensure future reliable seismic hazard assessment, it is essential that this should be the aim for the UK strong ground-motion network.

4.3 Methods of determining V_s at a site

Methods of measuring V_s are highly varied, requiring different equipment and levels of expertise. It is possible to conduct laboratory tests to determine V_s velocities for a specific deposit, for example, bender element testing (Kuwano *et al.* 2000). However, the disadvantage of laboratory testing is the maximum sample size that is possible to test. These are small compared to the *in situ* conditions and produce results representative of intact rock (Chapter 2). The results of such tests do not account for the presence of discontinuities which can be critical in ground response (Foti *et al.* 2014).

In the UK, much of the near surface rock has undergone substantial weathering, glaciation or freeze thaw damage (Hunter & Easterbrook 2004). Thus, the rock within the top 30m can no longer be considered intact. As *in situ* testing also assesses the soil at similar deformation levels to expected earthquakes in low seismicity regions, it was decided that *in situ* testing would be the focus of this

element of the research.

Techniques for *in situ* testing are generally divided into two groups: invasive and non-invasive. From the engineering perspective, invasive testing techniques are considered more conventional (*Brown et al.* 2000). They have more similarity with geotechnical site investigation, are generally carried out by the engineering community and are highly accurate, if carried out correctly (Crice 2002). However, they are significantly more expensive than non-invasive tests (Wair *et al.* 2012) and most give no information on lateral heterogeneity unless multiple tests carried out at a sites.

Non-invasive testing has the main advantage of not requiring any form of drilling, dramatically reducing the cost. As these methods are developed and are better understood, they are being used more frequently to characterise shallow subsurface parameters (Boore 2006). They can be used to collect data over a large area very quickly. However, the results from non-invasive tests are often challenging to processes, with significant uncertainty still remaining in the interpretation (Garofalo *et al.* 2016). Each method varies in execution often due to personal preference and to date full unbiased comparisons of the techniques are rare (Hunter & Crow 2012).

When deciding which method would be used for the testing of the UK SGMS, the more common techniques were reviewed to outline where they may be useful to a practising engineer and where their use would be limited, as well as the value of the information they can add to a project (Table 4-1). A more detailed outline of the techniques is included in Appendix 4-1.

The categories are proposed based on the analysis carried out in Appendix 4-1. The methods are first classed by type in terms if invasive or non-invasive method, how the waves are generated and then measured *i.e.* through a borehole or through reflection analysis and finally which type of waves are measured: surface or body waves. The cost of each test was harder to categorise as the final cost generally depends on ground type, the depth of the desired measurement and thus, what calibre of equipment is used. However, a low cost was assigned to a single test that typically could be carried out for less than £5 000, medium from £5 00 to £10 000 and high over £10 000. Very high was only assigned to cross-hole tests which require more than one borehole to be drilled, each borehole likely

to have a high cost.

Ambiguity of the results indicated how straightforward the results were to extract from the testing equipment. This was related to how likely the results would be interfered with in the field by noise or for example passing through a different layer to the one that was expected to be measure. This is related to processing difficulty, which is defined by the complexity of equations and level of engineering judgement required to achieve an accurate interpretation. Limitations indicated geological environments or structures where the use of the method would be unsuitable, while value added suggests where the method is useful or if it can provide further information beyond V_s at little or no extra cost. Finally testing time gives a typical length of time for a single test.

Table 4-1: Summary of comparison of *in situ* testing methods: Invasive methods. Appendix 4.1 contains a fuller explanation and important references for each method.

Method	Description	Relative cost of a field test	Relative ambiguity of results	Limitations	Testing Time	Relative processing difficulty	Value added
Seismic Downhole	Invasive, active, surface triggered, single bored, body waves.	High	Low	Depth of test limited by damping of material	Several days for BH	Low	Can determine thin layers and copes well with horizontal anisotropy
Seismic Cross-hole	Invasive, active, triggered at depth, single bored, body waves.	Very High	Medium	Prescience of high velocity layers may disrupt results	Several days to a week for BH	Low to medium if seismic tomography used	High accuracy particularly with thin layers and velocity reversals
Suspension PS Logger	Invasive, active, triggered at depth, single bored, body waves.	High	Low	Soil must have a higher V_s velocity than fluid used	Several days for BH	Low	Can easily achieve depths over 50m.
Seismic Cone Penetration Test	Invasive, active, surface triggered, single CPT, body waves.	Medium	Low	Test cone strength capacity to push through material	Several hours for setup and the first, but then more quickly dependent on depth	Low	Invasive with no BH and good coupling

Table 4-1: Continued. Non-invasive methods using body waves. Appendix 4-1 contains a fuller explanation and important references for each method

Method	Description	Relative cost of field test	Relative ambiguity of results	Limitations	Testing Time	Relative processing difficulty	Value Added
Seismic Reflection	Non-invasive, active, surface triggered, reflected body waves.	Medium to low	Medium-dependent on processing	A highly damping soil will prevent deep results. May be obscured on noisy sites.	Several hours to days for deep, accurate, basin surveying	Medium	Can achieve the maximum depth of all the non-invasive active tests and large amounts of lateral data
Seismic Refraction	Non-invasive, active, surface triggered, refracted body waves.	Medium to low	Medium-dependent on processing	Velocity reversals cause issues as well as thin layers. May be obscured on noisy sites.	Several hours to days for deep, accurate, basin surveying	Medium	Detailed data in the near surface

Table 4-1: Continued. Non-invasive methods using surface waves. Appendix 4-1 contains a fuller explanation and important references for each method

Method	Description	Relative cost of field test	Relative ambiguity of results	Limitations	Testing Time	Relative processing difficulty	Value Added
Spectral analysis of surface waves (SASW)	Non-invasive, active, surface triggered, surface waves. Two receivers	Low	Medium-dependent on processing and number of test points	Higher modes not distinguishable, so directional noise sources can cause issues. Spacing of receivers depends on depth of target	Several hours with work to move the receivers	Medium	Useful in difficult soils such as gravels & debris flows. Little equipment required.
Multi-channel analysis of surface waves (MASW)	Non-invasive, active, surface triggered, surface waves. 1D line of receivers	Low	Medium-dependent on processing	Struggles with environments with extremely damped soils or bedrock close to the surface	Several hours to half a day	Medium	Better field production rate, more robust and rigorous than SASW
Horizontal to vertical spectral ratio (HVSr)	Non-invasive, passive, surface waves. One receiver, non-directional source.	Low	High-dependent on previous knowledge of the site	Must have previous knowledge of the site in order to find results.	Several hours for a transect, less than 20 minutes for one recording for 30m depth	Medium	An upper bound of the fundamental frequency of the site can be determined.

Table 4-1: Continued. Non-invasive methods using surface waves and arrays. Appendix 4-1 contains a fuller explanation and important references for each method

Method	Description	Relative cost of field test	Relative ambiguity of results	Limitations	Testing Time	Relative processing difficulty	Value Added
Spatial autocorrelation (SPAC)	Non-invasive, passive, surface waves. 2D receiver array, non-directional source.	Low	Medium to high-dependent on processing	Source of passive noise must not be directional and so struggles with urban environments. The ground also needs to be flat between receivers. Bedrock velocity may be poorly resolved.	24hrs or more	High	Can reach depths of over 50m even in soil with high damping and can cope with velocity reversals.
Frequency-wave number ambient noise array (f-k)	Non-invasive, passive, surface waves. 2D receiver array, directional source.	Low	Medium to high-dependent on processing	Bedrock velocity may be poorly resolved. Source of passive noise must be directional and so struggles with rural environments.	24hrs or more	High	Works well in urban environment and can cope with velocity reversals.
Refraction micro-tremor (ReMI)	Non-invasive, passive or active, surface triggered, surface waves. 1D receiver array, directional source.	Low	Medium to high-dependent on processing	Often less accurately and rigorously used than SPAC or f-k.	Dependent on set up active/passive	High	Being both active and passive, the test can easily cover all the main frequencies for the site.

4.4 Methods used to determine V_s profiles at the UK strong ground motion stations

When determining, which tests should be used for UK strong ground motion stations, there are specific considerations given the limitations of each technique and the geology at the different stations. The first and most constraining requirement is the cost of the investigation. A total of 15 separate sites were selected for investigation, including several with repeat investigations. This had to be completed on a reasonable budget, less than £10 000 for all tests (excluding CPT testing which was carried out in kind). Therefore more-costly methods, including boreholes, would not be possible.

Thus, the accuracy of the final results would be limited by this budget, but also the time available. Traditional invasive methods are of limited usefulness due to the time required to complete the testing and the subsequent data interpretation. The time requirements had other implications for the complexity of the methods. Each method had to be fully understandable to a competent, geotechnical earthquake engineer, such that it could be feasibly carried out accurately, both in the field and during the data processing. Thus, array methods such as SPAC and f-k are not viable as much experience is required to carry these out correctly. Moreover, the equipment had to be available in the time frame required; this is currently limited in the UK.

In addition, the sites being tested had to be considered. They represent the vast variability of the UK geology not only between sites, but also on the site itself. A major consideration is that most sites are likely to have some form of soil overburden. Few sites are expected to have bedrock exposure at the surface. Finally, it is important that at least one method of testing is applicable to all the sites to provide a common reference frame for comparing results.

Given these considerations, three methods are chosen: HVSr, MASW and SCPT (Table 4-1). The SCPT method is chosen as it is the least expensive and time consuming of all the invasive methods. Similarly, the MASW is chosen as it is the easiest to carry out and process of the non-invasive methods. However, to perform MASW at all the chosen sites was cost prohibitive. Therefore, HVSr is chosen as the primary method, with MASW and SCPT being carried out at sites in need of further validation.

Using HVSR is a compromise between the ability to test at all sites and the cost of the testing. It is the least expensive and quickest to carry out in the field. However, the results of the method are indeterminate and require prior knowledge of site conditions to be used. In the case of the UK SGMS the geological models formed in Chapter 3 are used to constrain the results and so this is relatively easily overcome. Nevertheless, the method is generally only used as supplementary information to other techniques. Therefore, to be able to use it as the primary investigation method requires further examination and validation of its limitations.

4.4.1 HVSR Method

The Horizontal/Vertical Spectral Ratio (HVSR) technique depends on the ambient wave field within the ground (surface waves). Surface waves are formed by a number of sources including ocean waves which produce waves generally below 1Hz frequency as well as anthropogenic noise which have frequencies typically above 1Hz (Foti *et al.* 2014). In the HVSR method, it is assumed that the wave field is predominately formed of Rayleigh waves which have retrograde elliptical rotational paths in the near surface (Foti *et al.* 2014).

The shape of the Rayleigh wave elliptical rotation is also frequency-dependant in a non-homogeneous layered medium (Bard 1999). The polarisation or shape of the ellipse can be determined using the ratio of the amplitude of the horizontal to the vertical component (H/V). If the difference in stiffness of soil layers is sufficiently large, a sharp peak is formed in the H/V ratio near the fundamental frequency of the site (Foti *et al.* 2014). In a simple two layer model at low to medium frequencies, this peak at fundamental frequency is caused by the vanishing of vertical component as the direction of rotation changes and the motion is instantaneously purely horizontal (Bard 1999). A sharp dip is also produced in the higher frequency range associated with the vanishing of the horizontal (Foti *et al.* 2014). If a parameter such as the depth of the first layer is known, the H/V curve can be then iteratively fitted to the frequency of the peak using the relationship between frequency, layer thickness and V_s (Castellaro & Mulargia 2009).

It has previously been conjectured that this explanation is only valid for simple profiles of two layers.

However, evidence from such as Konno & Ohmachi (1998) indicates that this is also valid for more complex profiles. It is also limited by the assumption of only Rayleigh waves are present in the ambient wave field. Though generally considered to be related to Rayleigh wave ellipticity, the wave field is also dependant on Love waves and body wave resonance.

Love waves exist in the horizontal plane and so affect only the horizontal components creating imbalances with the vertical component (Foti *et al.* 2014). In addition, in environments with high impedance contrasts, the Love wave group velocity minimum can coincide with the minimum vertical Rayleigh motion causing a larger peak than would be expected (SESAME 2004). Other minima and maxima also in the Love wave field can distort the horizontal trace.

The relationship between body waves and the H/V plot is even more complex and the subject of ongoing research (Bonnefoy-Claudet *et al.* 2004; Oubaiche *et al.* 2016). It is expected at high frequencies (>10Hz) p waves are likely to amplify the vertical component due to the general p wave velocities being over 1000m/s. Therefore, surface peaks may be masked by body wave interactions, particularly at high frequencies (Bard 1999).

First developed by Nogoshi & Igarashi (1971), but popularised by Nakamura (1989), the HVSR method still has no full analytical proof (Malischewsky & Scherbaum 2004). However, recommended guidelines for the technique were commissioned by the SHARE project (Woessner *et al.* 2015). These SESAME guidelines (2004) provide recommended procedures for field experiments, data processing and interpreting for the HVSR method. They are widely followed and are used as guiding principles in this research. These recommend only considering consistently determined peaks, over 2 in HVSR amplitude to overcome the challenges posed by the wavefield.

Therefore, the procedure uses a sensitive seismometer to record three translational components of ground movement. These are converted into the frequency domain by Fast Fourier Transform. Using the Nakamura (1989) H/V method the converted, horizontal spectra are geometrically averaged:

$$H_{av} = \sqrt{HE \cdot HN} \quad [4-1]$$

where H_{av} is the averaged horizontal spectra, HE is the eastern horizontal spectra and the HN is the

northern horizontal spectra. This method does introduce a directional error as the mean is orientation dependant. For each measurement, it is aligned as close to north as possible, but will introduce an error which is included in the overall measurement error. The average horizontal spectrum is then divided by the vertical trace to produce the H/V plot.

The HVSR method has continued to increase in popularity, because of its relatively low cost compared to the other techniques. However, if used without a good geological understanding of a site, the results can be completely misinterpreted. This leads to inaccurate or even unfeasible geological profiles (Mulargia & Castellaro 2009). The method is also open to issues of interference from noise, especially anthropogenic noise and has difficulties with hard, man-made layers in the near surface (Hunter & Crow 2012). Consequently, measurement errors of up to 20% of the true V_s velocity have been reported (Micromed 2013b), though, this is still less than general proxy method errors.

However, when used correctly, the technique can provide cost-effective information about a site. Moreover, the equipment is easily portable with an adaptable layout to suit a site and a changeable time scale, which can be less than 20 minutes per recording. The analysis does require caution (Micromed 2013a), but is not complex. The results are often to a much larger depth than other surface wave methods as it is not dependant on an active source (Hunter & Crow 2012).

For the UK SGMS, the geological models produced using the Site Specific proxy method (Chapter 3) could be used initially to constrain the HVSR results. Thus, the testing results could add information directly into the model. In addition, the technique does little damage to the sites themselves. There is currently a small core of HVSR expertise within the UK. Thus, this method is more readily available and comparatively well-established within site characterisation practice.

Consequently, the HVSR method is chosen as a preliminary method for determining V_s profiles at all sites. The results are then used to highlight challenging sites or stations where the HVSR results and the site-specific model showed poor correlation. In these cases, more supplementary tests such as the SCPT and MASW could be carried out. Using the HVSR technique, sites could be relatively rapidly tested for little expense. Thus, it is an ideal method for preliminary site assessment as it allows

evaluation of initial geological model to determine whether further testing is required for the development of detailed ground models.

Field Testing

Currently, there are no standards of practice available for the HVSR method. HVSR can be carried out either using existing earthquake records or from direct measurements of ambient noise (SESAME 2004). The relationship between the two methods is still under discussion. The earthquake recordings used are predominantly body waves rather than surface waves, making the processing more challenging. In addition, for the UK and similar low seismicity regions, not all sites have suitable earthquake recordings. This is the case for the 15 stations being investigated in this research. Therefore, the direct ambient noise measurement is used. One site, station ELSH, did have a recording within its proximity from the M4.0 2007 Folkestone earthquake. Thus, part of the validation of the method included comparison of the earthquake recording with the ambient noise recording (Section 4.5.5).

There is no standard equipment for the HVSR method. In this study, a Tromino Zero instrument is used (Figure 4-5). This is manufactured by Micromed Geophysics (Micromed 2013b), now Moho, closely linked to the University of Bologna. This instrument is purpose built to measure microtremors and conforms to the SESAME (2004) guideline requirements. It has been used in investigations for high profile international institutions; for example NEHRP (Cakir & Walsh 2012) and the Geological Survey of Canada (Molnar *et al.* 2014). The instrument is a three component combined velocimeter and accelerometer. It is connected to the ground using three metal spikes attached to its base (Figure 4-6). A brief manufacturer's specification is attached in Appendix 4-2 and technical aspects are outlined in Table 4-2.



Figure 4-5: Tromino Instrument installed in a testing hole with removed earth visible on the right. On the left side of instrument an arrow can be seen which must be pointing north disregarding the direction of transect.

Table 4-2: Tromino sensors technical specification (Micromed 2012)

Sensors	6 velocimeters: 3 low gain, 3 high gain differential sensors 3 accelerometers monopolar sensors
Instrument Response Spectrum	Equalised between 0.3Hz and 200Hz
Sampling Frequency	Instrument: 64 kHz per channel Output: 128Hz
Saturation Levels	Low gain: $\pm 45.6\text{mm/s}$ High gain: $\pm 1.2\text{mm/s}$ Accelerometer: $\pm 5\text{g}$
Instrument noise	$< 0.5 \mu\text{V r.m.s.}$ at 128 sampling on the high gain velocimeters

The previous version of the Tromino instrument did have issues with the quality of recording due to the high self-noise of the instrument below 3Hz frequency (Tasic & Runovc 2012). This was addressed in the updated design of the Tromino Zero (Castellaro 2015) and the instrument noise reduced so that is it is comparable to the low noise model of the Earth wavefields from 0.1Hz. During field testing two different instruments were used, but both were the new Tromino Zero models.

The instrument is set up by initially attaching the metal spikes to the base (Figure 4-6). Longer spikes are preferred as they were found to produce better coupled results. A hole approximately 200x300x150mm is then dug into the topsoil to ensure good contact with the soil beneath and to remove any turf or surface material (Figure 4-5). At shallow hard rock sites this was not always possible. In this situation, the long spikes are used with a shallower hole or at the surface with any vegetation removed. If the long spikes could not be sited, the short spikes are used and recorded in the observation log. However, if possible the short spikes were avoided and only used where bedrock was

exposed at the surface (*e.g.* Station WLF1).

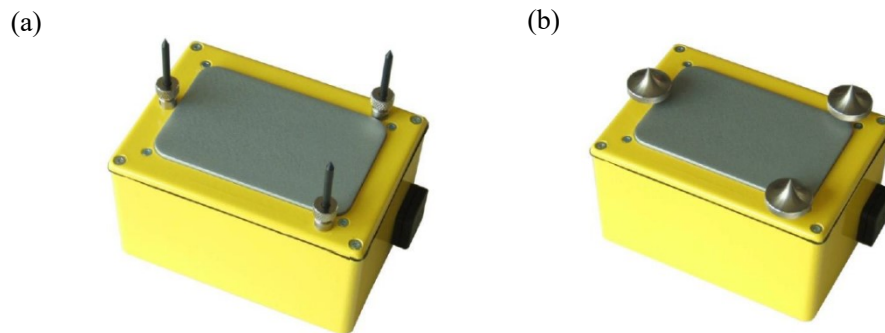


Figure 4-6: Base of Tromino with two sets of spikes (Micromed 2013b): (a) the preferred long spikes which provide better coupling with the ground and (b) the short spikes for extreme cases such on exposed bedrock.

Once the instrument is configured, it is pushed into the prepared and aligned hole (Figures 4-5 & 4-6). As the spikes provide coupling between the instrument and the ground, ensuring good contact with no air gaps or movement from the original insertion points is critical for accurate results. Therefore, although it is desirable for the instrument to be level as it is inserted, this was not done at the expense of decreasing the ground contact. The instrument can tolerate up to $\pm 5^\circ$ tilt (Micromed 2013b). Exceeding this tolerance can be seen in a difference between the two horizontal components (Section 4.4.1 Processing). If the coupling or tilt criteria were not met then the instrument was reinserted in a new position adjacent to the original, but clear of the original contact holes.

The contact materials are important. Made ground or asphalt cause velocity reversals in the very near surface, influencing the accuracy of the instrument readings (SESAME 2004). The majority of UK SGMS are on “green-field” sites. However, disturbed soils, such as soft muds, ploughed soils and saturated soils, should be avoided as these can distort the wave fields (SESAME 2004). Near field ambient noise can also degrade the quality of the results from the HVSr method. At many of the more elevated UK SGMS, wind noise is problematic. In these cases, a plastic box was placed over the instrument. This removed much of the wind interference and ensured the ground surface and wave field near the instrument were not disturbed. Trees and unstable fence lines are also avoided so the wind blast is not transmitted into the recorded wave field (SESAME 2004).

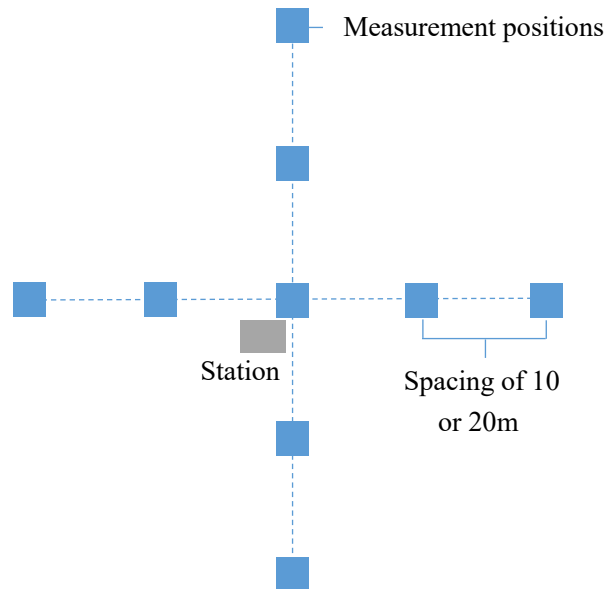


Figure 4-7: Typical testing layout used for the HVSR. The instrument is moved between the positions of blue rectangles forming the dotted line transects. The station being tested is generally positioned as in the grey rectangle. The recording positions were generally spaced at 10 or 20m depending on the site restrictions.

The surveys were conducted with a single instrument that was moved between recording positions to produce a traverse (Figure 4.7). This was conducted in two perpendicular lines crossing at the station. This layout was chosen as the lines could be positioned to follow the geological structure or the topographical contours allowing a clear view of the station profile. However, in some cases this was not possible due to space restrictions in the region of the station. For example, station HTL was placed in a fenced corner of a field close to a tarmac footpath (Figure 4-8). Therefore, the instrument positions were asymmetric, but still intersected close to the station. Spacing of the recording positions were generally 10m or 20m, depending on the location (further outlines in the Station Appendix).

Measurements at each of the recording positions were taken for 14 minutes. The initial two stations tested, Station ELSH and OLDB were only tested for 10 minutes, but then confirmed with other techniques. The 14 minutes recording period allows frequencies just below 1Hz to be considered (further in Section 4.4.1 Processing of the HVSR Method). Recordings were sometimes repeated if, for example, they had been significantly disturbed for more than a minute, such as by a sheep when investigated the instrument. Any disturbances shorter than this, such as wind gusts, were recorded in the observation logs and removed during processing.

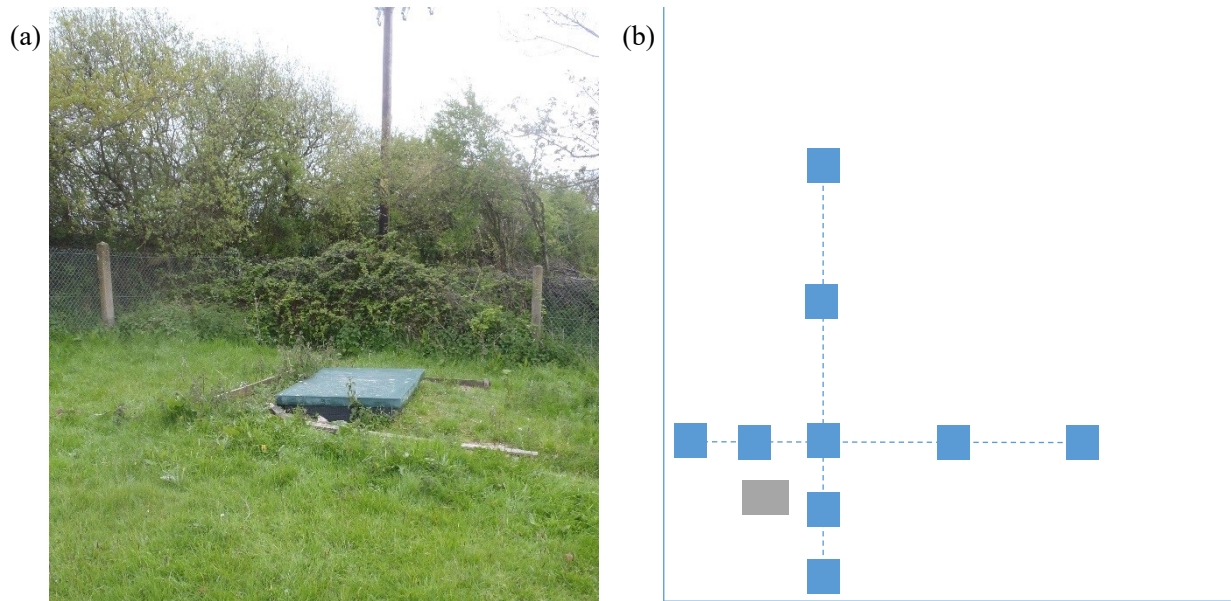


Figure 4-8: (a) Station HTL seen as green drain cover in the foreground. This is located in the corner of the field with a footpath running just behind the fence line. (b) Layout for instrument positions in blue rectangles, forming the traverses of the dotted blue lines with the station as the grey rectangle.



Figure 4-9: (a) Station ELSH seen as grey drain covers with the line of traverse marked by the tape measure. (b) Tromino recording on site. The hole spoil can be seen to have white pebbles of chalk,

For example, Station ELSH, at Elham, was tested on 09/09/14. The weather was sunny with low wind speed. No significant disturbances occurred during testing. The X-shape of nine recordings was adopted with 10m spacing (Figure 4-7). Although, holes could be dug for each of the recording positions, levelling was slightly more difficult due to the soil being extremely dry and stiff. Each measurement was recorded for 10 minutes.

Processing of HVSR Method

A number of open source software options are available for processing H/V traces, including J-SESAME (Atakan *et al.* 2004). This is produced by the authors of the SESAME Guidelines (2004). However, in this research, the Grilla software version 6.4 was used (Micromed 2013a). This is the software of Micromed (now Moho) and is included with the Tromino Zero instrument. This was chosen, in part, because UK industry is familiar with the software, but also it includes an iterative fitting algorithm to constrain the traces in terms of V_s profile.

Initially, the traces can be viewed in their raw displacement form (Figure 4-10). These are carefully inspected to determine if there had been any noise peaks during the recording. If the timing of the peak matched any recorded disturbance in the observational log, for example a car passing, then that time segment is noted so it could be removed during cleaning. The traces are also checked to determine if they are significantly unbalanced between the directional components. If one component had a much larger amplitude than the other two, this may suggest poor coupling of the instrument or a directional noise source.

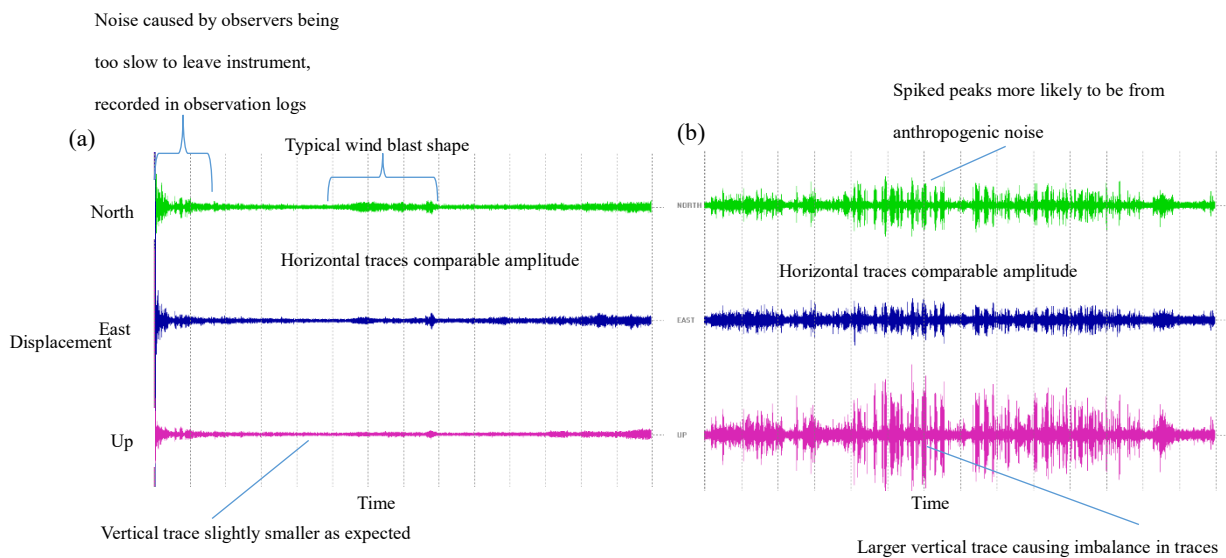


Figure 4-10: Two microtremor recordings in the displacement domain (Micromed 2013a). (a) Relatively quiet recording with some observed noise at the beginning of the record, which is to be removed during cleaning, as well as a small amount of wind blast. (b) A much noisier trace, possibly from anthropogenic activity as the peaks are spiked. However, as the trace is unbalanced with the vertical component being larger than either of the horizontal traces, it may also be caused by poor coupling of the instrument with the soil.

The displacement components are converted to the frequency domain using a Fast Fourier Transform. During this process, the components are smoothed by 10% of the central frequency through triangular windowing of a 20 second period (Micromed 2013a). This produces the component spectra for each recording (Figure 4-11). These spectra are used to verify whether any peak in the later H/V trace is in fact stratigraphic in origin. If it is, the component spectra form an “eye” shape between the two horizontal and the vertical components (Figure 4-11a), *i.e.*, the spectra diverge and then converge over a defined frequency range (Castellaro 2014). Poor levelling is also visible in the spectra if the horizontal traces are largely separated (Figure 4-11b) (Micromed 2013a). This may also be caused by an unbalanced trace (Figure 4-10). In addition, other interference is visible in these spectra including love wave interference (Figure 4-11c) and overwhelming anthropogenic noise (Figure 4-11d) (Castellaro 2014).

The component spectra are converted into the H/V trace, by geometrically averaging the horizontal components. The average is then divided by the vertical component to produce the H/V plot (Figure 4-12a) (Nakamura 1989). This is plotted alongside the standard deviation in the Grilla software (Micromed 2013a). The standard deviation is calculated from the recording 20s window samples of the total 14 minute measurement (SESAME 2004). These are treated as multiple recordings of equal weight. Plotting the standard deviation makes the identification of noise easier within the trace as the standard deviation increases (Figure 4-12b). This should be decreased during the cleaning of the recording. The trace is also checked for peaks above the maximum amplitude and those in the extremely low frequencies (Figure 4-12c). These can be caused by specific or spurious noise sources and may cause the viability of the trace to be questioned.

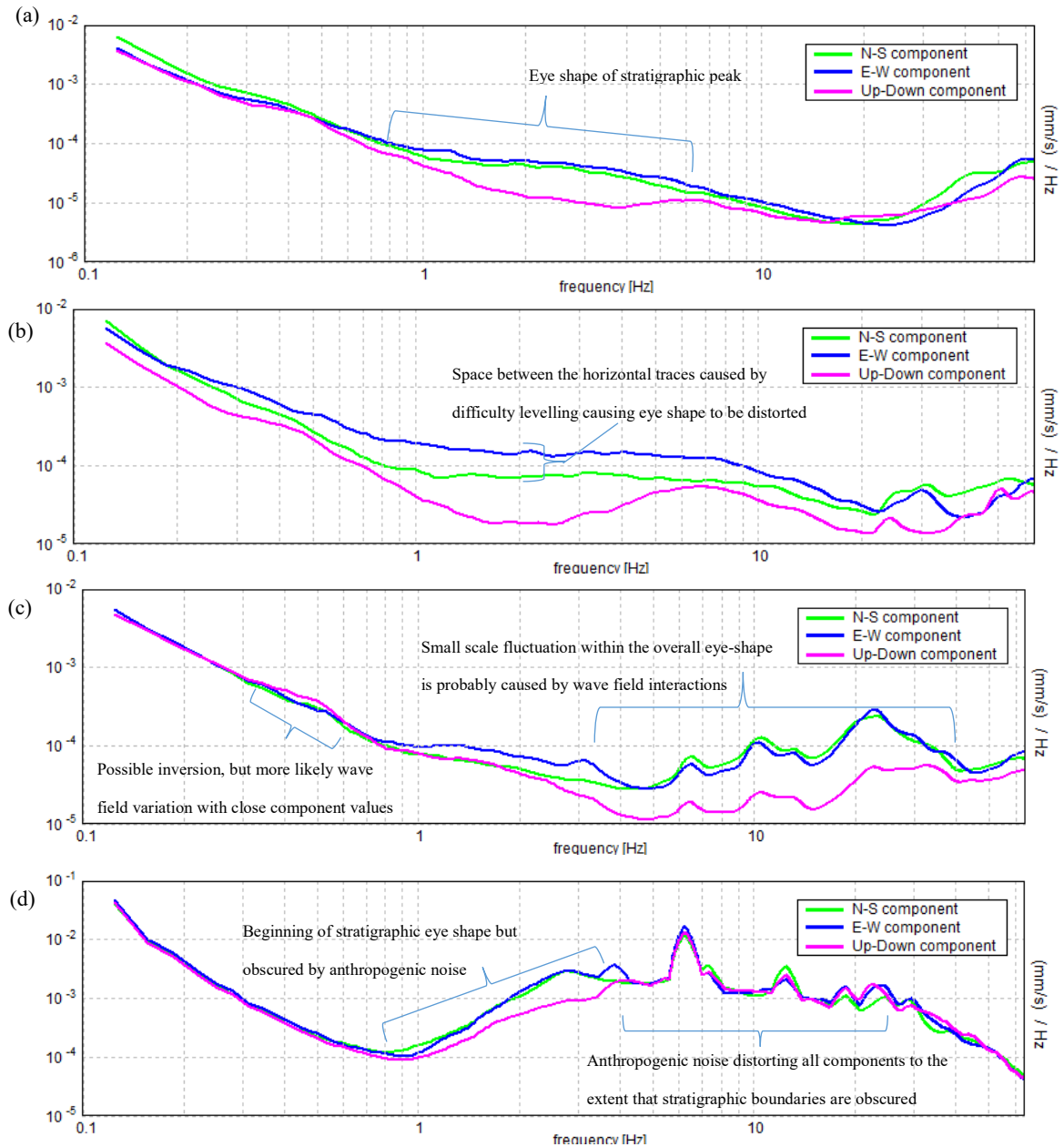


Figure 4-11: Examples of frequency spectra after conversion from displacement measurements through Fast Fourier Transform. Note all are from different sites so are not directly comparable.

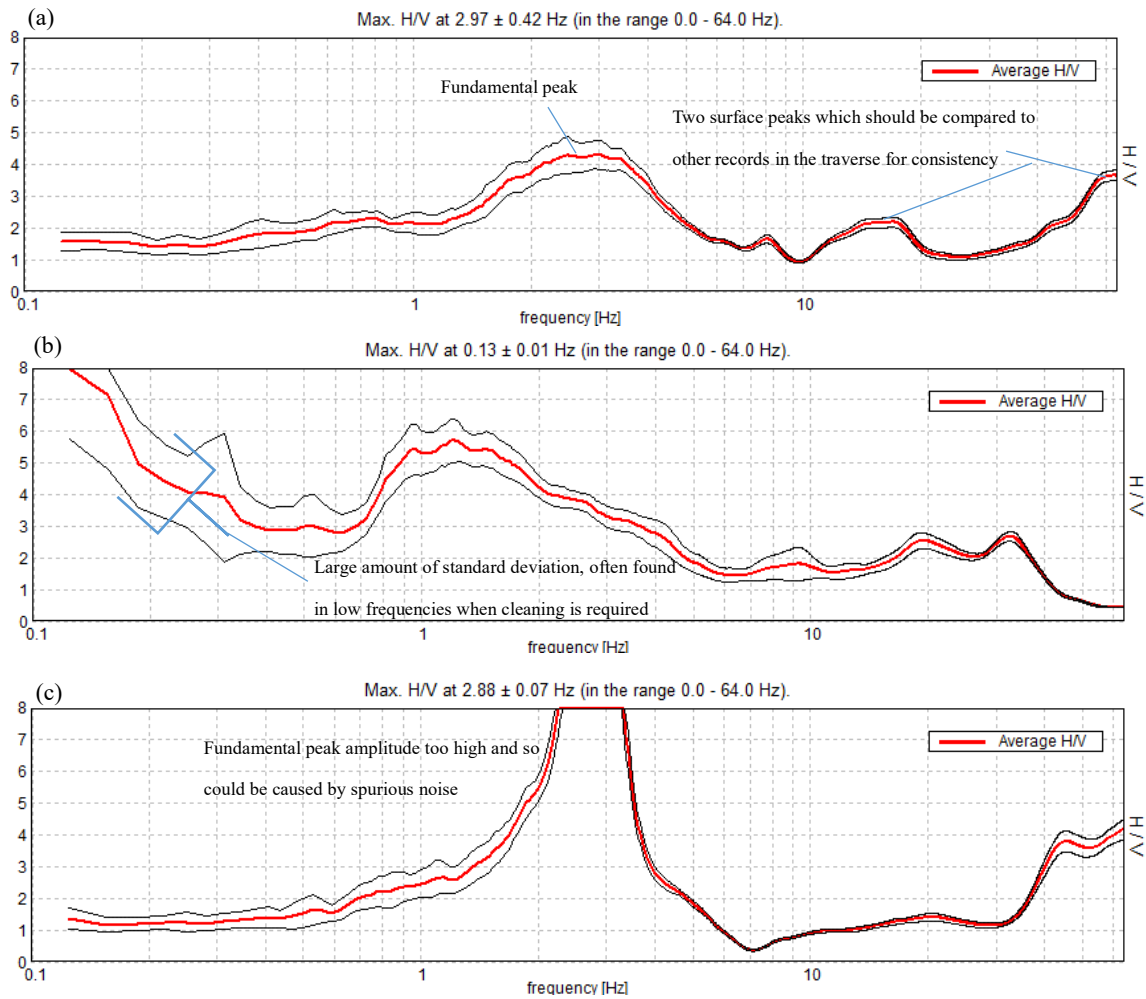


Figure 4-12: Examples of H/V traces before cleaning. Note all are from different sites so are not directly comparable.

Each of these considerations aids in the cleaning of the trace, which aims to remove as much spurious noise from the recording as possible to reveal the true signal. This is carried out by removing 20 second segments that are indicated to be saturated with noise at certain frequencies (Figure 4-13). This can be caused by such disturbances as wind blast or human activity. If the saturated segment occurs at the same time as a known disturbance recorded in the observation log, this is then removed. Then segments are removed that have persistent noise, where more than one frequency is saturated, even in low levels, (Figure 4-13a & 413b). Then the remaining noise over amplitude 7 is generally removed (Figure 4-13c).

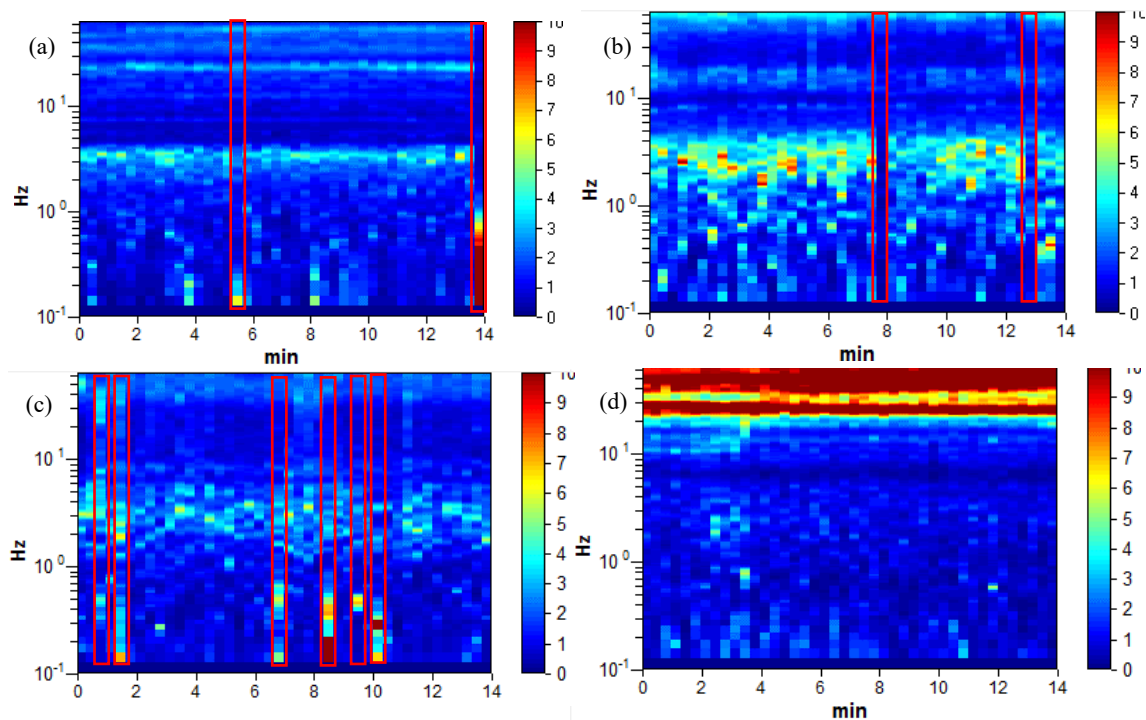


Figure 4-13: Noise charts for four different H/V traces before cleaning. The 20 second segments to be removed are highlighted in red. (a) At 14 minutes there is a segment with high pervasive noise which would be removed as well as a smaller amplitude noise at low frequency. (b) The two segments highlighted have a pervasive lack of signal throughout all frequencies. These segments are completely different from all of the other so are unlikely to be representative and would be removed. (c) A noisier trace with four occurrences of high amplitude noise in low frequencies in 6-10 minutes. Also in the first few minutes there are two traces with pervasive low amplitude noise. These can be seen not to separate between ~8-30 Hz and noise is present over most of the trace. (d) This site had a pump running at high frequency throughout the testing which can be seen in the noise chart. To retrieve results, the higher frequencies are filtered. Note that this is a subjective process, with the possibility of further or less cleaning for each of the charts. For example in (b) all segments with noise amplitude over 7 could also be removed.

No trace used if less than 60% of the original recording time remained after satisfactory cleaning. This ensured that frequencies above 1 Hz could be reliably interpreted. With 60% of 14 minutes just over 8 minutes of the recording remained making the minimum wavelength that could be measured equivalent to over 1 Hz frequency (SESAME 2004). In practice, 70-90% of the recording time is retained allowing 0.8-1hz also to be included (SESAME 2004), but the process is subjective. The aim is to remove as much spurious noise as possible from the H/V trace particularly, the peaks. However, if the cleaning was seen to dramatically change the peak frequency, without cause from the observation logs, cleaning was ceased. The reliability of all the peaks is tested using the SESAME (2004) criteria.

The SESAME (2004) guidelines produce a set of recommendations for ensuring the reliability and the clarity of the H/V peak produced by the measurement. The first three conditions ensure the reliability of the peak. Two are concerned with spuriously generated peaks caused by the length or number of windows during the Fast Fourier Transform (SESAME 2004). As the original trace is recorded randomly, non-stratigraphic spiked peaks can be produced. If the smoothing is not successful, the peak may appear in the H/V trace, because the windowing length is too short. Equally if the recording is too short and not enough measurement cycles or windows are present, peaks may appear more significant (SESAME 2004). Therefore, the first two conditions check that the fundamental peak is in at least ten cycles of recording in each of the windows and the recording length for the fundamental frequency is sufficient.

The third reliability check is concerned with peaks with high standard deviation (SESAME 2004). If the standard deviation surrounding the peak is too high, the fundamental frequency may vary if more cleaning is conducted. It is also possible that the peak may be spurious and caused by noise. Therefore, if this condition is violated and more than 60% of the trace remained, further cleaning would be performed to reduce the standard deviation would be carried out.

Traces were not used for the recordings if these three conditions were not met. Two sites, stations MCH1 and WACR, were exempted from this criterion. Station MCH1 (discussed further in Section 4.5.1) is a simple bedrock site and no peaks were produced (SESAME 2004) as there is no change of stiffness. However, this did mean no V_{s30} estimate could be attempted. For Station WACR fundamental peaks were produced, but at a very low frequency. The standard testing time of 14 minutes is too short to measure a reliable peak at such low frequency and so the traces failed the test. However, as the peak is consistent across all the traces, it is considered as a preliminary result with further testing recommended.

The peaks are also checked for clarity using the SESAME (2004) Guidelines. These are specific parameters dependant on the shape of the peak, for example is a clear and single H/V peak dominant within the trace (SESAME 2004). This may not always be the case if a broad peak is present, where

the width of the peak makes the fundamental frequency of the layer difficult to define. Equally, if the peak is too sharp, it is more likely to be caused by the result of anthropogenic noise rather than the structure of the profile (SESAME 2004). There are six criteria based on the amplitude of the peak, its standard deviation, its relative value to peaks in other frequency bands and its singularity, *i.e.*, that only one peak is present and the peak is not composed of two merging peaks of similar frequencies forming a wide crest.

SESAME (2004) recommends that five out of six of the criteria for a clear peak be met. However, in practice, it was rarely found to be possible to fulfil this condition. In general, the full criteria were more likely to be met by traces known to have been significantly disturbed by anthropogenic noise which formed clear peaks. However, these are discounted at the cleaning stage. This included those at Station JDG where a pump at a specific frequency was being used. The peak related to this frequency passed all of the required criteria, but when this was removed, the true stratigraphic peak present at a lower frequency did not. Therefore, four out of six criteria being met is considered acceptable for the testing results. This diminishes the SESAME (2004) criteria of five passes slightly to allow the majority of traces to be used, with the smallest reduction in quality possible.

In practice most traces did not meet the SESAME (2004) clarity criteria, only because of the broadness of the peaks preventing the condition of a clear maximum from being met. This is thought to be caused by the relatively lower impedance contrasts at many of the sites. The guidelines consider sites that often have a higher contrast of V_s velocity between strata, for example an alluvium on bedrock (SESAME 2004). While for the UK SGMS, many sites are bedrock covered with colluvium or residual soil. In these cases, the soil-rock boundary is a gradation or the change in V_s is low. At sites with only three conditions being met, the trace had to be highly consistent and have a clear reason for failing the SESAME (2004) acceptance criteria before being considered.

If the H/V peak passes the SESAME criteria (2004) as specified above, it is accepted and used a result for the site. Two main site characteristics can be determined from the trace: the fundamental frequency f of the site and the V_s profile. For sites of sufficient impedance contrast, the frequency of the

predominant peak in the H/V spectra has been shown to be an upper bound for the fundamental frequency of the site (Foti *et al.* 2014).

Determining the V_s profile for the site is more complex. V_s profile models are iteratively fitted to the H/V spectra. For the UK SGMS, the initial model used is the Site Specific proxy profile. This provides the required knowledge of one parameter to the indeterminate process, generally the thickness of the first geological layer (Castellaro & Mulargia 2009). This stratum is assumed to form the first stratigraphic peak on the H/V spectrum, the frequency of which gives the V_s velocity of the first layer using Equation 4-2 (Kramer 1996):

$$f = V_s / (4h) \quad [4-2]$$

where f is the frequency of the peak, h is the thickness of the layer and V_s is the shear wave velocity. The amplitude/shape of the peak is formed by ratio of V_s between the first and second geological strata layers which affects the polarisation of the elliptical rotation path (Foti *et al.* 2014). Thus, the V_s velocity of the second layer can be iteratively determined, by fitting the peak. As the frequency of the next peak is associated with this second layer, its thickness can also be modelled and so on. This process has successfully been tested in California, Japan, Geneva and Northern Italy (Micromed 2009) and therefore are expected to be appropriate for the UK environment.

It should be noted that because of the nature of surface waves no H/V spectra are entirely stable, even for long recordings. Subsequently, it is critical that only the main peaks or the characteristic site signature (Cox *et al.* 2015), which appears consistently over several traces, is modelled (Figure 4-14). Smaller peaks or the general trace should be ignored as they are more likely to be caused by noise or include the instrument response (Castellaro 2014).

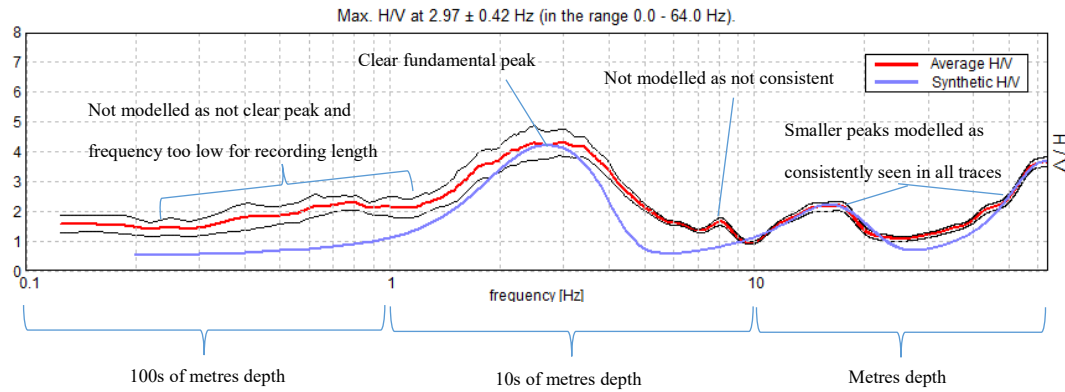


Figure 4-14: H/V trace (red) being modelled by a geological profile converted to H/V trace (blue). All the consistent peaks seen across all of the measurements for the traverse are modelled. Parts in between, non-consistent peaks, unclear peaks and very low frequency are ignored as all could be highly influenced by noise. The likely depth range indicated by the frequency of the peak is also recorded below the graph.

This procedure is carried out for every measurement in the traverse. All are processed, cleaned and the peaks checked according to the SESAME (2004) conditions. If viable, the peaks are then fitted to the geological model. A V_{s30} value was then calculated for each of the V_s profiles produced and the mean result was taken as estimate of the V_{s30} velocity for the site as well as several other key parameters. The latter include fundamental frequency of the site, depth to bedrock and V_s velocity of overburden.

In some rare cases the geological profile did not correlate well with the expected profile. At several sites this could be simply explained by slightly altering the geological model parameters, but ensuring the alteration was within 10% of the limits of the geological model. This could include a small increase in depth to bedrock. In cases where simple parameterisation did not produce acceptable correlation, the geological model was then re-evaluated. For example, for Station FOEL the dip of the rock had been miscalculated and the corrected model fitted well with the testing results. If the model re-evaluation did not produce a satisfactory match, then the site was retested.

It is critical to this method that the geological models from the Site Specific proxy method are not forced to fit the HVSr testing results. This is because of the indeterminacy of the results which means

the measurements could be forced to fit any profile if unconstrained. Therefore, the results were retested using the HVSr (Stations CCA1 and WLF1) or tested with another method (Stations ELSH or LBWR).

All viable measurements from the whole traverse are then used to produce pseudo-seismic stratigraphy cross-sections for each site. Assuming a common V_s for the traces, the H/V records are converted from frequency to thickness along the vertical axis (Equation 4-1) with the log of the H/V amplitude forming the contours (Figure 4-15). The traces are then correlated horizontally by spatial correlation, developing an indication of the near surface ground conditions (Figure 4-15). The instrument position for each recording is indicated by the black dotted lines (Figure 4-15).

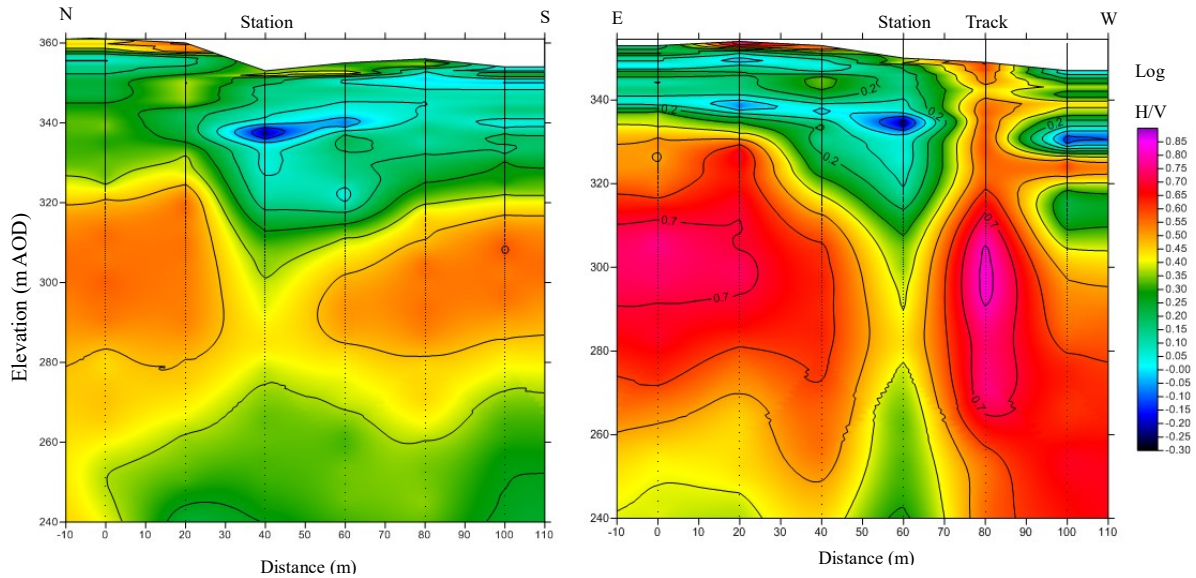


Figure 4-15: HVSr pseudo-seismic cross-sections of Station LBWR. Section processed at an average V_s of 700m/s. It should be noted that the weathered depth appears slightly greater than expected in these plots. This is most likely caused by the processing speed which may be slightly low for the bedrock.

These traverses aid clarification of the HVSr testing and a useful tool in illustrating the geology beneath the stations. In heterogeneous sites, this illustration could give a 2D image connecting the more variable H/V traces for an overview of the site structure. However, the sections do have one major limitation which is the assumption of one V_s velocity over the entirety of the traverse. This means that often the depths indicated on the traverses are not identical to those correlated to the H/V traces. This can be misleading and give an incorrect impression of the site. Therefore, though some of

the traverses are included to illustrate results, all of the depths used in the final profile are taken from the H/V traces. The results of the tests are detailed in the Station Appendix, Section 4.5 validation and Chapter 5.

4.4.2 MASW Method

Multi-channel Analysis of Surface Waves (MASW), like HVSR uses surface waves rather than body waves. Instead of one receiver, MASW uses an array of multiple receivers (Figure 4-16). These are used to measure the surface waves from an active source deployed from several points along the receiver line (Foti *et al.* 2014). The data is then collected and converted to the phase velocity vs frequency domain (Foti *et al.* 2014). This forms a dispersion plot of the wave frequencies which are picked using spectra maxima to form the dispersion curve. This is iteratively modelled to a V_s velocity profile through an inversion.

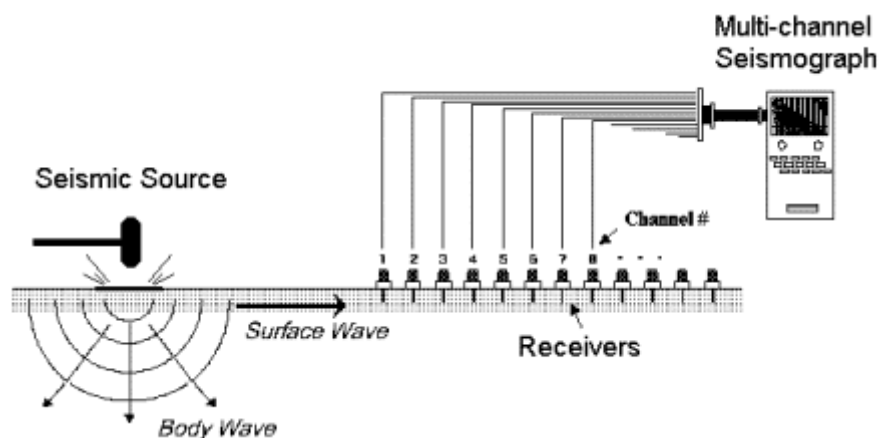


Figure 4-16: Typical MASW set up with a string of geophone receivers (Kansas Geological Survey 2003).

This method was first developed to improve the production rate of the Spectral Analysis of Surface Waves, SASW, (Hunter & Crow 2012). The SASW method only uses two receivers with the receiver spacing changing for each shot, to capture all the required frequencies for the dispersion curve (further discussed in Appendix 4-1).

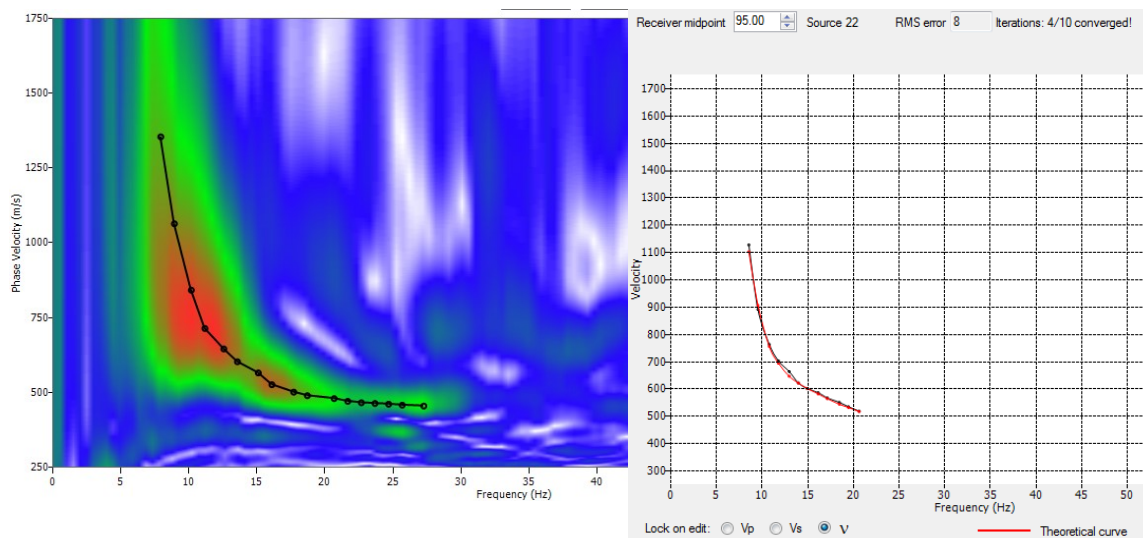
The MASW method is still limited by many of the disadvantages common to SASW. These include higher mode or noise interference distorting the results as well as the limitation of the inversion not

being able to detect velocity reversals (Hunter & Crow 2012). MASW also performs poorly in shallow bedrock and in extremely soft soils, as the signal energy is absorbed reducing the depth of penetration (Hunter & Crow 2012). However, MASW is more robust in processing than the SASW and the results are less subjective (Hunter & Crow 2012).

MASW is chosen as a supplementary method to HVSR, as it can capture near surface velocities extremely accurately (Foti *et al.* 2014). Being a passive method, HVSR has more difficulty with interference in the near surface, but can perform measurements to lower frequencies than the MASW. Thus, MASW and HVSR provide complimentary data. This is a common combination also used by the USGS (Cakir & Walsh 2012).

MASW is also cost-effective for use at several sites, although not so inexpensive that it could be used at all the UK SGMS in this research. It also requires more complex processing than HVSR, which is significantly more time consuming. For example, once the geophone recordings from the impulsive shot are converted to dispersion curves via the time variable frequency domain, each curve is manually picked to determine the phase velocities (Figure 4-17). The Site Specific proxy models are then used as the starting model for Occam's inversion (Constable *et al.* 1987) to determine the V_s profile. The inversion is carried out iteratively by the software to achieve the closest correlation with the dispersion curve (Deco Geophysical 2016).

Therefore, it is used at three sites of concern: sites that have complex geology or do not correlate with the expected V_s profile from the Site Specific proxy method. The MASW results are used to validate the HVSR method at these sites (Section 4.5.2; Appendix 4-3).



4.4.3 SCPT Method

The Seismic Cone Penetration Test (SCPT) was developed from the more widely used Cone Penetrometer Test or CPT (Appendix 4-1). It uses a 45mm diameter rod that is pushed into the ground by a hydraulic ram (ASTM 2014). The rod contains two geophones, separated by a known distance (Figure 4-18). These record the wave arrival times when a source is activated at the surface (ASTM 2014). The difference in arrival time and the geophone spacing are used to determine the V_s velocity (Section 4.4.3). The rod is then lowered at 0.5m or 1m intervals and the test repeated to form a V_s profile.

The main limitation of this test is the cone capacity, which is often determined by the capacity of the hydraulic ram. Stronger materials can exceed the ram capacity leading to refusal. Therefore, this method is not suitable for outcropping or shallow hard rock sites (Hunter & Crow 2012). Local harder layers at depth can also be an issue. In some cases, it is possible to pull the cone out and drill directly

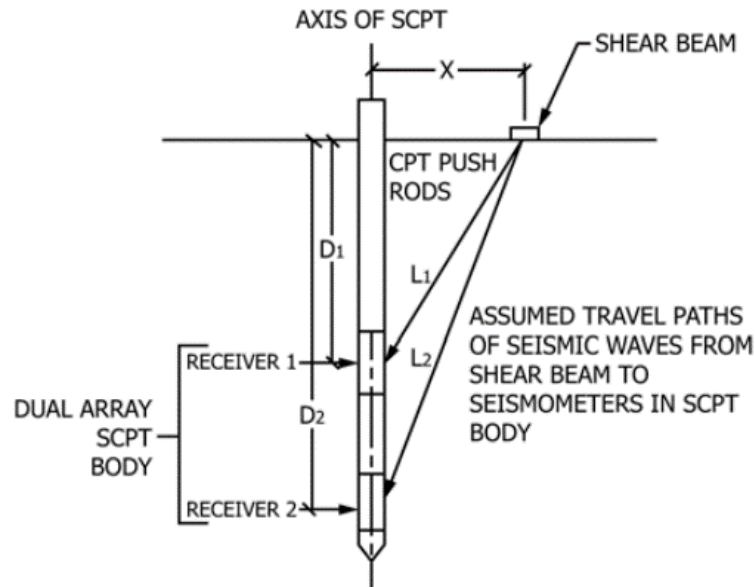


Figure 4-18: Typical set up for a SCPT Test (ASTM 2014). This is very similar to downhole testing (Appendix 4-1) except no borehole is required as the cone is pushed directly into the ground.

through the layer, before recommencing the test. As an invasive test, it does not produce a direct geological log and there can be no visual conformation of the geology at depth (Kramer 1996). It is also significantly more expensive than both the other techniques used, whilst only providing a 1D profile.

Despite the limitations, the SCPT was chosen as a supplementary test at soil sites of concern. The method is efficient and does not require the drilling of the borehole, making it the least expensive and best coupled invasive test. For the UK SGMS stations, it also had the significant advantage of providing validation for the HVSr method (Appendix 4-3).

4.5 Validation of the HVSr Technique

Whether the HVSr method alone is sufficient to characterise a site fully is debateable. Although, it is not a new method, it is generally conducted as a supplementary test rather than performed in isolation, because of the limitations associated with the indeterminacy and accuracy of the technique (Bard 1999). Therefore, validation testing was carried out on the HVSr method to ensure confidence in the final testing.

Initially, the results from the HVSR method are compared to data from a highly tested or “known” environment, as well as results from the simplest of the stations, as control tests. It is then compared to the two other test methods at three sites to determine the accuracy when combined with the Site Specific proxy method. This is further evaluated by comparison, where possible, between previous borehole records and HVSR tests. The aim being that these could be used as anchoring for the indeterminacy in depths at the sites.

Visual comparisons are also conducted at two different cliff sites to determine the level of accuracy that can be achieved. The results of the HVSR at Station ELSH are compared to the earthquake record H/V at TF01, the closest earthquake recording to any of the UK stations. The spacing parameters of the method were also tested, as well as repeatability at a site. Finally, the HVSR testing is carried out in a more challenging and unknown environment to see fully examine its limitations.

4.5.1 Control testing in known environments

EAGE Geophysics Bootcamp

HVSR testing was carried out at the EAGE Geophysical Bootcamp test site in Europe. This site has been extensively tested with invasive measurements as well as geophysical tests including seismic reflection and refraction surveys (Appendix 4-1). Therefore, the site is thoroughly characterised in terms of depth and V_s velocity of the strata and is considered an ideal control site.

The testing was carried out along one of the central survey lines at the EAGE site, parallel to prior reflection and refraction lines. A traverse of six recordings of 10m spacing was carried out (Figure 4-19a). The resulting pseudo-seismic stratigraphy is found to correlate well spatially with the results from the longer reflection survey, (Figure 4-19b). The first thin layer of mixed deposits is seen running into the second dipping structure in both traverses.

The refraction survey shows an initial layer of 0.6m of around 180m/s. Though a surface layer is indicated in many of the HVSR traces, the crest of the peak is beyond the maximum 64 Hz measurable by the method. However, the second fundamental peak, though not large in amplitude, is consistently

visible in the HVSR traces and correlates with the expected 5m boundary depth. The velocity of the bedrock correlated well, being approximately 1600m/s as expected from the refraction data. The fundamental frequency for the site is expected to be approximately 32-35 Hz from previous tests. The average value from the HVSR testing is 34.9 Hz. As a known upper bound to the V_s fundamental frequency, this result concurs with the previous testing. The consistency of these results is particularly interesting given how much noise there was located on the site including wind, tress, underground services and concurrent seismic testing.

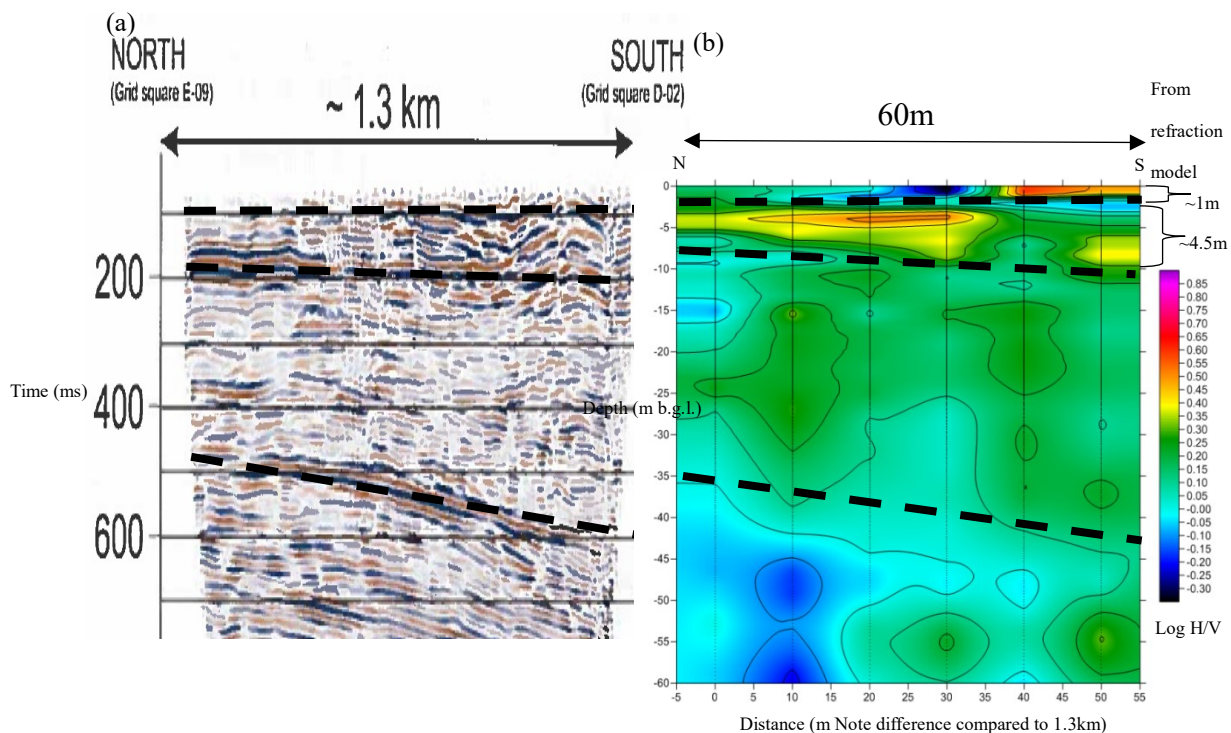


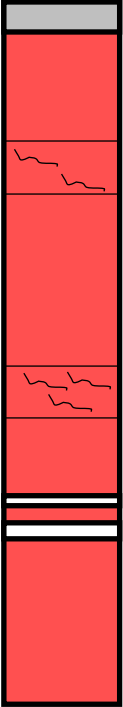
Figure 4-19: (a) Seismic reflection survey results (EAGE 2015). The structure is more linear than the HVSR plot, but both correlate well. The layer dip also appears larger than in the HVSR plot as it over a much greater horizontal distance: 1.3km compared to 60m. (b) Pseudo-seismic cross-section for EAGE test site. First three levels fit well with refraction model when processes at 1050m/s. Dipping rock structure highlighted with black lines also correlates with the known rock structure

Station MCH1

Station MCH1 is located in the Welsh Borderlands at the edge of the Black Mountains. Of all the UK SGMS this has the simplest geology consisting of a single rock type with no known anthropogenic disturbance, beyond that resulting from the installation of geophysical equipment (Table 4-3). There is some uncertainty about the extent of weathering and the depth of the resulting residual soil profile.

However, no large impedance contrasts were expected. Thus, the HVSR results should show no peaks in the H/V trace. This forms the opposite control to the EAGE Geophysics Bootcamp site where certain peaks were expected. Two traverses crossing at the station were performed. With the exception of rain, which is seen on the recordings, no main disturbances were experienced on site.

Table 4-3: Summary of geological model for Station MCH1.

	Stratum	Depth b.g.l. (m)	Description
	Station Box and Concrete	~0.5	Station box and thin isolated concrete plinth set on bedrock.
	Old Red Sandstone (St Maughans Formation) V_s compared to marls, interbedded combinations and Sand/Siltstone.	To End of Profile	Red marls, sand and siltstones which form a cyclic progression. May contain calcerous bands. Expected to be weathered and fractured to end of profile, particularly the mudstone/shale deposits. The sandstone is thought to be in more intact condition.

The H/V traces have no peaks reaching an H/V ratio of two (Figure 4-20b). As microtremors are considered a random wave field, some little variation will always be present (Castellaro 2014). Therefore, these are considered flat traces and no impedance contrast is present as expected from the geological profile.

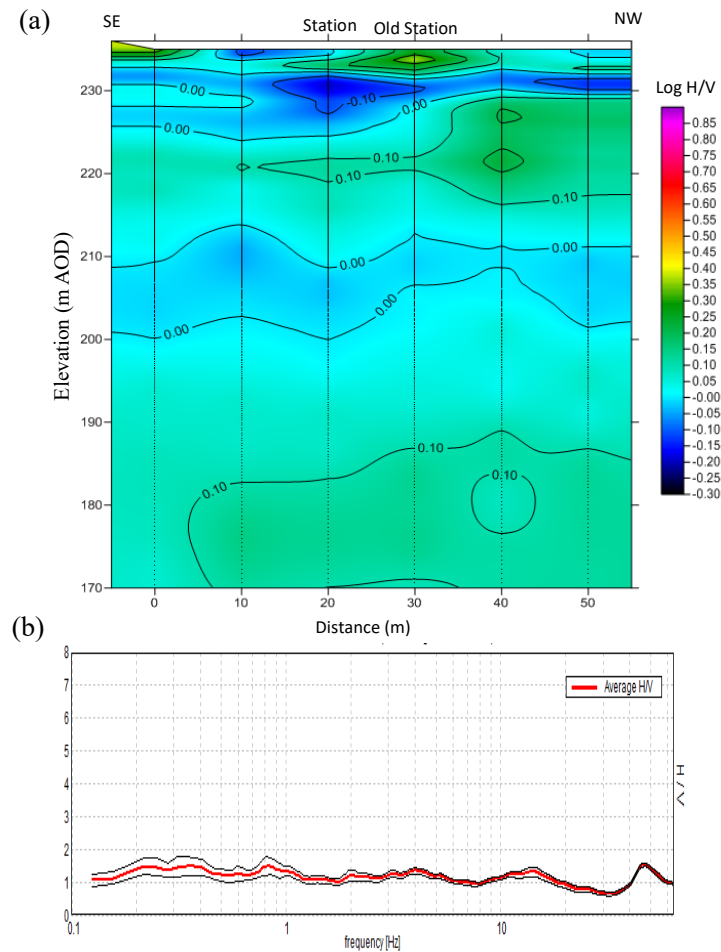


Figure 4-20: (a) The SE-NW traverse from the HVSR testing for station MCH1, processed at 1000ms. There is some small disturbance in the upper few meters, likely caused by the Station MCH1 and the previously installed old Station MCH. However, overall the change H/V ratio is extremely small. (b) A typical H/V plot from the recordings. No true peaks are seen as none are above amplitude two and therefore, are more likely to be caused by noise.

This does present an issue of determining a V_{s30} value for this site. The H/V peaks are used to model the geological profile and without a peak any single V_s value could be fitted to the trace. However, as there is no significant change in velocity within the near surface, the weathering is not thought to be extensive and the rock likely to be relatively intact. Therefore, this is not a site of concern for site amplification and could be invasively tested at a later date should it be necessary.

4.5.2 Comparison of HVSR with SCPT and MASW

At three of the UK SGMS HVSR, SCPT and MASW testing were carried out in varying combinations. This ensures that not only the HVSR is determining the correct values in more complex geology, but also to add confidence at sites where the HVSR profile and the expected geological profile from the Site Specific proxy method do not correlate as well as expected.

Station LBWR

Station LBWR is located in the Peak District on interbedded sandstones and shales. The main uncertainty at this site was the depth of weathering. This could be quite significant given the softness of the rock and its location just below the maximum glacial trimline in the region (See Station Appendix). Both these conditions make it susceptible to freeze-thaw weathering.

HVSR testing at this site consisted of 11 measurements in the typical cross-shape with the station at the centre (Figure 4-7). The V_{s30} results are inconsistent with a varied range of 519-828m/s. It is also found that, the closer the H/V trace is modelled, the more the V_{s30} reduced. As the H/V curves are variable in the upper frequencies, there were no clear consistent peaks in the near surface (Figure 4-21). This made the processing challenging as it was unclear which are stratigraphic peaks in the upper frequencies.

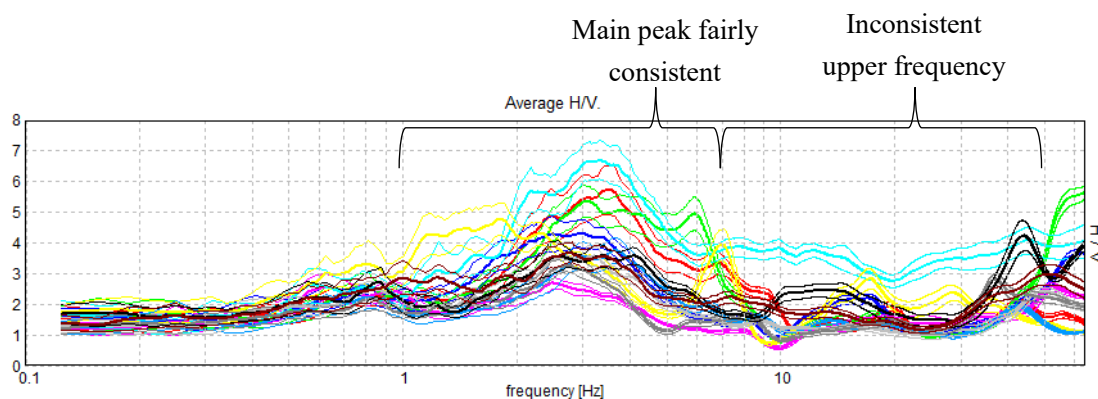


Figure 4-21: Collation of H/V traces from the Station LBWR traces. The peak at around 3Hz is consistent and thought to be caused by the boundary between fresh and weathered rock. However, above this the traces are variable.

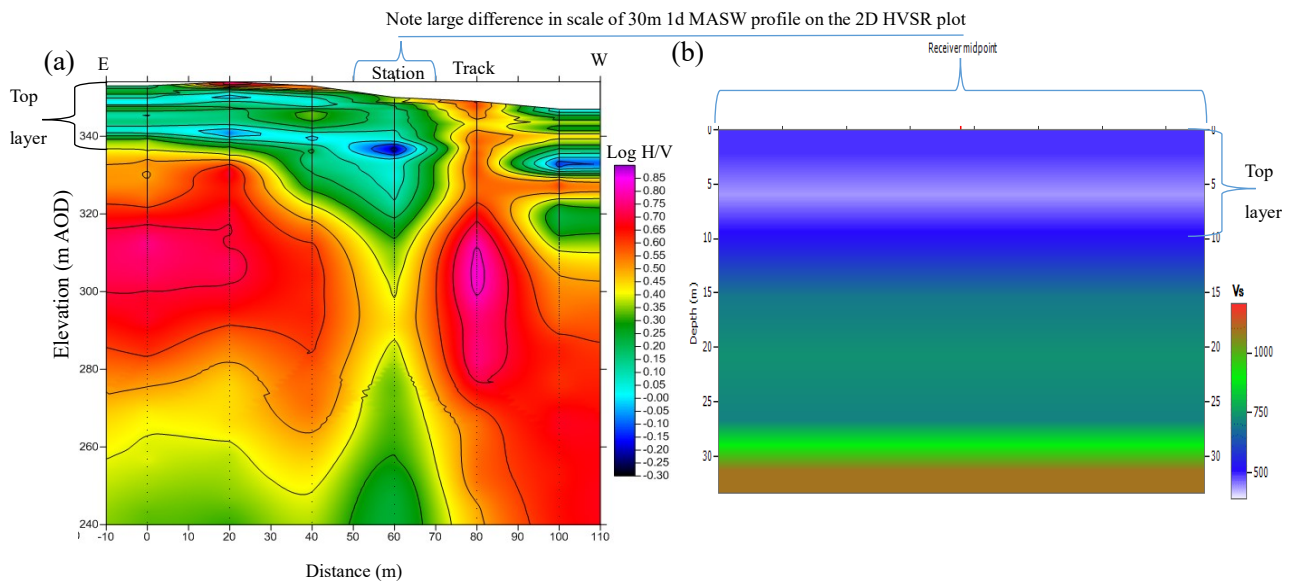


Figure 4-22: (a) HVSR pseudo seismic stratigraphy of the EW traverse for Station LBWR, processed at 600m/s. A clear top layer is visible, but has variable depth. (b) Averaged velocity profile for the centre point at the station, with a hammer source. It should be noted that the scale is misleading and it is only a 1D V_s profile at the station itself equivalent to the measurement position line on the HVSR labelled station. This too shows a reduction in V_s velocity in the upper 15m.

Therefore, MASW testing is carried out at the site. This took the form of a single line of 96 geophones at 2m spacing in the same location as the east-west HVSR line, though extending out beyond it. Both hammer and weight drop sources were used.

The results from the MASW testing with the hammer and plate method (Figure 4-22b) show a greater reduction in V_s velocities, particularly in the first 5m, where velocities are less than 500m/s. This agrees with the findings of the HVSR, with bedrock at around 15m with hard bedrock at 30m. The weight drop results also correlate with the bedrock and hard bedrock depths, but do not resolve the very low velocities in the near surface. This may be a result of the lack of high frequency from this source.

The HVSR profile is much more detailed than that from MASW. However, this may be deceptive and the MASW more representative of what can be inferred from the testing. Estimates for the V_{s30} from the two methods differed by 13%: 653m/s for the HVSR and 567m/s for the MASW. This is considered a satisfactory result for field testing in a heterogeneous site where the aim is to obtain multiple results

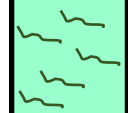
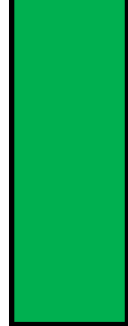
with less than 10% variance.

The HVSR results are within the standard deviation of the Site Specific proxy method and within 10% of the proxy mean value. The MASW difference from the proxy mean value is more significant at 23%, though still within the standard deviation. However, overall, the results from the testing concur well with the geological profile and estimated V_{s30} range. Both HVSR and MASW are lower than the expected suggesting the weathering has influenced the profile.

Station ELSH

Station ELSH is located in the Weald, north of Folkestone. This site is on a small knoll between two dry river valleys. The site was designated a confidence of Class 4 (Section 3.4.1) as the depth of the Middle Chalk strata were uncertain (Table 4-4). With its location in the South-East of the UK, there is also a high possibility that this site experienced periglacial activity during the last glacial period, reducing the near-surface rock mass integrity (Stations Appendix).

Table 4-4: Summary of Site Specific proxy geological model for Station ELSH. Expected V_{s30} range: 800m/s ± 210 , confidence profile Class 4, some topographical ridge effects possible.

	Stratum	Depth to bottom of layer (m b.g.l.)	Description
	Station Housing	0.3 -1	Concrete base plinth for station with station box.
	Weathered New Pit Chalk (Middle Chalk)	1 -10	Greyish clay with interbedded fine sand with gypsum layers. Firm at the surface and softening with depth. Mudstone gravel/pebbles increasing with depth.
	Vs compared to structureless and weak chalk deposits.		
	Unweathered New Pit Chalk (Middle Chalk)	5-15	Likely to be a layer of peat possibly interbedded with the clay, sometimes described as organic clay. May not always be present
	Vs compared to intact chalk deposits.		
	Holywell Nodular Chalk (Middle Chalk)	15m to 30m	Red marl with subordinate layers of grey/green marl for first few metres.
	Vs compared to competent.		
	Zig-Zag Chalk (Lower Chalk)	(End of Profile)	Thin strong band of conglomerate pebbles and gravel within a weak siltstone matrix.
	Vs compared to lower chalk.		

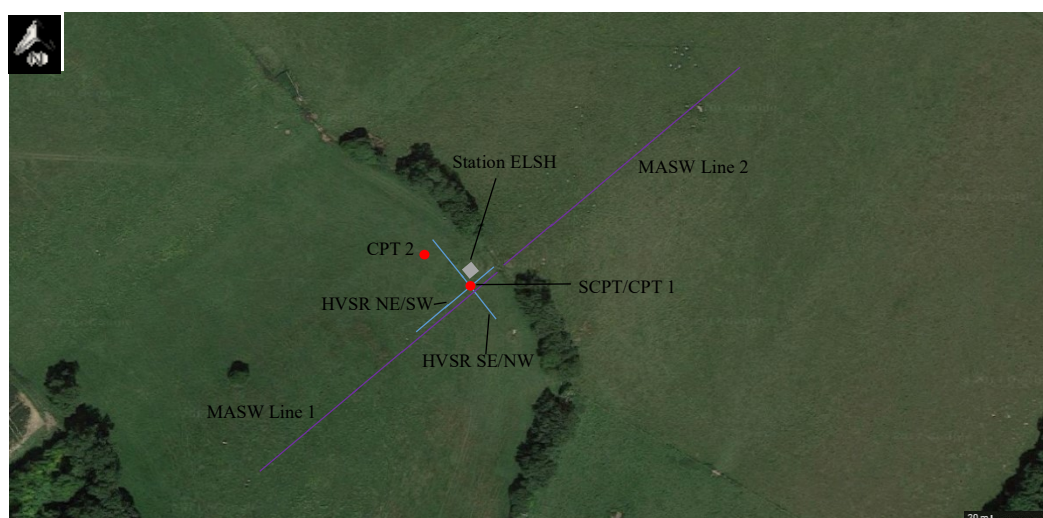


Figure 4-23: Outline of *in situ* testing performed at Station ELSH.

HVSR testing was performed in the typical cross shape, with eight measurements (Figure 4-23). The weather was sunny, with little wind and there were no other disturbances during testing. The results from the testing are generally consistent, with a frequency peak around 0.5 Hz and another at 9 Hz (Figure 4-24). However, these were low in H/V ratio amplitude making them difficult to differentiate from background noise.

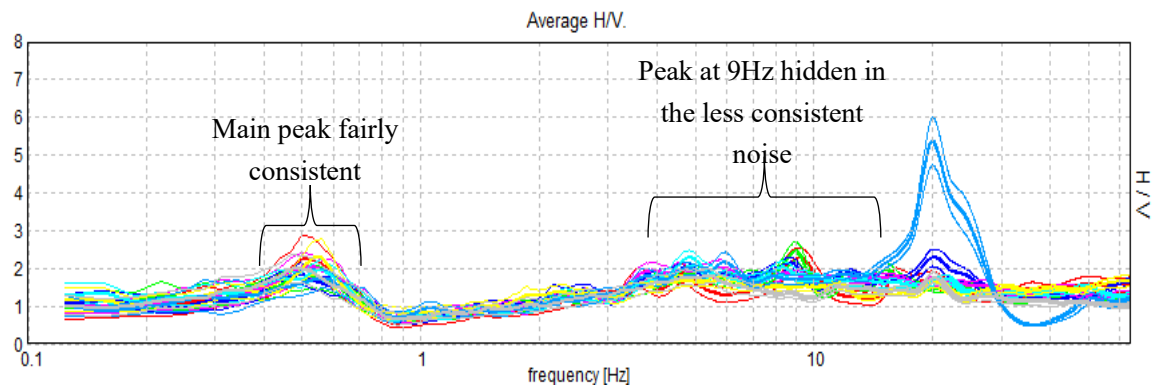


Figure 4-24: Collation of H/V traces from the ELSH traces. The peak at around 0.5Hz is consistent and thought to be caused by the Lower Chalk. However, the higher frequency peak, though the only other consistent peak, is hidden in the lower amplitude noise.

The pseudo seismic stratigraphy also shows few impedance boundaries apart from a layer at 30m b.g.l. expected to be the boundary between the Middle and Lower Chalk (Figure 4-25). However, the expected upper strata are not distinct. It is assumed that the boundaries have been altered by weathering. Chalk is susceptible to hydrolysis when water enters the fracture network in the rock. The expected thickness this process has affected is large, with a maximum of 10m determined in the geological model.

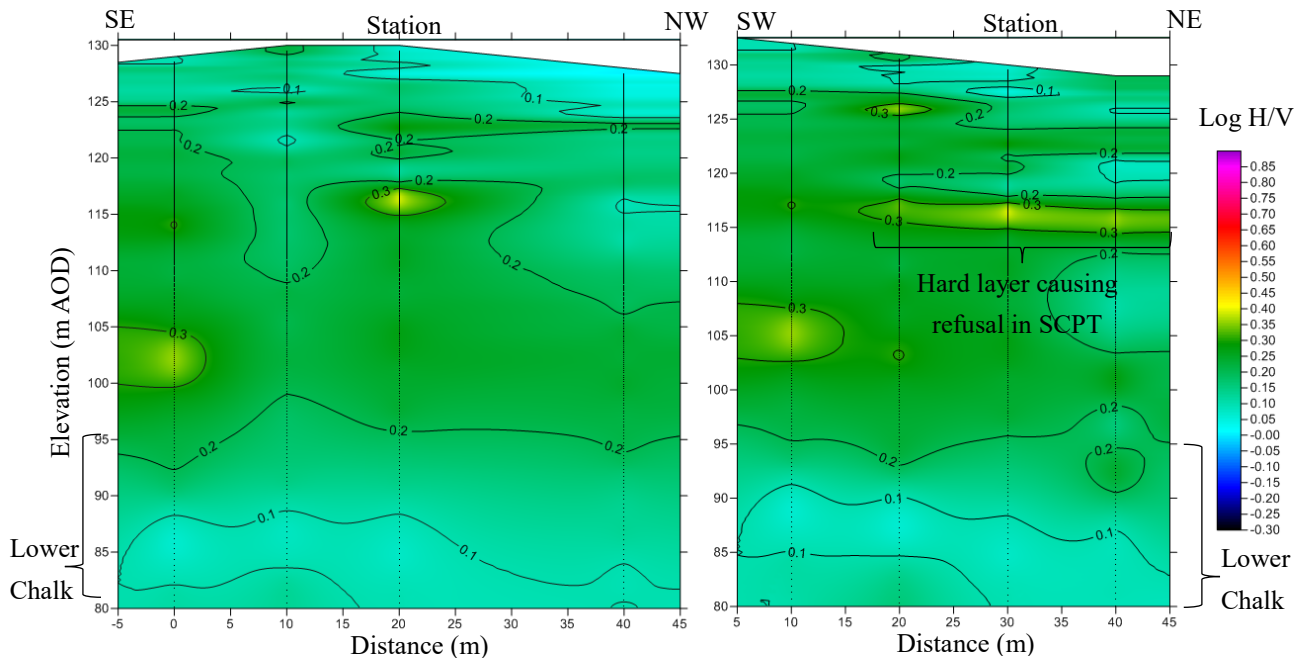


Figure 4-25: Pseudo seismic stratigraphy results for the HVSR testing at Station ELSH processed at 550m/s. The H/V ratios do not show clear boundaries for the expected strata, except for at ~95m Above Ordinance Datum (AOD) which is expected to be the Lower Chalk. In the SE-NW cross-section there is a strip of higher velocity at ~116m, found to be resistant to the SCPT.

The MASW testing is carried out over two different lines (Figure 4-22). As the geology of the hillock is unclear, it was hoped that by performing testing further down the hill may give an indication of how it is related to the bedrock in the region. The resulting MASW dispersion curves are varied across the site, indicating a heterogeneous environment. Average results from both the testing lines show the potential stiffer layering in the near-surface which is also found in the HVSR (Figure 4-25).

However, nearer the crest of the slope in line 1 (Figure 4-22), the recordings indicate a harder surface layer not present in the lower slope. These measurements on line 2 have a more conventional profile of increasing V_s with depth. Both profiles indicated bedrock or a harder layer at 30m b.g.l. This would have been thought to be deeper on the crest profile and shallower on the lower slope. This may be caused by the 1D averaging of the profiles causing the bedrock to appear consistent. Alternatively, this could be caused by a layer of weathering across the site.

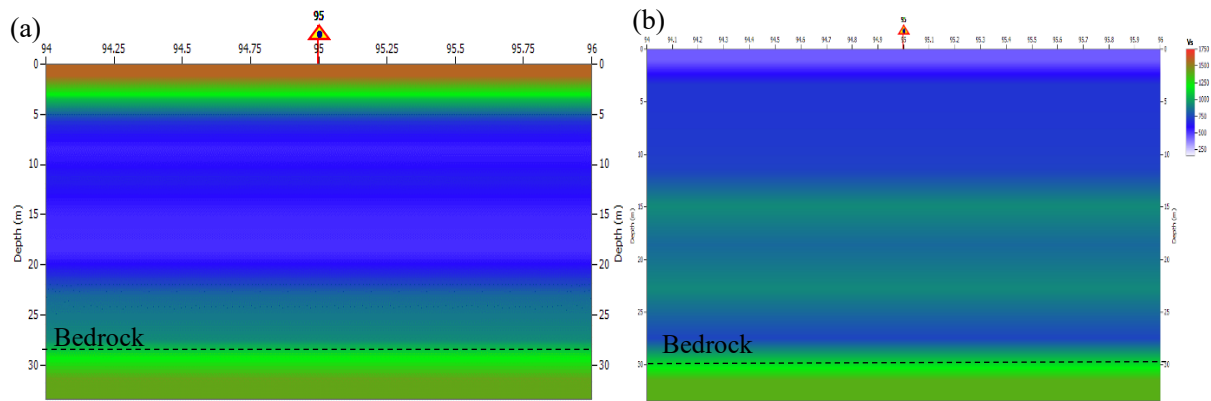


Figure 4-26: (a) 1D averaged profile from the first line near the station along the crest of the hillock (MASW line 1, Figure 4-22). This appears to have a higher velocity, possibly dissected layer, at the surface. (b) 1D average profile from the second line, downslope of the station. This does not appear to have a dissected crust, but the bedrock layer is at a greater depth than expected (MASW line 2, Figure 4-22).

The average V_{s30} is determined to be 524m/s for MASW line 1 (Figure 4-26) and 702m/s for MASW line 2 on the lower slope. The second line results are higher than expected given that the bedrock depths are not dissimilar. By including the first modal resonance for line 1, the results are further reduced by 10% while on the second line the reduction is only 2%. This could indicate the near surface in the upper slope is significantly less stiff than in the lower slope.

When compared with the HVSR results, the MASW average V_{s30} is lower, but still within 10% of that from the mean HVSR result. However, the MASW V_{s30} is 10m/s outside the lower boundary of the standard deviation of the Site Specific proxy method. The HVSR result is only just within the boundary at 610m/s.

Therefore, SCPT testing is carried out less than 1m away from the seismic station by In Situ Site Investigation. This is combined with two CPT tests, one close to the station and the second in the hollow seen in (Figure 3-13a). CPT and SCPT show the presence of soft, likely weathered chalk in the near surface layer as well as deeper in the section (Figure 4-27). However, like the MASW and HVSR results, the SCPT also indicates a harder surface layer. This is interpreted as a colluvial horizon caused by desiccation of the surface layer. It should be noted that SCPT measurements in the first metre generally tend to be less reliable than at depth due to the speed of the returning wave.

The V_s measurements range from a minimum of 244 m/s in the surface to a maximum of 1021m/s located in at 7.0m depth (Figure 4-27). Though from the CPT results, there is a local alternation in the hard and soft chawks, there is an overall increase of shear wave velocity with depth. This trend would be expected to continue through the Middle Chalk and the Lower Chalk beneath. The V_s measurements provide a time averaged velocity of 583 m/s in the top 8m of ground.

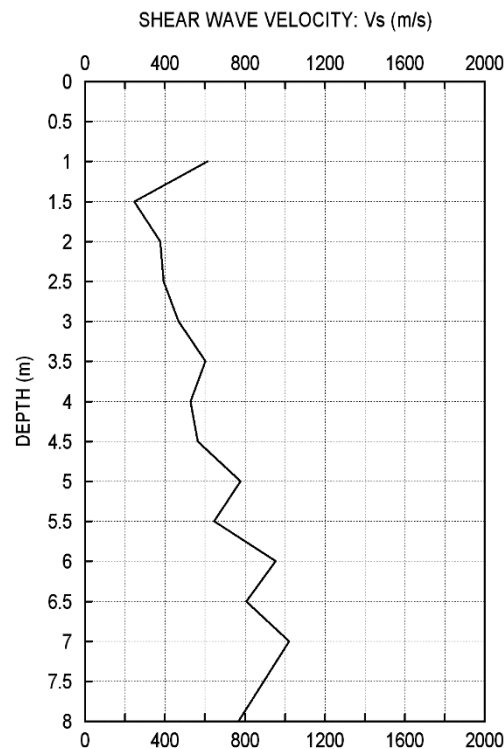


Figure 4-27: Results of the SCPT test at Station ELSH. The variation in the chalk velocities can be clearly seen.

If linearly extended, the SCPT test would indicate a V_{s30} value closer to the HVSR than the MASW. It also fits spatially with the HVSR testing, reaching ram capacity just above the higher H/V ratio layer at 8m, (Figure 4-25). However, this extrapolation does not account for the possibility that this is not the bedrock. If the velocities did not significantly increase below this layer, the V_{s30} profile may have values similar to the average MASW result.

In a different study of the site using refraction survey (Alotaibi 2016), a higher V_s velocity was found of 750m/s. This is more indicative of the HVSR result. It is clear, however, that this site is highly variable making a definitive representative V_{s30} velocity challenging to determine. Therefore, it is

expected that the Station ELSH has a lower V_{s30} than expected by the Site Specific proxy method, but the results are uncertain. Notably, this uncertainty is made immediately clear in the HVSR results whereas the SCPT and MASW considered alone initially appear more definitive.

Station OLDB

Station OLDB is located in the Severn Estuary and has approximately 10m of sand and silt before the bedrock of Mercia Mudstone (Station Appendix OLDB). However, within the superficial layer, a stratum of organic peat is expected which is likely to cause a velocity reversal within the profile (Table 4-5). This is a complex profile for any non-invasive testing and so a good validation site for the HVSR.

Table 4-5: Summary of geological model for Station OLDB.

Stratum	Depth to bottom of layer (m b.g.l.)	Description
Concrete Plinth and Station Box	~0.5	Concrete base plinth for station with station box.
Estuarine Alluvium	7-10	Greyish clay with interbedded fine sand with gypsum layers. Firm at the surface and softening with depth. Mudstone gravel/pebbles increasing with depth.
V_s compared to Silty/Sand Clay or Clayey Sand/Silt		
Peat	8-11 (Not always present)	Likely to be a layer of peat possibly interbedded with the clay, sometimes described as organic clay. May not always be present
V_s compared to Peat & Organic Clays		
Mercia Mudstone	15-32	Red marl with subordinate layers of grey/green marl for first few metres.
V_s compared to Marl & shallow, weak Mudstone		Followed by unweathered mudstone possibly some siltstone and sandstone.
V_s compared to Mudstone & Claystone		
Basal Conglomerate	31-35 (Not always present)	Thin strong band of conglomerate pebbles and gravel within a weak siltstone matrix.
V_s compared to sandy/sandstone conglomerates		
Sandstone (Mangotsfield Formation)	Base not confirmed (To end of profile)	Red argillous sandstone with significant gypsum and carbonate inclusions. Weak to strong depending on clay content.
V_s compared to sandstone with clay or mudstone		

A T-shape section is performed at this station due to the site constraints (Figure 4-28). The HVSr results correlate well with the previously assumed geological profile (Figure 4-29). Although it is possible to fit the HVSr profile without including the peat reversal layer, the fit is significantly improved when this stratum is incorporated. This highlights the importance of the indeterminacy in this method. However, as velocity reversals are challenging to characterise accurately, MASW testing is also performed to confirm the HVSr profile.

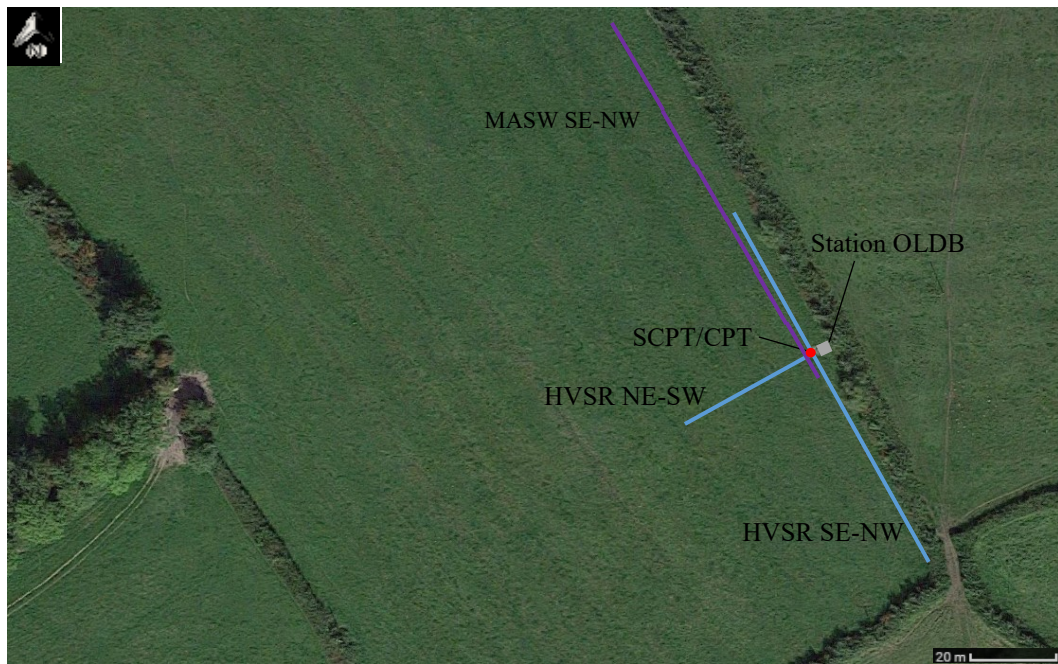


Figure 4-28: Outline of *in situ* testing performed at Station OLDB.

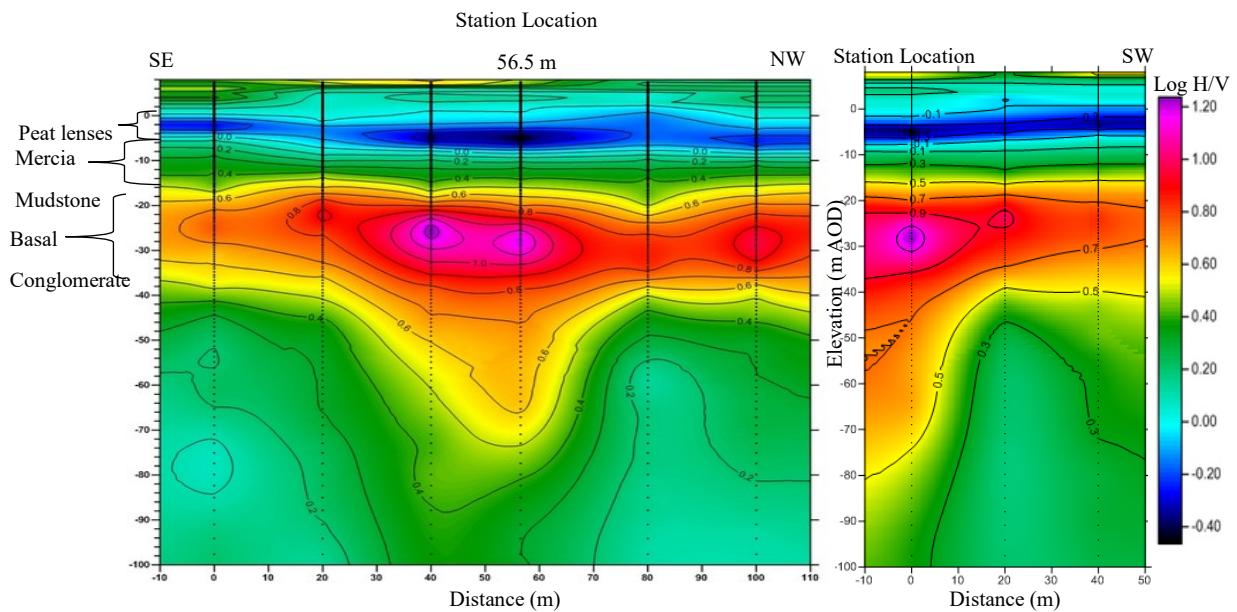


Figure 4-29: HVSR pseudo seismic stratigraphy of north-east/south-west transect and south-east/north-west transect with OLDB station located at 56.5m. Low contrast lenses of likely peat at 10m below ground level followed by more competent Mercia Mudstone. Processed at 400m/s with slightly enlarged scale (normally log H/V -0.3 to 0.9).

The MASW was performed in the same south-east/north-west line as the HVSR (Figure 4-28). The array comprised of 24 4.5 Hz geophones spaced at 2m. Off-line shots were included in this testing in order to ensure as many frequencies as possible were recorded.

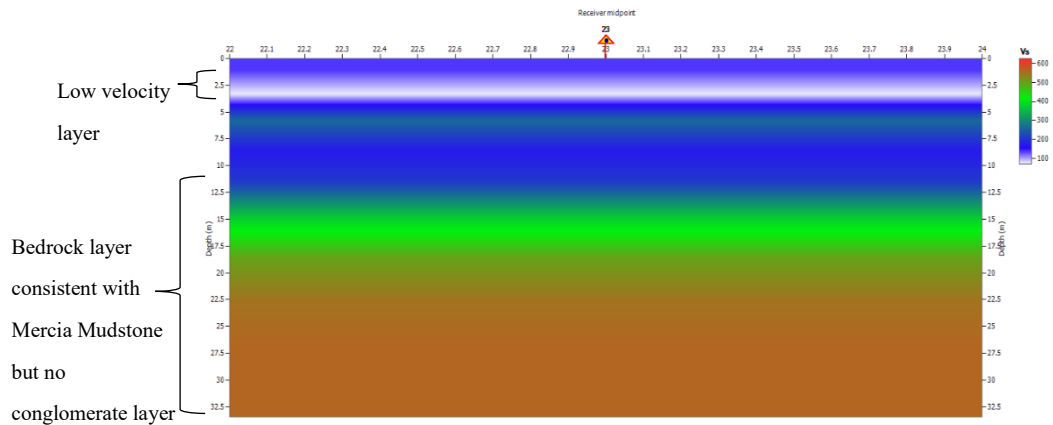


Figure 4-30: 1D averaged profile from the MASW testing at Station OLDB. The low velocity layer near the surface is unclear whether peat or dissected top layer. Basal conglomerate was not seen at depth.

The MASW 1D profile shows a low velocity layer at 4m. It is unclear if this is a peat layer or if there is a desiccated surface layer, the ground on the day of testing being extremely dry (Figure 4-30). The results did correlate well with the surface deposits, but the high velocity basal layer was not measured. This is likely caused by attenuation of the surface waves through the near-surface silt layers and so the waves would not penetrate beyond the Mercia Mudstone. The final averaged result was 39% different from the HVSR testing. The difference is most likely caused by the velocity of the basal layer not being included. Further testing was recommended to address the poor correlation.

Both SCPT and CPT profiles were carried out with an offset from the station of 0.5m (Figure 4-28). Both of the tests reached 8m in depth and recorded a low resistance/low velocity surface deposits, which correlates well with the top of the Mercia Mudstone (Figure 4-31).

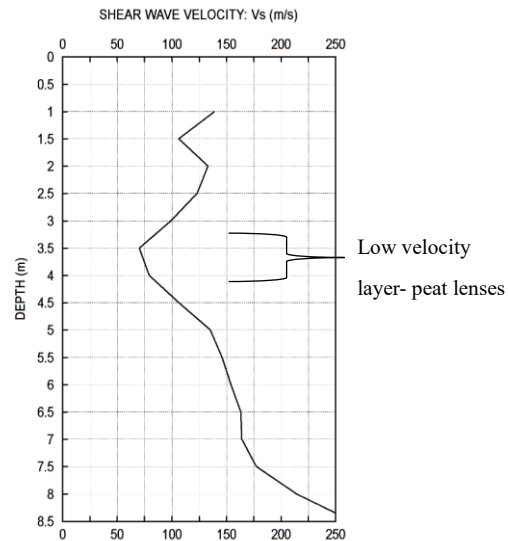


Figure 4-31: SCPT testing from Station OLDB. The lower velocity layer can be seen between 3.5m-4m. This is thought likely to be the peat layer.

The SCPT results concurred with MASW with peat determined to be at 4m depth. HVSr had indicated the peat was at 10m b.g.l. This highlights the bias in the combination of HVSr and Site Specific proxy methods. The Site Specific proxy method had identified from previous *in situ* measurements that the velocity reversal was around 10m in depth. In order to fit this expected profile, the thickness of the first layer was assumed to be too large, causing the peat layer to appear to be lower in elevation. Therefore, when large velocity reversals are expected to occur in V_s profiles, the HVSr testing should be correlated with at least one other test. Nevertheless, the HVSr did pick up the reversal as well as the basal conglomerate, while neither of which the other tests did. This may mean that the HVSr V_{s30} value is more appropriate for this site as it is slightly higher.

4.5.3 Comparison of HVSr with previous borehole records

Having carried out the comparison with known sites and other techniques, the main area of uncertainty in the HVSr method is the V_{s30} fitting. To produce a good estimate for the V_{s30} , accurately defining the depth of the first layer is determined to be critical. Therefore, for sites with no secondary testing, an HVSr measurement is taken at the location of a previous borehole record that have been performed in the local surroundings and with an accessible borehole log (Table 4-6). This provides validation of HVSr under local geological conditions. This is conducted at all stations with a previous borehole record within a reasonable distance of the station and of easy access. Seven of the fifteen stations were tested with this method.

Table 4-6: Results from HVSr performed at reference boreholes for the UK SGMS.

Station	Correlation	Comments
FOEL	-	Location of reference borehole had thick made-ground deposits (>1m) as well as heavy rain during the recording. This disrupted the HVSr results and the profile was unusable.
JDG	Medium	More indirect results as station is located on a site with many previous borehole records before construction dam. Therefore, the results had to be adjusted for dam foundations.
LBWR	High	Reference borehole use was far-field to ensure same deposit. However, profiles produced were analogous.
LMK	Medium	Complex site geology, but confirmed location of inversion so it could be accounted for in the final V_{s30} estimate.
MCH1	High	Thicker soil deposit at reference borehole location allowed estimate of V_s in rock.
SWN1	High	Significant human interference & V_s in chalk at station location unclear. HVSr measurement from reference borehole correlated well with result from the station and confirmed lower V_s determined in chalk.
WACR	High	Very similar HVSr profile at the site, but confirmed that the strata boundaries were not strongly detected.

For example, Station SWN1 had significant human interference being located on the edge of the airfield. Therefore, it was significant to determine how much the human interference had impacted on the measurements. In addition, there was some uncertainty surrounding the V_s in the bedrock. This had expected to be high as it is sited on chalk bedrock (Chapter 3). However, although the geological model fitted well, the velocity of the chalk was determined to be lower than previously expected.

The site of the Markham Hill borehole (BGS 2013, Figure 4-32) was inaccessible. However, this was the closest and most detailed of all the previous *in situ* records in the surrounding area. Therefore, the reference measurement was carried out on a public footpath, 100m from the record. This site, like the original borehole is relatively close to a busy road, but had clear signs of chalk. There was also little recent human interference on the site, being pastoral land.

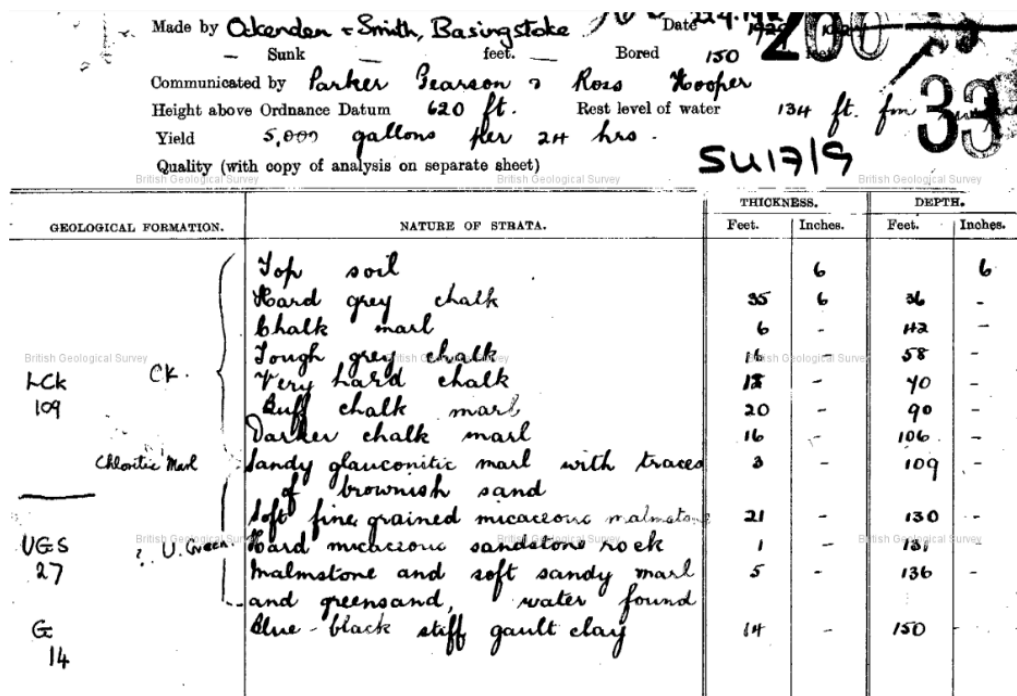


Figure 4-32: Markham Hill borehole record (BGS 2013), similar profile to that expected at Station SWN1, but slightly lower elevation so the chalk thickness is reduced.

The H/V trace from the reference measurement (Figure 4-33), was analogous to the Station SWN1 traces, though it did have a higher amplitude. It also fit well with the record at this site with 32m of chalk. The measurement site had a slightly thicker topsoil, but this would be expected through lateral variability and being further downhill to the station. This suggests the human alterations had little impact on the station measurements. To ensure the correct depth of the chalk for this site, the V_s velocity was slightly lower than that of Station SWN1. However, this independently confirmed the chalk V_s to be lower than expected in the geological model from the Site Specific proxy.

Therefore, the method is successful for anchoring the geological depths for constraining the HVSR measurements. Although the reference ground profiles often slightly differed from the station site, the test highlights what detail can be observed from the HVSR recordings. Importantly it also shows what cannot be readily revealed from HVSR surveys.

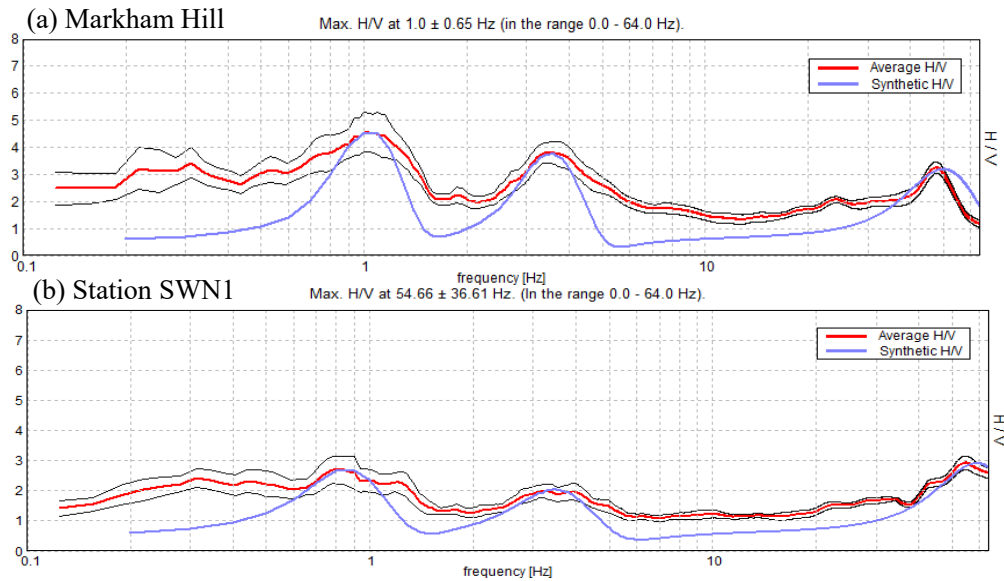


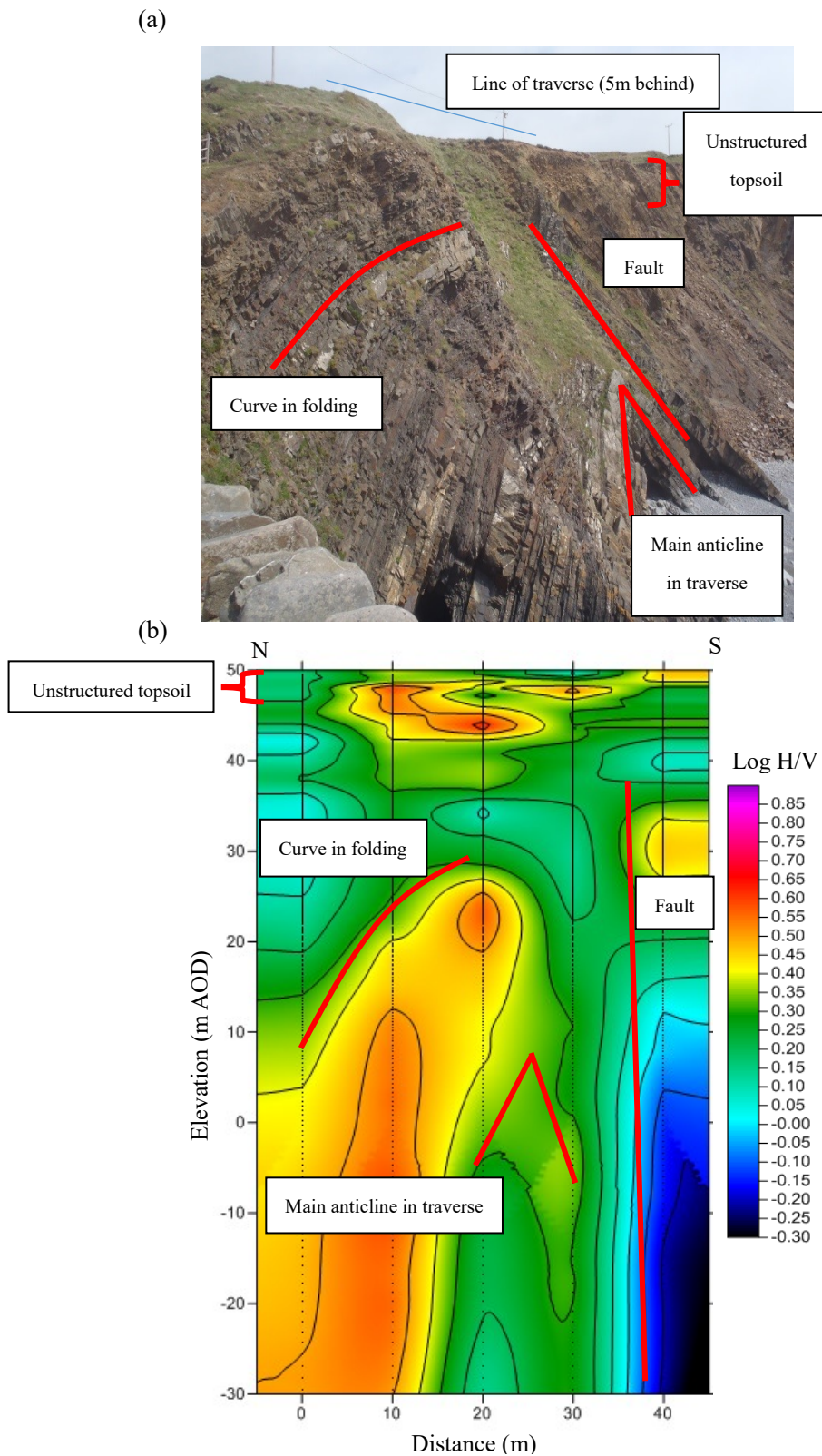
Figure 4-33 (a) Reference H/V measurement for Markham borehole compared to (b) that taken at Station SWN1 and seen to be almost identical if slightly higher amplitude.

4.5.4 Visual validation of the HVSR traverses

To determine what structural detail could be measured using the HVSR method two tests are conducted adjacent to cliff sections where the geological structure was exposed. These are performed in the same geology as two of the sites: at Hartland Quay, 2km west of Station HTL and Folkestone Warren, 8km from south from Station ELSH.

At Hartland Quay, the survey was conducted at 5m behind the cliff-edge. The main features from the cliff face are visible within the HVSR traverse (Figure 4-34). This includes the anticline in the middle of the section, as well as the faulting in the south. The fault has a more dramatic effect on the trace than the other structural features. Though the unstructured topsoil is visible, the near surface structure is less clear becoming better identifiable with depth.

The bedding in the rock is not visible, which is likely to be caused by little impedance between the layers. However, the rock is known to be layered from the geological profile. This records the layers to be of similar materials so amplification within the rock caused by this layering is unlikely. Far more important is the unconsolidated top of the cliff which is visible. Therefore, overall the HVSR profile is a relatively good representation even in this highly complex structure.



The same test was carried out at the Folkestone Warren. Similar to the comparison in the control test for sites of known geology, Hartland Quay was chosen as it had stiffness boundaries and so was expected to cause peaks in the H/V spectra, while Warren was chosen as the chalk sections of the cliff face have simple layering. Several of the small landslips have occurred along the cliff, but still have exposed faces. Therefore, only one impedance boundary is expected which is the layering between the rock mass and the true bedrock.

The expected impedance boundary is visible slightly below the level of the concrete path on the HVSR traverse (Figure 4-35b). However, this boundary is relatively poorly defined, likely because of the similarity of the chalk above and below. The chalk block on the traverse does appear fairly structureless above the level of the path with clearer structure at depth within the bedrock. Therefore, the visual testing shows that the strength of the impedance contrasts between materials is significant. For example, in the chalk block, the gravel inset has a slight dip which is not resolved by the HVSR.

However, both wave fields for these tests will be unusual. The free surface/high impedance contrast of the cliff face and the cave beneath the fault at Hartland Quay, will alter these results. Though, it is valuable to obtain a visual comparison, is not clear how extensively the wave field is disrupted. This alteration appears to be less than expected producing clear correlations. Nevertheless, this effect should be investigated further, if the aim of the test would be to estimate parameters from tests so close to a free surface.

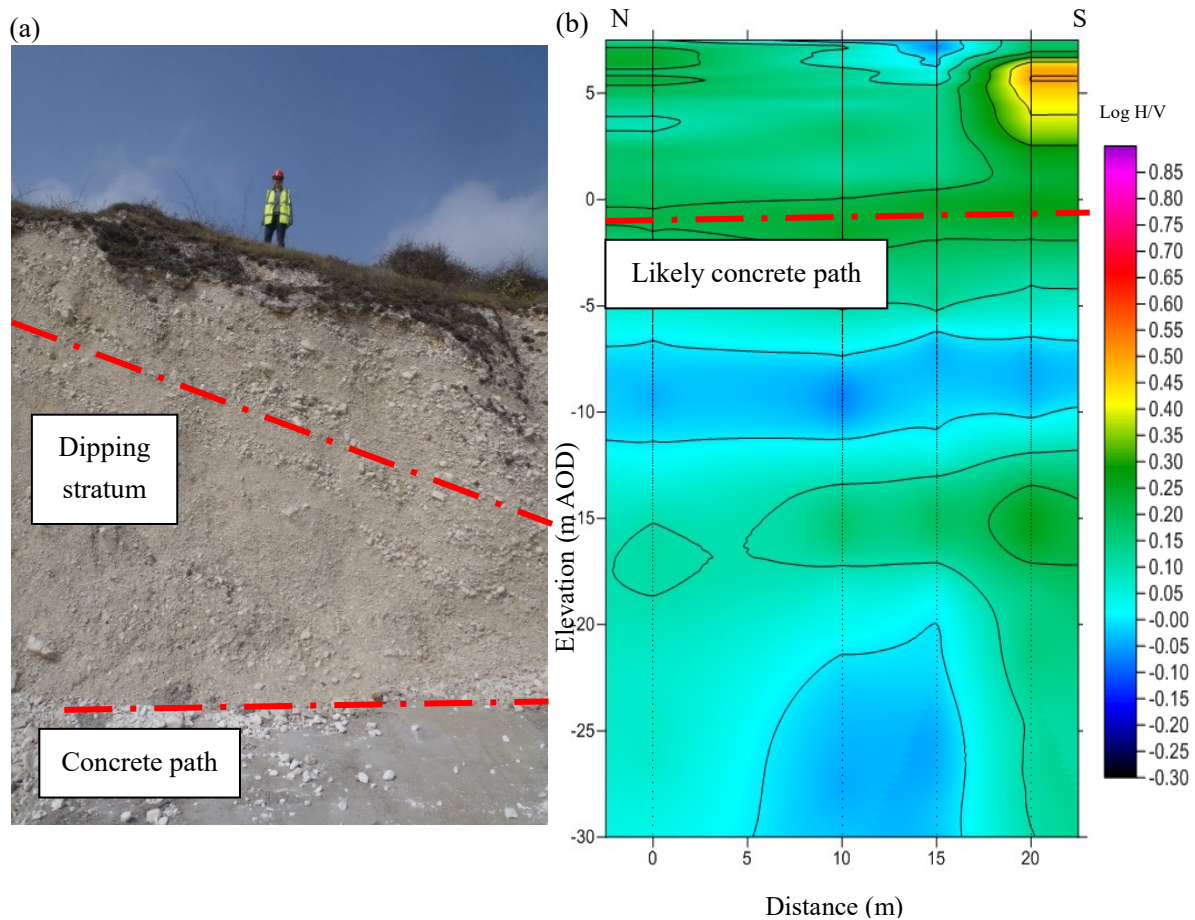


Figure 4-35: (a) Detached chalk face and concrete path in front. (b) HVSR traverse from exposed block. The likely base of the block being just below the concrete path highlighted with the red line.

4.5.5 Comparison of ambient HVSR with HVSR using earthquake recordings

There are several possible methods for performing HVSR tests. Not only traces from ambient recordings can be used, but also ambient or earthquake records from in place seismic instrumentation. In the UK, the M4.0 Folkestone earthquake is significant due to its intensity and the indication of associated site effects (Sargeant *et al.* 2008). The nearest recording of this earthquake was taken at Station TF01 (Station Appendix ELSH). This station has since been retired, but Station ELSH is located within 4km of the original site in similar geological conditions. Therefore, the ambient, HVSR recordings from Station ELSH are compared to that of the earthquake recording from TF01.

As the earthquake recording could not be formatted for the Grilla software (Micromed 2013a), both the ambient and earthquake traces are processed using a Matlab (2014) code adapted from Edwards (2016). All the traces were initially imported and a Fast Fourier Transform carried out on each component to convert them to the frequency domain. The horizontal components are then geometrically averaged and divided by the vertical component to produce the H/V trace (Nakamura 1989). It should be noted the first recording from Station ELSH (SH1) is not included as it had a connectivity issue during testing.

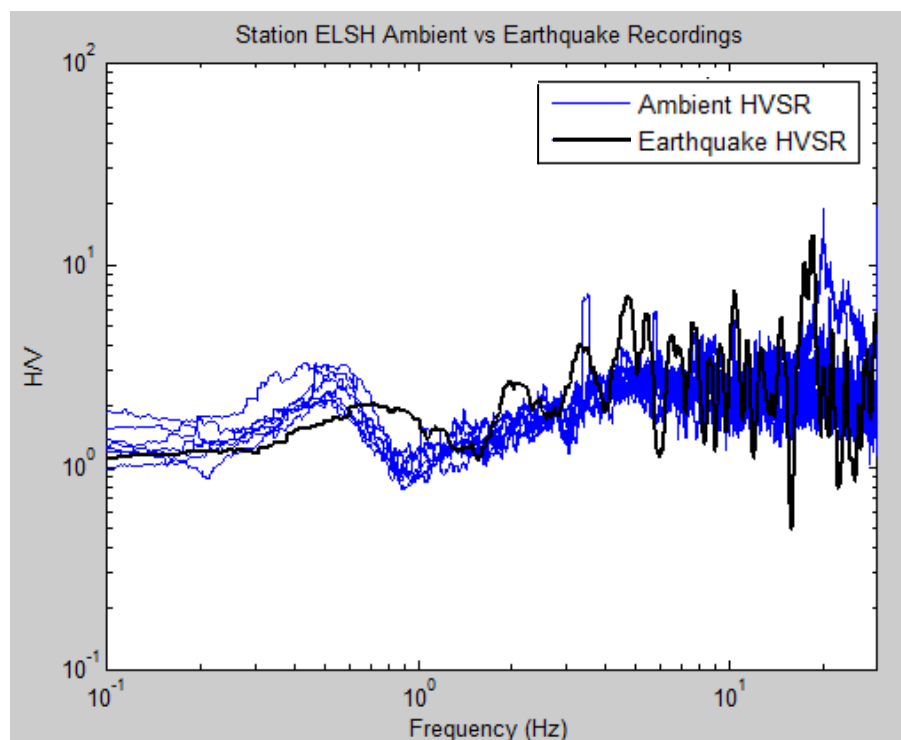


Figure 4-36: Comparison of earthquake recording HVSR with ambient testing HVSR. In the upper frequencies the overall trend fit is good, with the earthquake recording having specific peaks, on average a third larger than the ambient measurements. The slight misfit in the lower frequencies is caused by the differing structure between the two sites.

The two types of measurements correlated well, with the clear lower frequency peak (Figure 4-36). The slight shift between in this peak is expected and caused by the dipping bedrock geology between the two sites. This could also be caused by the HVSR record being too short to analyse the lower frequencies fully, capturing only the near surface, while the earthquake record is reflecting the whole source-to-site process. In the upper frequencies the trend is closely followed by both sets of results.

With only one earthquake recording, the trend is the clearest indicator. However, several peaks are correlated also by individual ambient recordings.

This result is also compared to an H/V study performed by Öttemoller *et al.* (2009) for Station TFO (Figure 4-37). Öttemoller *et al.* (2009) analysed clipped recordings from Station TFO over 86 time periods of 40s over 7 days, producing a HVSR spectra with clear peaks at 0.4 and 3.9Hz (Figure 4-37). Initially the result appears dissimilar to that calculated for the Station ELSH (Figure 4-37a.). However, this is caused by a difference in Y axis. When examined, the amplitudes of the peaks and trough are comparable, while the frequencies are seen to be only slightly shifted. As previously discussed, this would be caused by the change in geology over the two sites. Therefore, it is concluded the results correlate well for the two calculations.

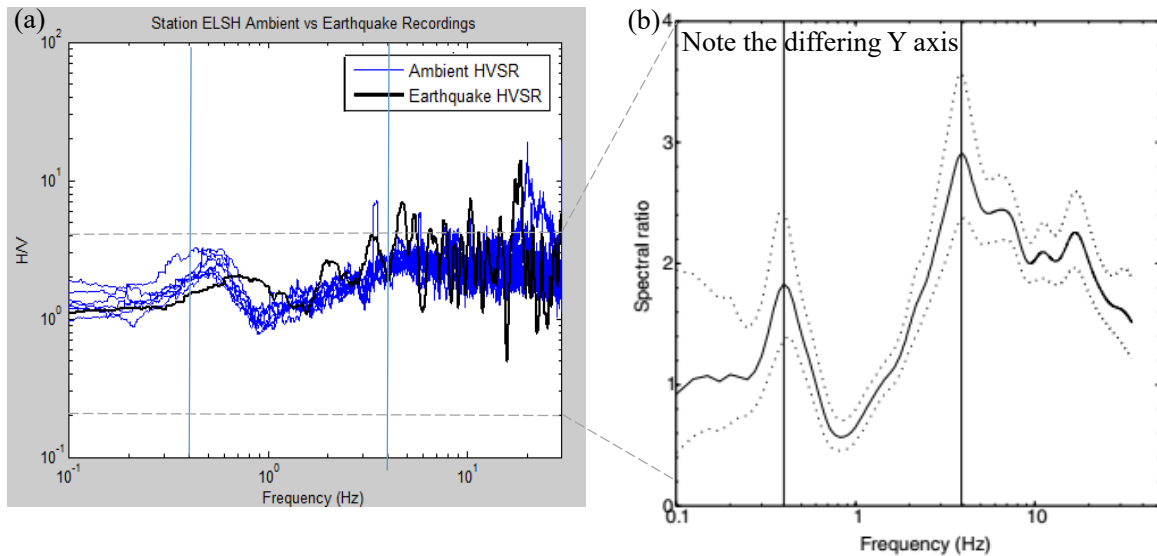


Figure 4-37: Comparison of (a) earthquake recording HVSR with ambient testing HVSR and (b) HVSR calculated by Öttemoller *et al.* (2009). Note the difference in scale on the y axis causing the two graphs to appear dissimilar when only they are only slightly shifted.

4.5.6 Spacing for the HVSR technique

The flexibility of the HVSR measurement array is one of its main advantages. However, it is not evident how much changing parameters will affect the accuracy of a traverse, especially the spacing between measurement points. Therefore, two testing grids were carried out at Station ELSH and Station HTL to determine the effect of different spacing in relatively complex geological structures.

Testing at the Station ELSH is carried out in a traverse perpendicular to the MASW lines and parallel to the south-east/north-west line, but 10m south-east from the station (Figure 4-23). The results are well correlated with the original testing line placing the boundary at the lower chalk at 30m depth and the top layer being around 5m thick (Figures 4-25 & 4-38).

In the middle layer, decreasing the space between measurements improves the quality of the traverse from 20m to 10m (Figures 4-37a & 4-38b). The definition of the layer is enhanced and a more detailed image of the lower layer is also produced. However, when reducing the spacing to 5m (Figure 4-38c), the improvement is less clear. Although the image again becomes more detailed, the likelihood of this being the actual structure in the geological profile is less clear. To interpret the traverse to this level of detail, more evidence would be needed. In this case the 10m spacing appears the most successful, though for preliminary testing the 20m is also sufficient at this site.

Similar testing was conducted at the Station HTL. A slightly different layout was used because of site constraint (Figure 4-8). Little change occurs in the results when the spacing is reduced from 20m to 10m (Figures 4-39a & b). Similarly changing between 5m and 2.5m spacing has little significance (Figure 4-39c & d). However, the difference between the 10m and 5m spacing is important. The dipping layer at the 10m spacing, instead becomes an anticline at the 5m spacing. This is a substantial change in the understanding of the rock structure beneath the station.

Therefore, 20m spacing is expected to be sufficient for a simple site or for an overview of a large site. The main geological features were determined at this spacing for both stations. A spacing of 10m is the most successful at both sites. Not only does it give a good overall view of the geology, but it is also specific enough to determine structural boundaries. At sites where the geology is complex spacing of 5m, specifically around the area to be profiled would be considered. However, large amounts of close spaced testing could prevent an overview of the geology. Therefore, if the site is suspected to be heterogeneous, 5m spacing could be carried out close 1D profile being characterised. This can then be extended to 10m further away to cover more area. Spacing layouts less than 5m are not thought to be valuable as the detail added is not necessarily representative of reality.

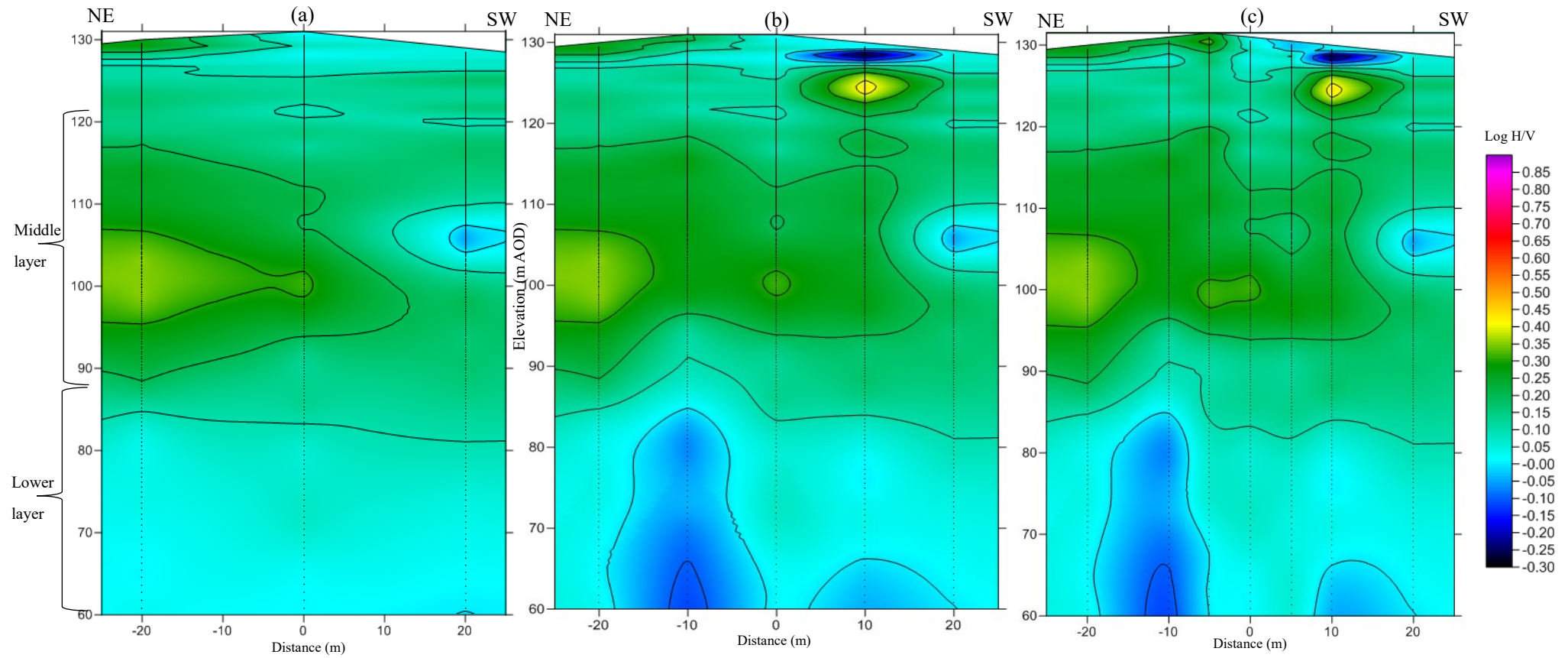


Figure 4-38: Three pseudo seismic stratigraphy of one traverse at Station ELSH: (a) with 20m spacing, (b) with 10m spacing and (c) with 5m spacing. The improvement in quality is clear between the (a) 20m spacing and (b) 10m spacing. However, between the (c) 5m spacing and (b) 10m spacing it is not clear if the improvement is realistic or if the measurements are accurate enough to be interpreted at the level of detail implied.

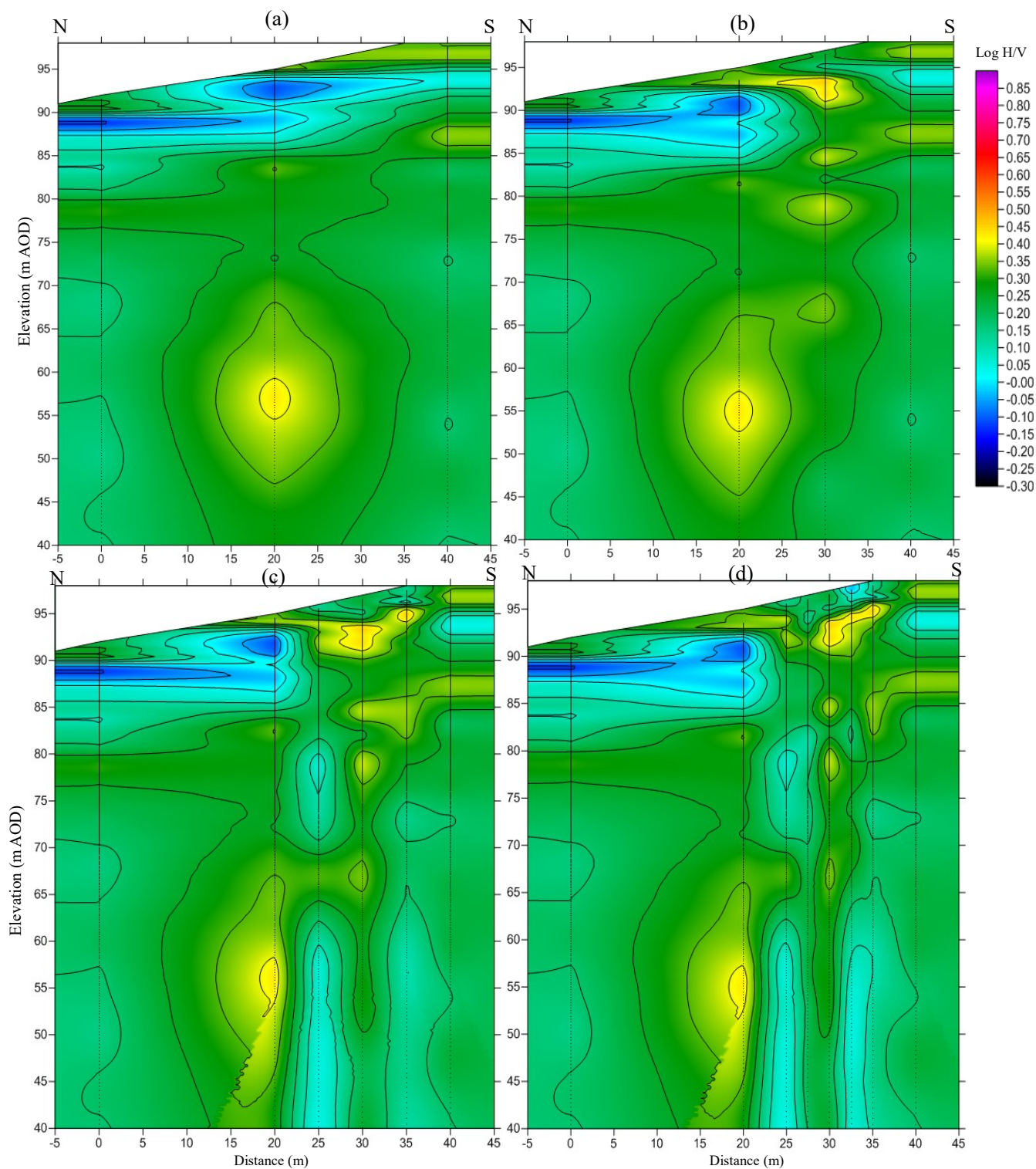


Figure 4-39: Four results from one traverse at Station HTL with different spacings: (a) 20m spacing (b) 10m spacing (c) 5m spacing and (d) 2.5m spacing. Both (a) and (b) capture the structure around 25m only when the spacing is reduced to (c) can it be identified as a possible anticline.

4.5.7 Repeatability

To verify that the results from the HVSR testing could be replicated, repeat tests were conducted on several UK SGMS sites. However, by the nature of the HVSR method the measurements recorded are from random sources. These are affected by time of day, weather conditions, season, tide times as well as many other factors. Therefore, identical traces would not be expected in this test. The aim is the assessment of the overall result and to quantify the repeatability of the investigation.

Repeat testing was carried out at both grid sites of Stations ELSH and HTL. The Station ELSH H/V trace correlate well over the two tests (Figure 4-40a). However, the Station HTL traces appear as two separate sets of results (Figure 4-40b). The original H/V testing has defined peaks at 2.5 Hz and in the upper frequencies. The secondary grid testing is much less defined and the traces appear flatter. This could be caused by the change in conditions on the sites. Though both tests at station ELSH are measured in similar weather conditions, the tests at station HTL are taken originally from dry soil and the secondary grid from wet. This could have an effect of the amplitude of the trace, by altering the

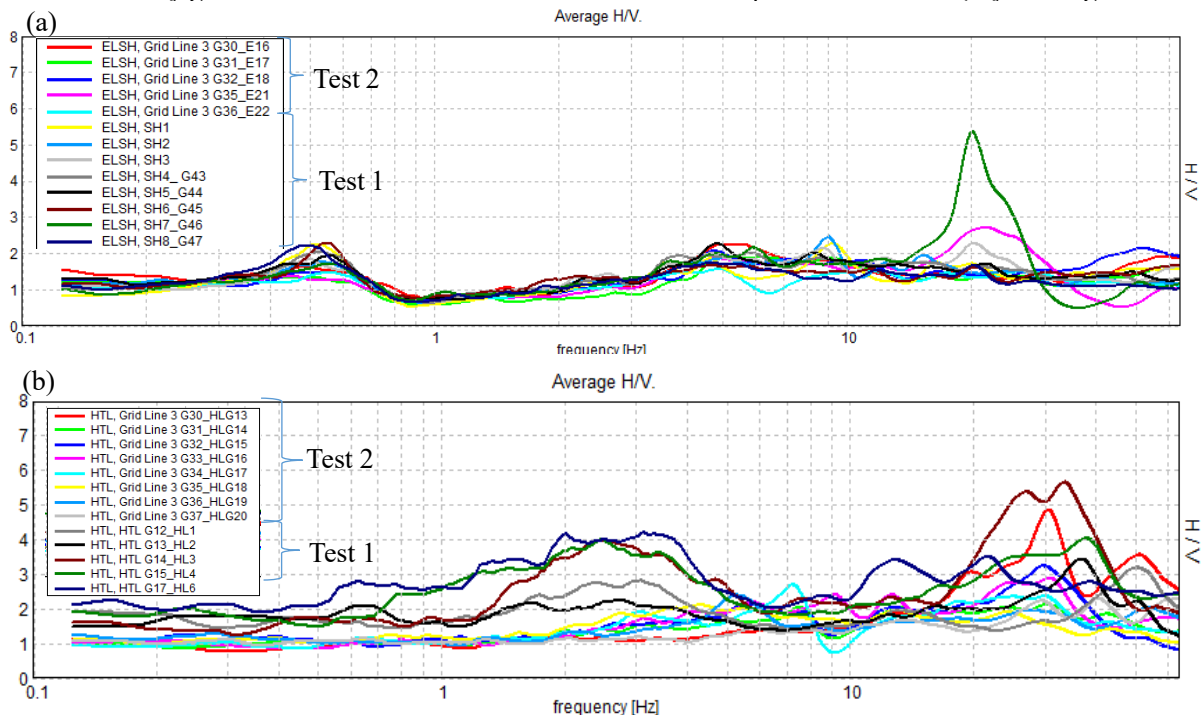


Figure 4-40: (a) Results from the Station ELSH taken over two tests taken over 6 months apart. The original tests (SH1-SH8) have slightly more variance in the upper frequencies, but the overall shape is similar with the repeat tests (Grid Line 3 E16-E22). (b) Results from the Station HTL also taken over two tests taken over 6 months apart. Unlike the Station ELSH results, the original tests for Station HTL (HL1-HL6) are different to the repeated tests (Grid Line 3 HLG13-20). The original tests have a different fundamental frequency and much higher amplitude response.

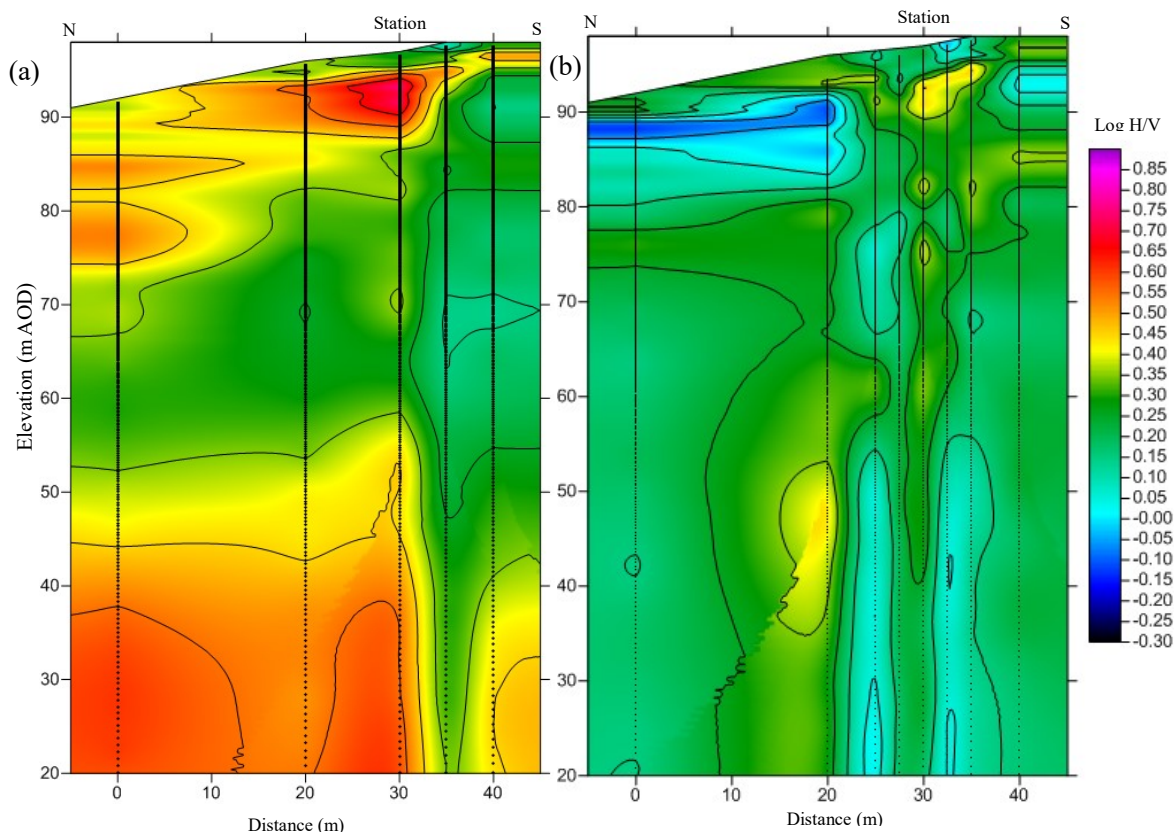


Figure 4-41: Pseudo seismic stratigraphy from two different tests in the same position at Station HTL. (a) The original test of the NS line. (b) The repeat grid testing of the NS line. Though the spacings are slightly different and the Log H/V amplitudes are not comparable, much of the larger structure is retained. This included the superficial layer and the possible anticline at 35m.

horizontal ratio while the vertical traces remain the same.

However, the results from the pseudo seismic stratigraphy of Station HTL are comparable (Figure 4-40). Though the amplitude of the impedance is different and the elevation levels are not exact, many of the structures seen are present in both sections. This included the most notable main features of the section: the superficial layer and the suspected anticlinal structure at 35m.

When processed, the repeated results did give a slightly differently geologically structured profile. The repeated results introduced an intermediate bedrock layer between the initial bedrock and the basement rock, not determined in the original profile. However, though not identified in the geological profile, it fitted with a bedrock increasing in stiffness. The presence of this additional layer made little difference to the overall V_{s30} which was 5% different from the original recordings. Therefore, both profiles from the test correlate well with the site.

Two more difficult sites, Stations CCA1 and WLF1, also had repeat tests carried out. Instead of being combined with grid tests, these stations had sections of their traverses specifically repeated due to failures in the recordings. This was caused in both stations by difficult conditions including wind blast, poor gravelly soils and exposed bedrock.

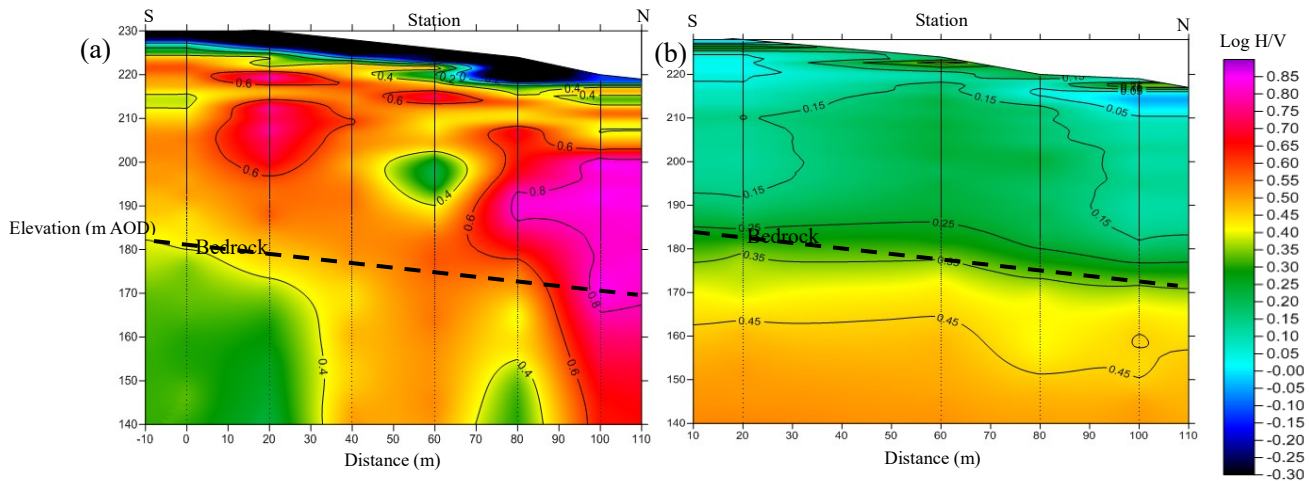


Figure 4-42: (a) Repeat of the South-North section for Station CCA1 compared to (b) the original. There is a significant low at the surface of the repeated trace which suggests a connection problem and causes a reversal of the other layers. The main transition layer in the original trace can just be seen in reverse in the repeated section.

In the original traverse for Station CCA1, only the long feet attachments were available which caused problems with levelling the instrument (Section 4.4.1). However, the shorter feet were requested for the second section. This may have caused poor connectivity with the ground which was often gravelly. This is reflected in the cross-section as an extreme low at the surface (Figure 4-38a). There is also evidence of wave field interference in the traces, indicating a lack of connectivity beyond the surface layer, which may have been compounded with strong winds that day. This caused difficulties with retaining more than 60% of the recordings.

The repeated cross-section has a strangely inverted trace (Figure 4-42a). Due to the strong low at the surface, there is a high where in the original cross-section there is the low of superficial material. In the repeated section there are lows in areas where the original had the highs of the bedrock. The waveforms of the spectra are also unusual with no strong eye shapes. It is thought that this occurred due to the connectivity problem with the Tromino Zero instrument.

The main peak across the repeat traces is fairly consistent, if different from the original measurements. The V_{s30} results in the repeated line are also generally broader than the first set, ranging from 700-971m/s. However, the mean V_{s30} is similar to the first set only being 3% different. It should be noted that the repeated results would not be considered without the first due to the uncertainty in the testing and processing.

For Station WFL1, the original results were uncertain and did not exactly fit with the expected geological profile. Therefore, further testing was deemed necessary. This was conducted in a consistent 5 metre grid around the station and the previous measurements in order to improve the model of the site (Station Appendix WFL1 7.2). Several of the positions in the grid were difficult to achieve as they were on outcropping or near surface rock. The shorter spikes were used in this case, but combined with the wind, caused connectivity issues. The majority of the recordings attempted on the bedrock failed because of imbalances in the resulting components. The remaining results produced similar results to the original measurements given the innate variability of the site (Figure 4-43).

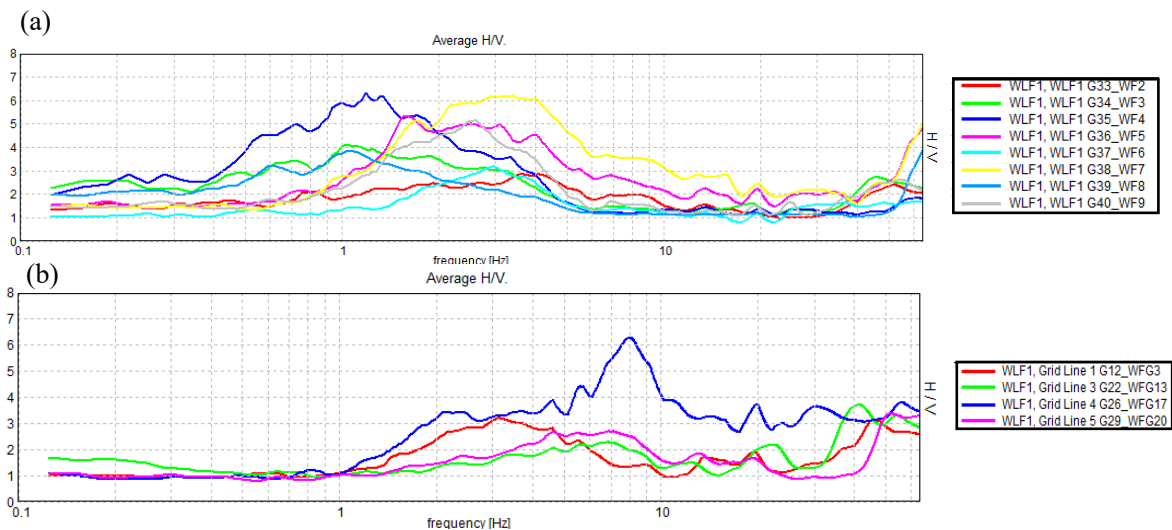


Figure 4-43: Results from (a) the original cross-section for Station WFL1. (b) One line of the grid of testing at Station WFL1 (NS line, 15m). This line had the most successful connectivity, but even within the measurement WFG17 there is variability.

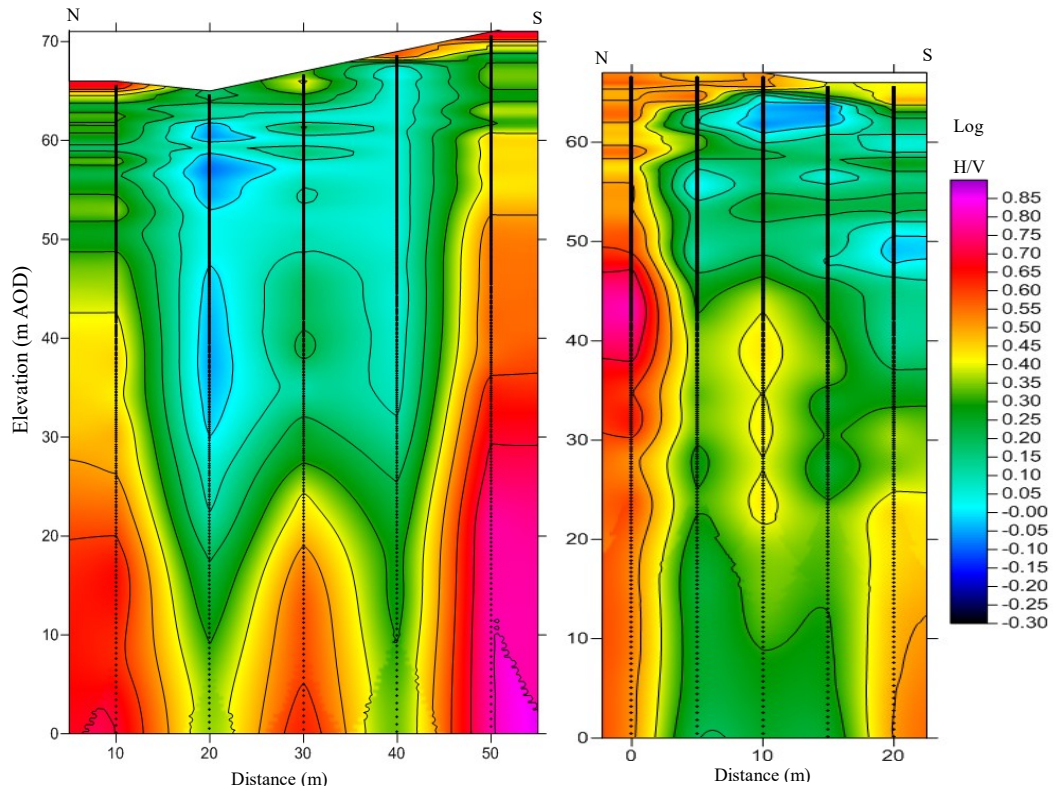


Figure 4-44: (a) Pseudo seismic stratigraphy for original measurements and (b) repeated grid NS line, 15m. This is conducted parallel to the NS line of the station but 5m to the east in the valley between the outcrops. The 10m is equivalent to the 10m of the original NS line.

The repeated cross-section at Station WLF1 is not similar to the original measurements (Figure 4-44). It has similar outcrop depths of 30-50m AOD as well as an overall trend of increasing superficial material toward the original mid-section. It also has a high stiffness layer across the near surface and the bedrock appears to be differently positioned.

However, the processed traces from the repeated results in the NS line 15m gave a similar profile to those from the original measurements. This was around 2m of superficial deposits followed by bedrock. The basement rock was generally found to be shallower at around 30m. The average V_{s30} velocity for this line was also found to be similar to the original estimate being less than 1% different.

Though not always giving identical results as would be expected from a random process, the averages for the all the sites repeated were within 5% of each other. However, it should be noted that this requires a sufficient number of tests to be carried out initially to give a good testing sample. Therefore, it is recommended that ideally at least 11 points should be attempted at a site. This could be increased or decreased depending on the site heterogeneity.

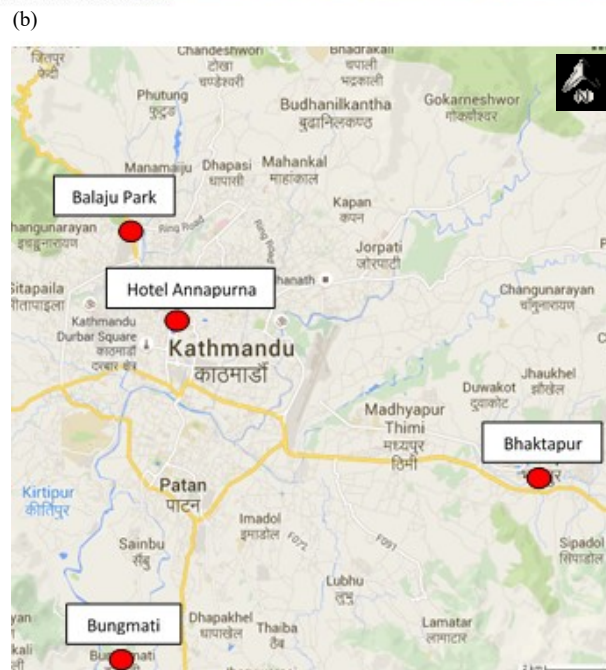
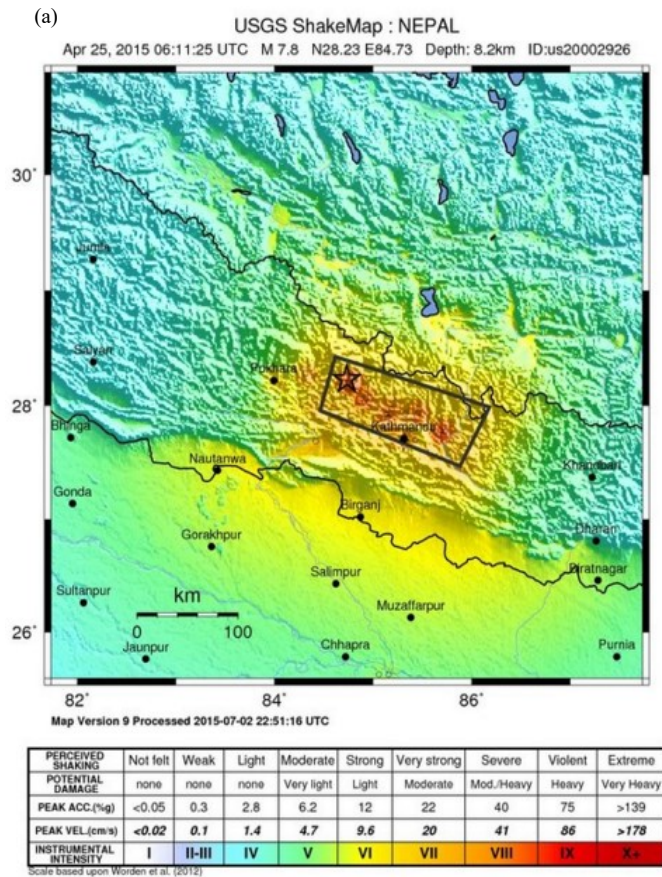
4.5.8 Testing in difficult conditions on an uncharacterised site

All of the validation testing was carried out on relatively unchallenging sites for the HVSR method. The sites tested have been in rural areas and, therefore, quiet. They have also had some level of prior characterisation. Therefore, testing in an unknown more challenging environment was undertaken to improve the understanding of the limitations of the method. (Appendix 4-4 for full paper; Tallett-Williams *et al.* 2016).

Background to testing

The 25th April 2015 M7.6 Gorkha earthquake caused significant damage to buildings and infrastructure in both Kathmandu and surrounding areas as well as triggering numerous, large landslides (NSET 2015). This resulted in the loss of approximately 8,600 lives (NSET 2015). In order to learn how the impact of such events can be reduced on communities both in Nepal and elsewhere, the Earthquake Engineering Field Investigation Team (EEFIT) reconnaissance mission was undertaken, aiming to look at damage patterns within the country (EEFIT 2017). Passive, microtremor recordings in severely damaged areas of the Kathmandu Valley, as well as at the main seismic recording station in Kathmandu (USGS station KATNP) were carried out by Tallett-Williams *et al.* (2016) to determine preliminary V_s profiles for each site. These could then be used to analyse the amplification in the valley.

In order to understand the role of site conditions on Nepal's building damage, four locations were chosen for investigation (Figure 4-45b): Bungmati (27.62930°N, 85.30364°E) and Bhaktapur (27.67172°N, 85.42809°E) in regions which both contained concentrations of historic unreinforced masonry buildings with severe damage; Balaju Park in the Siddhitol Region (27.73390°N, 85.30135°E) along the Bishnumati River, near where a concentration of foundation failures, soft storey failures, and tilting buildings were observed and the Annapurna Hotel (27.71110°N, 85.31569°E), chosen partly as it was in an area of low damage. The latter also provided a location with relatively undisturbed land close to the KATNP seismic station, the main earthquake recording station in the Kathmandu Valley.



27.62462°N 85.28189°E

27.62462°N 85.44965°E

Figure 4-45:(a) The USGS Shake Intensity Map of M7.6 Gorkha, Nepal earthquake (USGS 2015), the black rectangle marking the rupture plane and epicentre. (b) Areas investigated for site effects in the Kathmandu Valley (EEFIT 2017; Google 2016; Tallett-Williams *et al.* 2016)

Field Testing

One of the main challenges for carrying out the HVSR method in Kathmandu was the anthropogenic noise. The surface waves were seen to be masked or be influenced by human and environmental noise even during testing. The main disturbance was the evident reconstruction work in Nepal which often caused the vertical component to be enlarged, unbalancing the trace.

Finding areas without made ground too was challenging. This often causes velocity reversals in the near surface which masked stratigraphic peaks in the traces. In addition, it made coupling and levelling of the instrument spikes more difficult as the surface itself was often gravelly or had air pockets.

However, the flexibility of the instrument was found to be an asset in the environment. It is small and so easily portable on foot. It can be used both in traverses as has been used for the UK or as single measurements. The traverses allowed the general area signature to be determined, often despite the anthropogenic noise as the consistency could be checked between traces. This could then be used to anchor the single measurements in particularly damaged sites in the surrounding areas, similar to the reference borehole measurements (Section 4.5.3). This allowed more confidence in the measurements despite the challenging environment.

Processing

The human and environmental noise is visible in the H/V traces for the Siddhitol Region after processing (Figure 4-46). Narrow peaks can be seen in the higher spectral frequencies at the Balaju Park site (Figure 4-46b). These are caused by man-made surface waves, possibly by the building works nearby. These affect the H/V trace for the site (Figure 4-46a) which has small “peaks” which are not in fact stratigraphic.

These peaks are absent from the spectral trace near Bishnumati River (Figure 4-46d), close to Balaju Park, a relatively quiet part of the city. The river site is in undisturbed soil rather than made ground. This gives a classic H/V peak of a low impedance rock (Figure 4-46c) which is elongated rather than the sharp peak found in the Balaju Park (Figure 4-46a) which may have been disrupted by the interference. In addition, the subtle peaks representing near subsurface strata may not be visible in the

Balaju Park profile because they are masked by the noise peaks. However, in general, both sites correlated well in V_{s30} and H/V fundamental frequency.

In Bhaktapur, individual measurements were carried out in the damaged old section of the town and in Bungmati near to collapsed buildings. In both of these towns, no clear centre of undisturbed earth was found close enough to the damaged buildings for a good comparison, therefore transects were not attempted. The recordings that were taken were sited on made ground, therefore there were disturbances in the trace particularly in the vertical spectral component. In Bungmati, the traces were too disturbed by environmental noise to be used. This was suspected to be due to poor ground contact with the accelerometer in the north component. However, when compared to the eastern horizontal component alone, the trace was similar to that of Bhaktapur with deep bedrock of over 250m. Some intermediate layers were seen in the Bungmati trace, but both sites had similar fundamental frequencies.

As so few accessible borehole records exist in Kathmandu, the recordings were constrained instead by previous microtremor V_s measurements carried out by Paudyal *et al.* (2012) and the Wald & Allen (2007) topographical proxy method implemented in the Kathmandu Valley by Goda *et al.* (2015). The recordings were more challenging to process as less information was available for each site than any previously tested. Therefore, several estimates were formed for each site, each of which forming a possible solution. These were compared to both the geological profiles of the area developed by Paudyal *et al.* (2012) and other solutions in terms of stability before the final estimate was chosen. This processing is similar to Cox *et al.* (2015) method of determining the site signature from geophysical dispersion curves, though more simply implemented.

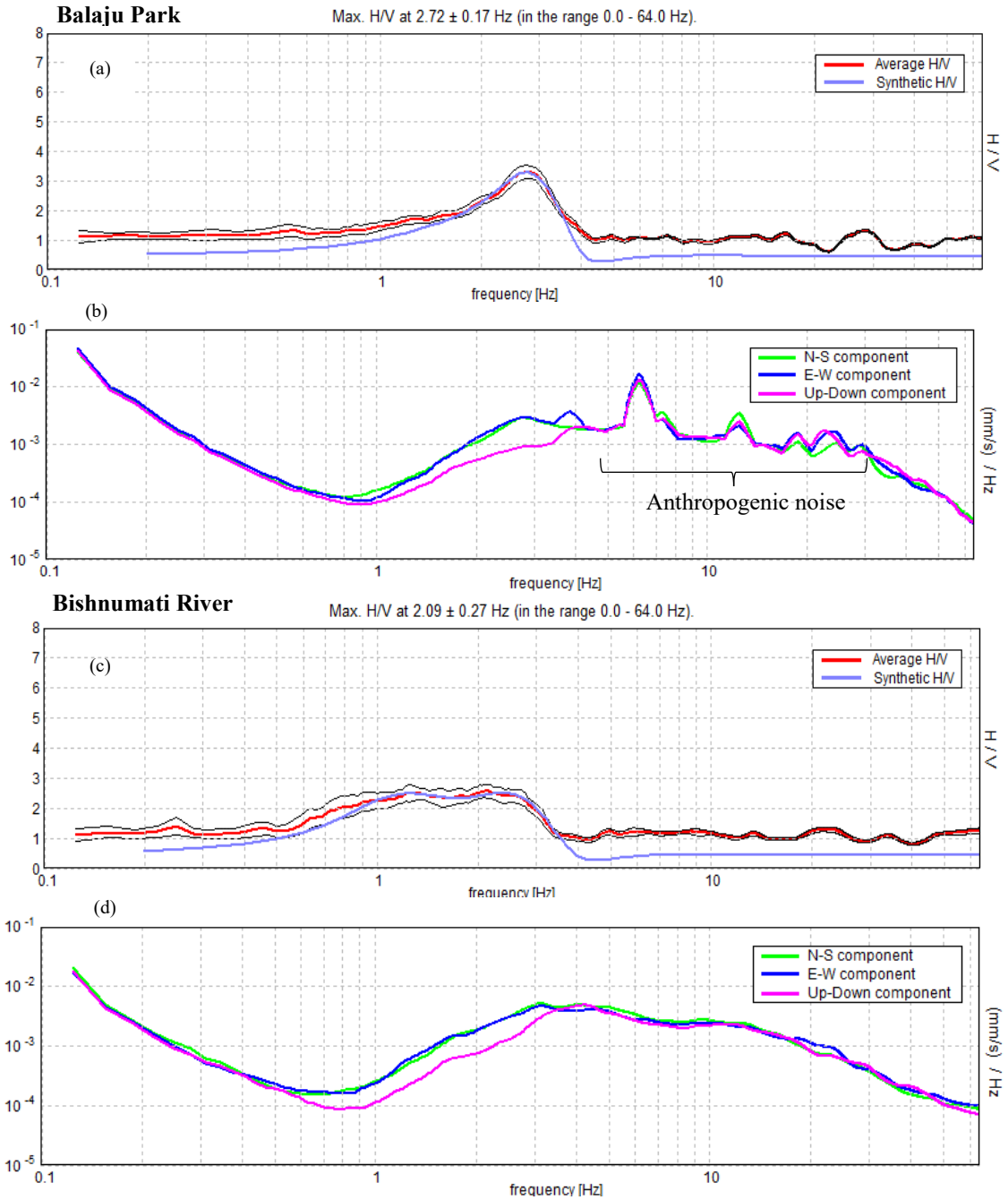


Figure 4-46: (a) and (c) are H/V traces with (b) and (d) being the relevant Fourier component spectra (Tallett-Williams *et al.* 2016). (a) and (b) are recorded from Balaju Park and Siddhitol. Noise interference in the trace is clearly visible as spikes in all components for frequencies over 4Hz in chart (b) (SESAME 2004). This spiking is absent in Bishnumati River bank recording (c) and (d). However, both (b) and (d) have clear 'eye' shapes where the vertical comes away from the horizontal components between 1 and 4 Hz indicating stratigraphic peaks (SESAME 2004).

Results

Profiles from the Siddhitol Region, at the valley edge, show bedrock at around 20-25m b.g.l. in Balaju Park (Figure 4-47a) deepening to 25-30 m b.g.l. near the Bishnumati River Bank (Figure 4-47b), establishing the bedrock trend at the edge of the valley. The profiles from the Annapurna Hotel (Figure 4-47c), situated more centrally in the basin, indicate deep sedimentary deposits extending to well over 40m b.g.l. A bedrock layer is detected several tens of metres b.g.l., however, the measurement points are spaced too widely to resolve the level accurately. Due to the difference in bedrock depth at these sites, there may be a completely different ground response depending on whether the rock or soil was more affected by the earthquake frequencies despite similar V_{s30} values determined by synthetically fitting the H/V curve.

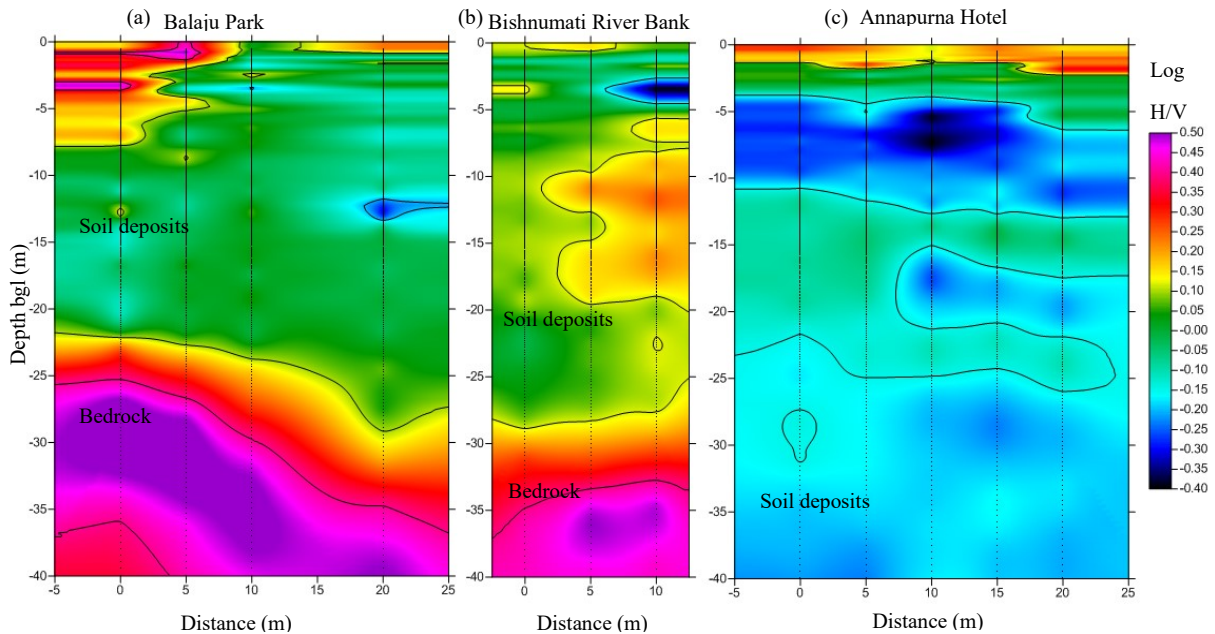


Figure 4-47: Cross-sections of traverses carried out at (a) Balaju Park, Siddhitol, (b) Bishnumati River Bank, Siddhitol and (c) Annapurna Hotel, Central Kathmandu (Adapted from Tallett-Williams *et al.* 2016). The purple/red colouring represents a stiff material such as rock while the blue is a less stiff indicating more soil-like material. The results indicate a rock-like material in the Balaju Park and Siddhitol Region at around 20-30m bgl with soil above. There is some thin hard layering in from -5-0m distance in (a). This is thought to be caused by an open drain seen adjacent to the recording. In contrast at the Annapurna Hotel results (c) indicate a thicker soil layer. The thin stiff layer at the surface is believed to be a manmade layer.

The Annapurna Hotel cross-section (Figure 4-47c) highlights the problem of velocity reversals in made ground. The top layer has a thin stiff layer at the ground surface which causes an equally, strong

negative contrast underneath, forming a dipole from -5 to -10m. This dipole does not reflect the nature of the deposits and so the layers in this region become masked (SESAME 2004). Thus, the near-surface strata that could have an effect on the V_s profile are concealed. The exact nature of these materials can only be obtained from invasive investigations. However, as the bedrock peak frequency and general H/V traces were highly consistent within the traverse and matched that of previous investigations (Paudyal *et al.* 2012).

Later spectral analysis of the HVSR results provided quantitative indication that the region of Siddhitol near Balaju Park did undergo site effects. Balaju Park appears to have been affected by the shallow bedrock, having a much higher amplitude response in shorter periods, closer to the natural frequency of the structures in this region. This is dissimilar to the Annapurna Hotel, Bhaktapur and Bungmati sites which had lower natural frequencies due to the deeper soil layer. The location of the Siddhitol region at the edge of the Kathmandu Valley may have contributed to this due to basin effects.

Discussion

Ground characterisation is generally carried out before an earthquake has occurred. This ensures the bedrock motion can be modelled and the actual motions going through the site can be analysed to improve the building performance after a seismic event. However, better characterization of the ground can be valuable to the rebuild process.

Despite its limitations, the HVSR test method is determined to be valid in this extreme environment as the site specific V_{s30} obtained indicates the general influence of the soil conditions on building performance. However, if this was being conducted for full characterisation of the sites, it would be suggested to be carried out at night when less noise is occurring. Deeper measurements holes would also be suggested to remove any made ground.

This environment is indicative of carrying out an HVSR test in an urban low seismicity region, rather than the rural locations of the UK SGMS. The method shows clear limitations in terms of the human noise interference and made ground. However, before this excursion, it was unclear if the HVSR recordings would be at all successful as the setting is extremely challenging for the passive measuring

equipment. The results are positive, but must be presented with caution as this environment type begins to limit the accuracy of the HVSR results. Therefore, in urban characterisation for low seismicity regions, other methodology would likely be preferred.

4.6 Conclusions

In situ testing is the preferred method for determining a V_s profile for a site. It can dramatically reduce uncertainty not only in the assessment of the V_s velocity itself, but also the characterisation of site amplification. However, both high and low seismically active regions are finding it challenging to implement this testing to the current state of the art, partly due to the expense.

There are numerous methods of carrying out V_s testing, each of which has its limitations and advantages. No one method is suited to all environments. These methods have been assessed for their applicability for the testing of the UK SGSMS. The main limitations found were the expense of the testing, the time limitation and the complexity of the processing.

Therefore, three methods were chosen. The first, HVSR, is a compromise between the expense of the test and its accuracy and is used as the primary method. The SCPT and MASW methods are combined as supplementary tests. This is not only to validate the HVSR method, but also to counteract its bias in combination with the Site Specific proxy method.

Other validation testing is carried out on the HVSR. It has been shown that HVSR testing can be well correlated in known environments and been successful in characterising sites alongside the Site Specific proxy method. Compared to the UK earthquake results, the ambient HVSR testing performs well. However, the strength impedance between the strata is fundamental to the successful characterisation of the site. It does also require caution when used in environments with velocity reversals and the measurements are limited in the first meter, though this is generally true for all geophysical tests.

The testing can be most successfully validated if carried out at a previous borehole location nearby to

the site. This is recommended for all sites. However, the validation does show that the HVSR has its limits, particularly in terms of the scale of what could be detected and what instrument spacing is sufficient. Anthropogenic noise is a fundamental limitation, but, for the rurally based UK SGSM, this is not an issue. Therefore, it is seen as a sufficient primary method of characterisation, if properly constrained with the depth of the first stratum.

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CHAPTER 5

Testing Results

5.1 Introduction

All 15 UK Strong Ground Motions Stations investigated in this study (Figure 1-1) were tested using the HVSR method with a Tromino Zero (Chapter 4; Micromed 2013b). This testing occurred in two stages. The first was initial testing of all the stations, except Stations HPK and GDLE. These were tested in the second stage, which also included the repeat and validation tests. MASW testing was performed at Stations ELSH, LBWR and OLDB as well as SCPT tests at Stations ELSH and OLDB (Chapter 4). The HVSR results were analysed using Grilla Software (Micromed 2013a), the MASW results using RadExPro (Deco Geophysical 2014) and the SCPT results with the software of In Situ Investigation (2014).

In this chapter, the testing results are summarised (Table 5-1). The results are compared to the Site Specific proxy method (Chapter 3) descriptions and a simplistic version of the Topographical proxy method (Wald & Allen 2007; USGS 2013).

5.2 Discussion of results

5.2.1 HVSR spectra results

The results for the measurement closest to the station show a wide variety of spectra (Figure 5-1). In general, the profiles are formed of three layers indicated by two peaks: a superficial topsoil or weathered material; near surface rock; and bedrock. These peaks form clear site signatures at sites with homogenous geology, while the spectra from heterogenous sites are more erratic as would be expected. However, otherwise there are few similarities between the HVSR spectra.

It should be noted that the curves are fitted on those peaks that are consistently seen across the site. This can give the appearance of poor fit in individual traces such as those recorded closest to the

stations (Figure 5-1). For example, for Station GDLE spectra, only the first rise in the main peak is fitted as the full peak was not seen as the same shape in the other test spectra.

Other traces such as Station ELSH and LMK had difficult structures with low impedance boundaries between strata. This led to lower amplitude peaks being fitted. However, for Station ELSH the peak at 9Hz is seen in every trace, while the shape of the main peak at Station LMK is distinctive due to the layering combination.

In several cases of thick rock, the fit is improved by including many thin layers of increasing V_s . However, this would have led to the inclusion of extensively layered profiles. Therefore, to abide by Occam's Razor (Micromed 2013a), only one mid-range peak is fitted on these occasions such as seen in Station CCA1 and WACR.

Only two traces are inconclusive: Stations MCH1 and JDG. As discussed previously (Section 4.5.1), the spectra for Station MCH1 are flat and thus, no velocity ratio between two layers could be fitted to the records from the station site. One measurement, from the site of a previous borehole record near the station, did give an indication for the likely V_s for the site, but could not be conclusive given the distance from the station and as only one recording was taken. For Station JDG, the curves were disturbed by the man-made nature of the site (a dam) and a pump running during the test. Thus, no single trace was representative of this site. However, combining traces with previous shear wave velocity measurements on the site could provide an inconclusive estimate of the V_{s30} for the site. Despite two inconclusive results at these stations, the HVSR testing did improve the understanding of each site and the testing is worthwhile.

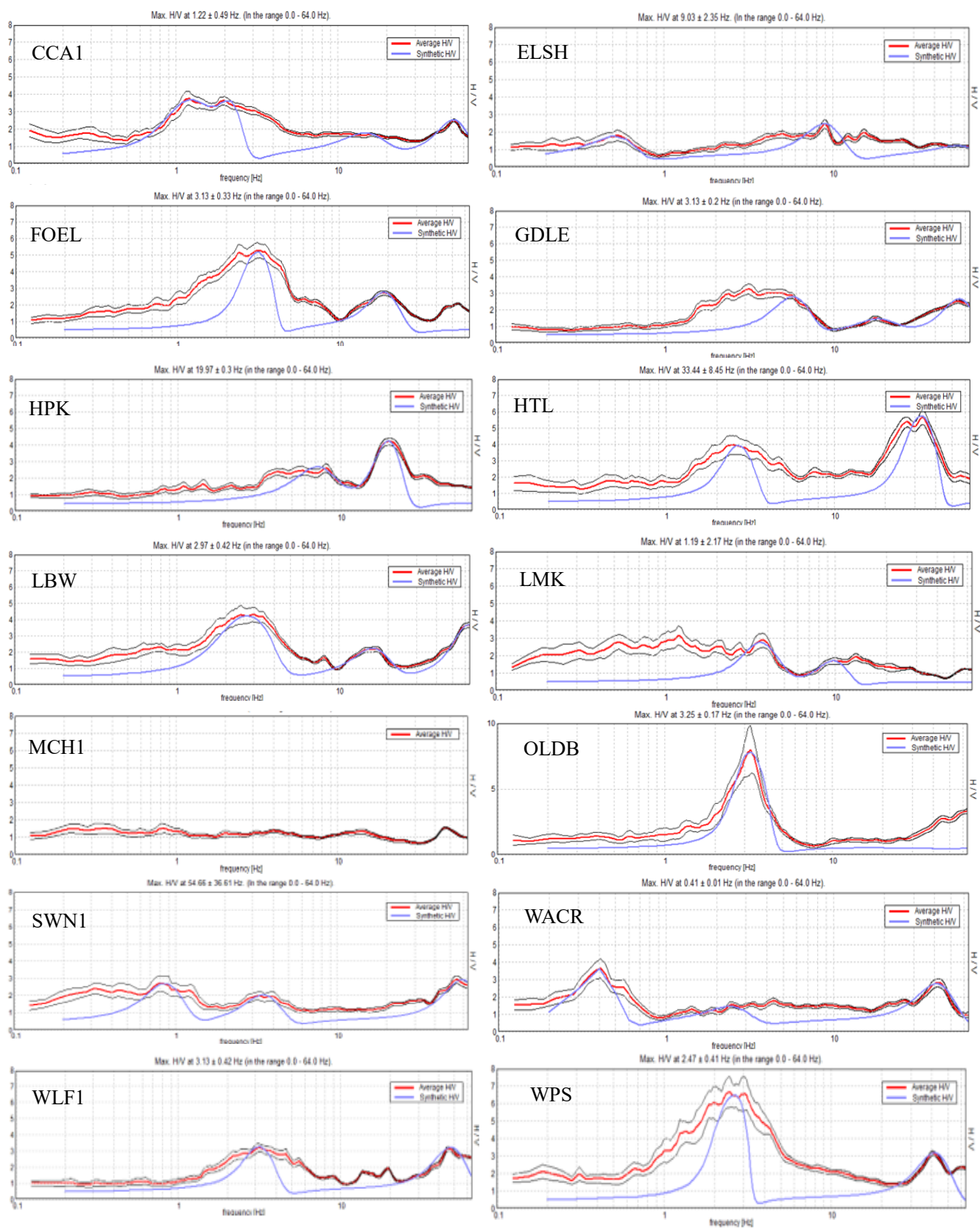


Figure 5-1: HVSR spectra results for the measurement closest to the UK SGMS. Note curves were fitted according to peaks that were consistently present for all of the traces. Thus, stations such as GDLE appear poorly fitted as several peaks were purposefully not fitted. Station MCH1 was not fitted due to the flatness of the trace (Section 4.5.1) and Station JDG is not included as the traces were severely affected by a working pump onsite.

5.2.2 Comparison to Site Specific proxy method

The HVSR results (Table 5-1) compared well with the expected values from the Site Specific proxy method (Chapter 3). A total of 14 of 15 stations are consistent with the Eurocode 8 (EU 2004) site classes determined by the Site Specific proxy (Figure 5-1). The incorrectly classed site was Station SWN1. However, this was expected to be over predicted during the proxy method due to a limited dataset for the expected geology (Section 3.5.3).

Using the HVSR results, a significant reduction in standard deviation could be achieved compared to the proxy method. Thus, seven stations could be redefined into a single Eurocode 8 (EU 2004) class from an overlapping class such as class A/B (Section 5.2.5). The testing results are determined to be on average 18% different from the expected V_{s30} velocity of the Site Specific proxy method. This is a good result given the dispersion of 50% assigned to other proxy methods (Seyhan *et al.*, 2014), particularly as 12 of the 15 stations were within 30% and only one over 40% different: Station SWN1 at 45%.

The high velocity predicted for Station SWN1 by the proxy method was noted at the time of the classification (Chapter 3). The geological profile of the Site Specific proxy did fit well with the testing results. However, to achieve this fit during the HVSR analysis, the first Lower Chalk layer (Zig Zag formation) had to have a lower V_s than that predicted by the Global V_s Database. This disparity is likely due to the limited number of results for chalk in the database. This lower V_s velocity is confirmed by investigation of a reference site where the depth of the first layer is known. Therefore, the V_{s30} velocity of the station is decreased from a Class A site to a Class B (EN 2004).

Similarly to Station SWN1, Station ELSH has a slightly lower V_{s30} (610m/s) from the HVSR testing as expected, being just outside the standard deviation from the Site Specific proxy model (838m/s ± 204). This difference is also attributed in the lack of chalk data in the Global V_s Database. The other two chalk stations (LMK and WACR) had slightly harder chalk deposits, so the difference is not as significant. However, all of the chalk stations did have specific similarities (discussed in Section 5.2.5).

Table 5-1: Summarised results from the testing of the UK SGMS compared to the Site Specific proxy method. Full results are included in the Station Appendix.
Confidence class is a qualitative assessment of uncertainty in the geological model for a site (adapted from Tallett-Williams 2013; Table 3-2, Chapter 3).

Station	Site Specific proxy V_{s30} (Standard deviation)	Mean tested V_{s30} (Standard deviation)	EC8 site class and confidence class from model	EC8 site class and confidence class from testing	Fundamental frequency (Standard deviation)	Topographical proxy method (EU site class)	Types of testing	Ridge Or basin flag	General profile description	Main uncertainty
CCA1	811 (611)	950 (189)	A/B (3)	A/B (3)	1.22 (0.49)	490-620 (B)	HVSR Repeat	N/A	Variable layer of residual granite, overlying Carnmenellis granite.	Depth of weathering and superficial deposits-heterogeneous site.
ELSH	838 (204)	610 (100)	A/B (4)	B (3)	9.03 (2.35)	350-490 (B)	HVSR Repeat MASW SCPT	Small ridge	Highly weathered Newpit Chalk (even to putty chalk) over Holywell Nodular Chalk and Lower Chalk	Degree and nature of weathering and strata elevations.
FOEL	864 (488)	780 (100)	A/B (3)	A/B (3)	3.51 (0.91)	>760 (A)	HVSR Reference	Crest	Weathered rock, overlying thick sandstone, followed by shale near crest of isolated hill.	Depth of weathering and far field <i>in situ</i> results.
GDLE	912 (511)	645 (100)	A/B (3)	B (4)	3.44 (2.27)	>760 (A)	HVSR	Change in slope angle	Highly heterogeneous sandstone, siltstone and mudstone/shale on steep scarp slope. Underlain by sandstone and mudstone.	Heterogeneity of deposits, likelihood of weathering & challenging test results.

Table 5-1: Summarised results from the testing of the UK SGMS compared to the Site Specific proxy method. Full results are included in the Station Appendix. Note that the results from Stations JDG are inconclusive and should only be taken as an indication.

Station	Site Specific proxy V_{s30} (Standard deviation)	Mean tested V_{s30} (Standard deviation)	EC8 site class and confidence class from model	EC8 site class and confidence class from testing	Fundamental frequency (Standard deviation)	Topographical proxy method (EU site class)	Types of testing	Ridge Or basin flag	General profile description	Main uncertainty
HPK	910 (290)	685 (100)	A/B (4)	B (4)	19.30 (5.25)	>760 (A)	HVSR	N/A	Glacial till underlain by interbedded sandstone, mudstone and shales.	Complex faulting in the region with heterogeneous Quaternary deposits.
HTL	948 (503)	950 (120)	A/B (3)	A (2)	Variable 3 peaks at 3,9 & 30	490-620 (B)	HVSR Repeat	N/A	Residual, weathered deposits with structured turbiditic sandstone and shale underneath.	Far field <i>in situ</i> results.
JDG	1084 (710)	1220 (400) (inconclusive)	A (2)	A (2)	Variable (inconclusive)	>760 (A)	HVSR Reference	Valley but no alluvial deposits	Concrete base of the dam, grouted Ignimbrite, weathered to intact Ignimbrite.	Final depth of grout and quality of rock beneath.
LBWR	809 (439)	650 (100)	A/B (3)	B (2)	2.97 (0.42)	>760 (A)	HVSR Reference	N/A	Thick layer of weathered rock followed by shale grit bedrock.	Depth & degree of weathering and far field <i>in situ</i> results.
LMK	625 (342)	525 (100)	B (4)	B (3)	1.21 (0.51)	620-760 (B)	HVSR Reference	Unstable scarp slope	Series of thinly layered limestone, mudstone, ironstone and sandstone underlain by thick Kimmeridge Clay.	Complexity of geology, degree of weathering and instability in the slope.

Table 5-1: Summarised results from the testing of the UK SGMS compared to the Site Specific proxy method. Full results are included in the Station Appendix. Note the results from Station MCH1 are inconclusive and should be taken as an indication only.

Station	Site Specific proxy V_{s30} (Standard deviation)	Mean tested V_{s30} (Standard deviation)	EC8 site class and confidence class from model	EC8 site class and confidence class from testing	Fundamental frequency (Standard deviation)	Topographical proxy method (EU site class)	Types of testing	Ridge Or basin flag	General profile description	Main uncertainty
MCH1	898 (426)	>1300 (inconclusive)	A (3)	A (2)	(inconclusive)	>760 (A)	HVSR Reference	N/A	A cyclic progression of sand/siltstones, with weathered shales.	Far field <i>in situ</i> results.
OLDB	379 (201)	360 (155)	B/C (3)	B/C (2)	2.90 (0.24)	360-420 (B)	HVSR MASW SCPT	N/A	Thick alluvial deposits, with around 1m peat at 4m b.g.l. , Mercia Mudstone & a thin basal conglomerate underlain by sandstone.	Presence & stiffness of the conglomerate and its effect on the profile.
SWN1	867 (197)	550 (100)	A (3)	B (2)	0.94 (0.27)	620-760 (B)	HVSR Reference	N/A	Man-made bunker, followed by Lower Chalk, with Greensand underneath	Low stiffness of chalk at depth.
WACR	798 (215)	850 (110)	A/B (4)	A/B (4)	0.43 (0.05)	300-360 (C)	HVSR Reference	N/A	Relatively thin layer of glacial till, overlying a series of weathered chalk, Upper Chalk and Middle Chalk.	Strata elevations, heterogeneous, poor impedance boundaries increasing testing uncertainty

Table 5-1: Summarised results from the testing of the UK SGMS compared to the Site Specific proxy method. Full results are included in the Station Appendix.

Station	Site Specific proxy V_{s30} (Standard deviation)	Mean tested V_{s30} (Standard deviation)	EC8 site class and confidence class from model	EC8 site class and confidence class from testing	Fundamental frequency (Standard deviation)	Topographical proxy method (EU site class)	Types of testing	Ridge Or basin flag	General profile description	Main uncertainty
WLF1	1093 (636)	900 (100)	A (4)	A(4)	3.00 (1.00)	360-490 (B)	HVSR Repeat	Local valley effects	Peaty clay overlying Coedana Hornfels to an unknown depth, underlain by similar metamorphic rocks.	Complex geology, strata elevations and far field <i>in situ</i> results.
WPS	1115 (650)	1100 (150)	A (3)	A (3)	2.83 (0.58)	360-490 (B)	HVSR	N/A	Glacial till over weathered mixed metamorphic rock consisting of schists, tuffaceous siltstone and sandstone with subordinate conglomerate banding.	Far field <i>in situ</i> results and depth of glacial deposits.

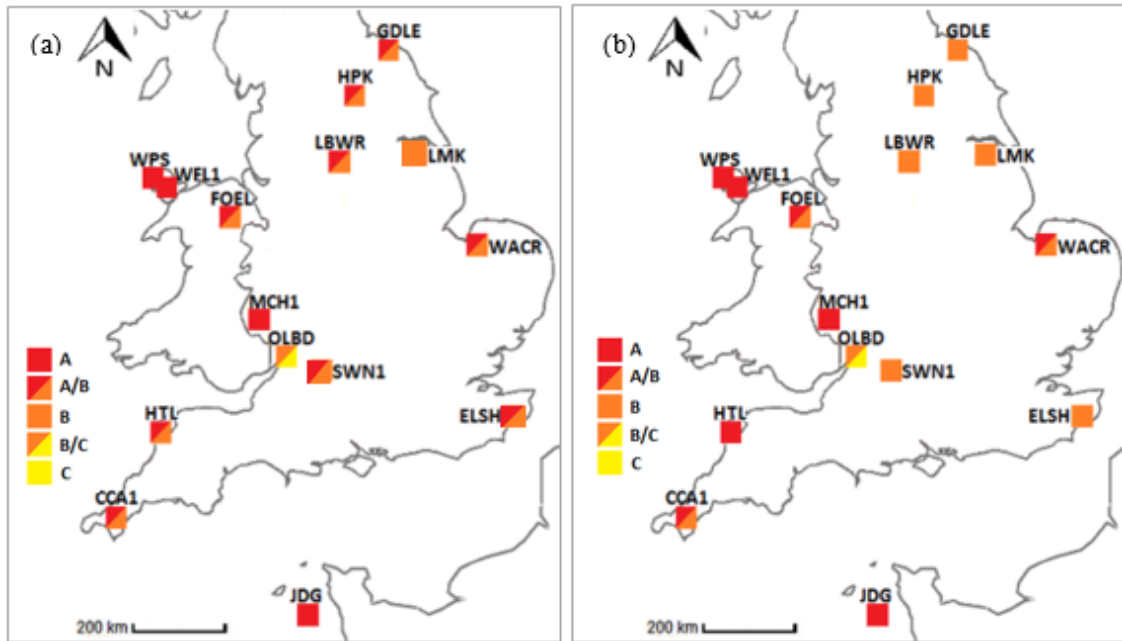


Figure 5-2: (a) Previous Site Specific proxy method assessment for the UK SGMS (Chapter 3). (b) HVSR testing results which are generally well correlated with the Site Specific proxy method results. One of the main differences is the lower than expected velocity rocks in the north-east of the region shown.

Three stations in the North East of England could be redefined as a class B sites, because of the reduction in standard deviation from the testing (Figure 5-2). All three of the stations are located on hillsides, which were expected to be formed of strong rock. However, the HVSR results indicate that the upper 30m is defined instead comprised of soft rock, reducing the V_{s30} (Section 5.2.4).

It is noted the fundamental frequency for Station HPK is high (Table 5-1). The peak at this frequency is expected to be caused by the large impedance contrast between the till and the underlying sandstone bedrock. The peak is variable, but generally had a larger amplitude than that associated with the true bedrock which has a broad, but low amplitude peak from 1-10Hz. Therefore, according the H/V results the fundamental frequency of the site is on average 19.30Hz. However, this site would need further testing to determine if the amplification at the till/bedrock boundary does overwhelm the overall profile response.

The *in situ* testing improved the confidence class or uncertainty assessment (adapted from Tallett-Williams 2013; Table 3-2, Chapter 3) in the geological profile for the Site Specific proxy method at seven sites. These stations commonly only had previous, far-field, *in situ* results so the site-specific

testing improved the understanding of the profile. Seven stations showed no change in confidence following testing. These were generally situated on heterogeneous deposits and therefore, it was challenging to determine a definite profile for those sites even with the testing. Finally, the testing led to a reduction of confidence class at Station GDLE. The testing results from this site could not be resolved fully with the simple profile expected. Despite this result, overall the testing correlated well with the Site Specific proxy method leading to an improvement in the understanding of the sites.

5.2.3 Comparison to Topographical proxy method

A version of the Topographical proxy method (Wald & Allen 2007) is available for V_{s30} assessment anywhere in the world (USGS 2013). This V_{s30} assessment is used to map the UK (Figure 5-3a). The V_{s30} classifications from the generated map at the stations are compared to those determined from the testing results (Figure 5-3b&c).

The USGS (2013) generated maps are meant to be used for general regional classification and not for specific sites. However, over half of the stations do not correlate with the site class determined from the HVSR results. This shows that the proxy method correlations used by the USGS (2013) are poorly adapted for the UK geology. A similar conclusion was determined by Lemoine *et al.* (2012) for sites in mainland Europe.

Wald & Allen (2007) assume that the increase of slope angle indicates an increase in strength and so an increase in V_s . The UK has strong deposits, which have relatively low slope angles similarly to other glacial environments. This includes the geology of Anglesey (Stations WPS and WFL1) where the topography is subdued compared to the age and strength of rock. Likewise, the classification of East Anglia (Station WACR) also appears low, possibly due to its flat, but glacial nature. However, the Black Mountains (Station MCH1) on the Welsh-English border are not flat, but have only a high B classification. This increases in stiffness to the West, but not as rapidly as would be expected.

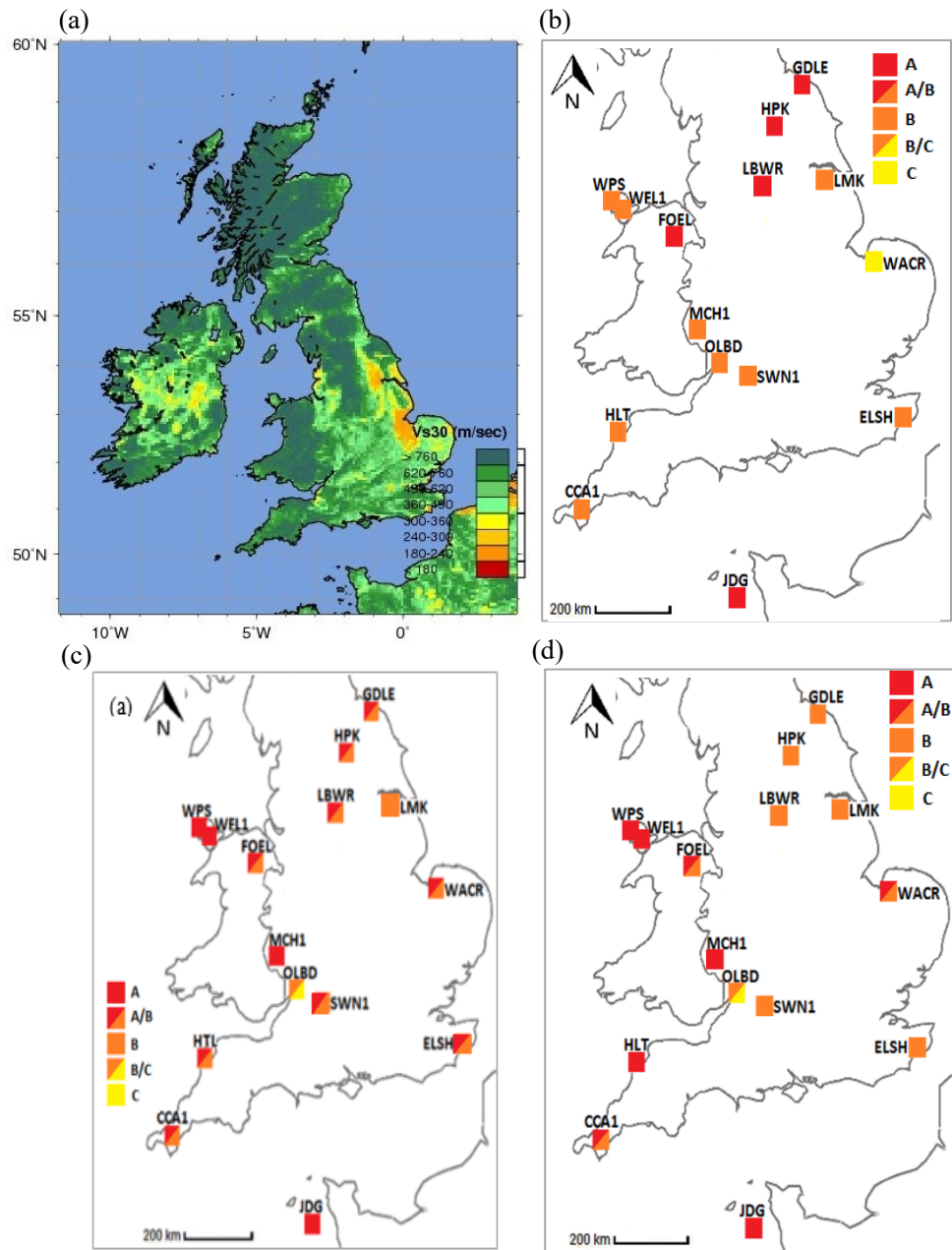


Figure 5-3: (a) V_{s30} map for the UK from the USGS (2013) based on the Wald & Allen (2007) Topographical proxy method. (b) Expected station class based on (a) with V_{s30} classes from the American Standards (BSSC, 2009) converted to the Eurocode 8 (EU 2004). (c) The results from Site Specific Proxy. (d) The HVSr testing results for the same stations.

5.2.4 Stations in the North-East of England

Three of the stations that were redefined as Class B sites (EN 2004) are located in the North-East of England (Figure 5-2): LBWR, GDLE and HPK. They are all situated on hillsides which were expected to have relatively stiff bedrock in the near surface. From the desk studies, the profiles were not considered greatly different from that of Station FOEL on sandstone and shale in Wales which was assigned an A/B classification even though some weathering was expected.

Conversely, it was determined that at two of the stations (LBWR & GDLE Figure 5-4a & c), there are at least 10m depth of low stiffness deposits in the near surface. These were generally not recorded on the geological maps. These appear to be residual rock deposits of low stiffness, reducing the V_{s30} .

In addition, the bedrock in this region was indicated by the testing to have lower velocities than expected. This occurred at all three sites (Figure 5-4). This may be the result of the age of the rock; Jurassic and Carboniferous compared to the Ordovician and older rocks of Western UK (Hunter & Easterbrook 2004). The bedrock at Station FOEL, though similar in nature and geomorphology to the north-east stations, is significantly older. It is likely to have been buried for longer and to larger depths, increasing its toughness, and hence, stiffness in the near surface. Further investigation is needed in this area as these materials have been assumed to be strong Class A bedrock. Lower V_s values may apply to more sites in the region or even those of younger rocks further north.

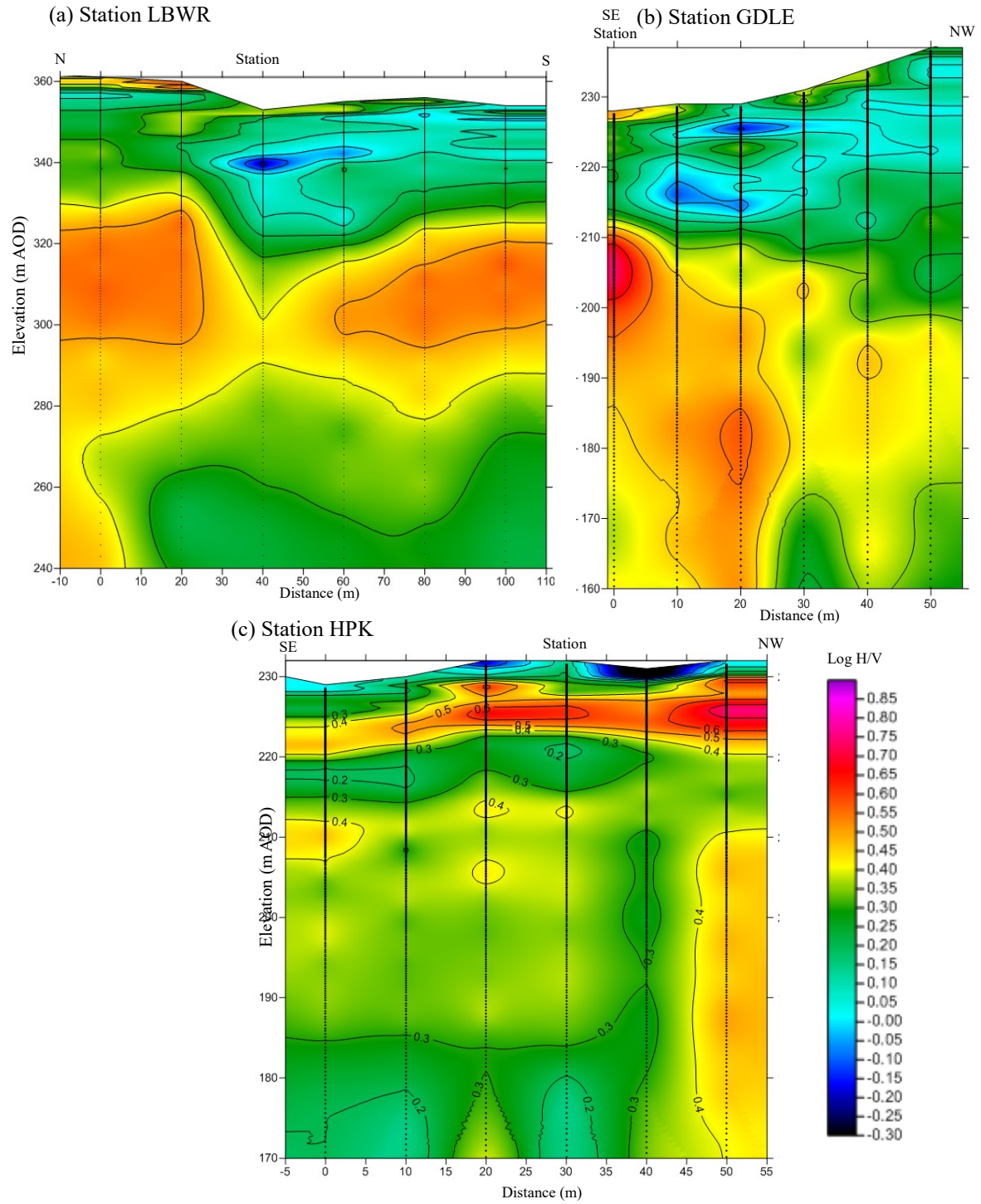


Figure 5-4: Pseudo-seismic stratigraphy the three North-Eastern England stations: (a) Station LBWR processed at 600m/s, (b) Station GDLE processed at 600m/s and (c) Station HPK processed at 680m/s. All three stations have significant layers of low stiffness material that was unexpected in the geological profiles.

5.2.5 Stations located on chalk

The HVSR method is open to large variations in anthropogenic and environmental noise. Therefore, its results are generally site-specific and only repeatable to a certain extent (Chapter 4 Section 4.5.7.). All the stations situated on chalk have this specific site signature. However, they also correlate remarkably well between sites, even though they are over 50km apart (Figure 5-5).

The results from the stratigraphic sequence have specific similarities at each of the chalk sites. The middle Holywell Nodular chalk appears variable with nodes of high impedance throughout the layer (Figure 5-5a&b). This is underlain by a lower impedance layer which had a clear boundary: the plenus marls. Generally, the lower chalk has significantly lower stiffness than the middle chalks (Figure 5-5). However, its upper surface was generally less linearly bounded than the plenus marls. Beneath the lower chalk, the greensands are indicated to be linear at the chalk boundary, but variable in thickness, possibly caused by channelization of the deposits below. At Station SWN1, the lower stiffness clay is also seen beneath (Figure 5-5c).

The results for the chalk sites could also be determined to larger depths than the majority of profiles. The pseudo-seismic cross-sections become nonsensical at depths generally greater than 50-100m in other deposits. This is linked to the 14 minutes recording time which limits the depth to which the instrument can reliably measure. In general, the pseudo-seismic sections would not normally be interpolated beyond 50m. However, the chalk pseudo-seismic sections correlate well with the geological mapped sections to depths greater than 100m.

In addition, the H/V recordings have a high consistency between measurements on chalk sites. Repeat surveys also show highly consistent profiles. This is an interesting result for the chalk which is known to behave variably in other tests. Therefore, it would be beneficial to test chalk sites further using this method as it may aid in the chalk classification.

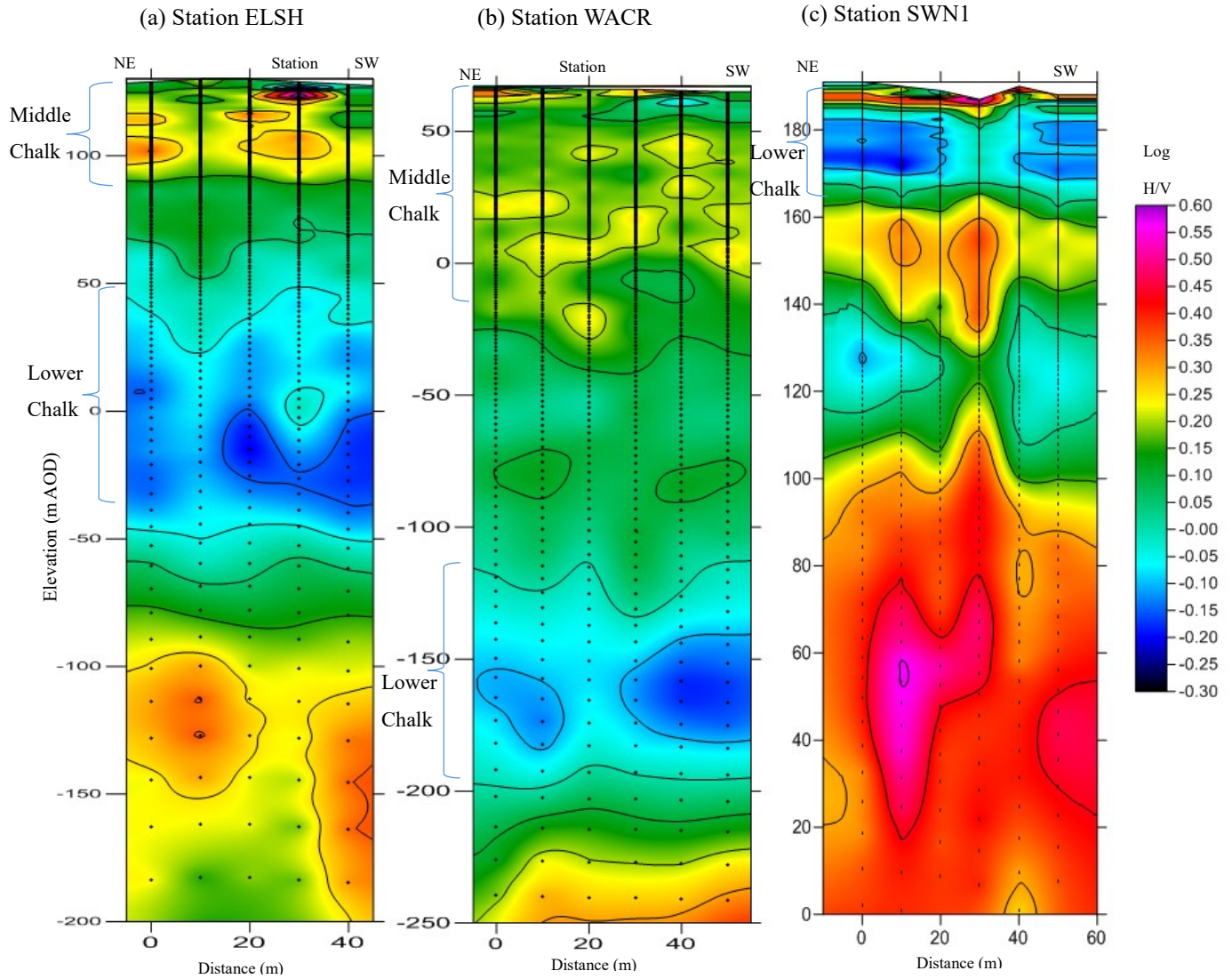


Figure 5-5: Consistency of HVSR method in chalk. Deep pseudo seismic stratigraphy for three stations in chalk: (a) Station ELSH (b) Station WACR and (c) Station SWN1. For the HVSR method, the consistency of the chalk layers is strong despite different layer thicknesses and depths from the surface testing.

5.3 Conclusion

The HVSR results compared well with the expected values from the Site Specific proxy method. A total of 14 of 15 stations were correctly categorised in the EU (2004) site classes and further allowed refinement of the models at seven stations. This improvement highlights the importance of site-specific testing to developing the certainty of results. Therefore, it is recommended the Site Specific

proxy method be combined with HVSR measurements where possible as the testing method has proven to be an economic test with easily validated results

The testing results are also compared to a basic a simplistic version of the Topographical proxy method (Wald & Allen 2007; USGS 2013). This method resulted in over half the stations being incorrectly classified. However, it is recognised that the method is only aimed to be a first order estimate.

Stations in the North East of England are determined to have a lower V_{s30} velocity than would have been expected given their location on hillsides formed of sedimentary rock. This is thought to have been caused by the bedrock being of younger age than those similar stations in Wales as well as significant weathering in the rock. While stations situated on chalk are determined to have a consistent response, especially in the HVSR cross-sections.

The significance of these results is potentially wide ranging. One example of their use is to constrain Fourier Amplitude Spectra inversions, by aiding the development of site effects parameters. This can then be used to improve the subsequent constraint of the inversions for source and path scaling. Thus, the robustness of GMPEs can be enhanced for seismic hazard applications in the UK.

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CHAPTER 6

Application of Bayesian Updating to site characterisation

6.1 Introduction

One aim of this study is to classify the uncertainty associated with V_{s30} for a site. This is initially quantified in the Site Specific proxy method (Chapter 3). However, the subsequent HVSR testing not only correlated well with the Site Specific proxy method, but also inexpensively improved the understanding of the UK SGMS sites. Therefore, it could be considered that the HVSR testing is an extension of the Site Specific proxy method. The combination of the two will both improve the accuracy of the results and reduce the associated uncertainty.

Quantifying the reduction of uncertainty caused by an *in situ* test is particularly important to expressing the value of a technique. The testing can add significant cost to a project easily identifiable to a client, especially if invasive testing is required. However, the significance of this testing to the design of a structure or station can be relatively obscure. Therefore, it is important to be able to demonstrate how the uncertainty in the design has been or will be reduced with each *in situ* test so that the cost of the testing is justifiable.

In this chapter, Bayesian Updating is applied to the estimation of the V_{s30} for a site. This is a method that makes use new or additional data in order to modify prior estimates of the nature of a random variable such as the V_{s30} . The Site Specific proxy method gives the initial estimate of the V_{s30} value and associated uncertainty. Then the HVSR results are used to update this initial estimate using a method that takes into account all of the sources of information that exist about the site. Finally, the sensitivity of the results to the initial Site Specific proxy input parameters is tested to determine how much it has altered the result.

6.2 Bayes Theorem

Bayes Theorem uses an initial estimate of a value or distribution of parameters and updates this initial estimate on the basis of supplementary knowledge (Nowak & Collins 2013). Thus, a set of n states is considered, for example, $A_1, A_2, A_3 \dots A_n$. In this set each of these states is mutually exclusive while the set is collectively exhaustive (Nowak & Collins 2013). This means that all possible states of being are represented within the set, but only one state will occur. Nowak & Collins (2013) describe these constraints on a set Ω probabilistically as:

$$\Omega = A_1 \cup A_2 \cup \dots \cup A_n \quad [6.1]$$

$$P(\Omega) = P(A_1 \cup A_2 \cup \dots \cup A_n) = 1 \quad [6.2]$$

If a new event E is now considered such as a test measurement, it must overlap with one or more the states within the set as these describe all the possible states of being. Therefore, if event E occurs then one or more of the states A_i must also occur (Nowak & Collins 2013). The probability of event E occurring can be determined through the Total Probability Theorem (Nowak & Collins 2013):

$$P(E) = \sum_{i=1}^n P(A_i) P(E|A_i) \quad [6.3]$$

where $P(A_i)$ is the probability that the current state is A_i and $P(E|A_i)$ is the likelihood of the event E or test result occurring given that the current state is A_i .

In most cases, event E is known to occur as the result of a test, while the current state of the set, A_i , is the unknown. An initial model of the likelihood of being in each state $P(A_i)$ can be updated given a supplementary knowledge of a test result, event E , to produce a new posterior model $P(A_i|E)$ for each possible state using Bayes Theorem (Nowak & Collins 2013):

$$P(A_i|E) = \frac{P(E|A_i)P(A_i)}{P(E)} \quad [6.4]$$

The $P(E|A_i)$ term is important as it describes how accurate and biased a given test is as its value is the probability that the test will produce a value E given that the real value is A_i . If the test is perfect then

this term is 1.0 at it will always produce the correct value. However, when the test is imperfect then the uncertainty in the test mean that this value will be less than 1.0.

6.2.1 Simple example of Bayes Theorem

To illustrate the application of this theorem, a simplified example is outlined in terms of estimating a V_{s30} for a site. This site is known to be a EU (2004) Class B site with a V_s between 360m/s and 800m/s. In this case, the V_{s30} required for design is required to the nearest 100m/s. Therefore, only four possible states (A_i) of being exist for less than 800m/s: 400, 500, 600 & 700. Note, this is a significant simplification that cannot be made for the UK SGMS (Section 6.3.1), but that is appropriate for explaining the mechanics of the Bayesian updating.

Having examined the geology of the region, an engineer estimates the probability of these states being present at the site (Table 6-1). These estimates are the prior model (Section 6.3.2). These can be formed via previous testing, inference or expert opinion (Nowak & Collins 2013). Note this example assumes there is no chance of the site outside class B. In general, the possibility of a misclassification is included. For the UK SGMS, the prior estimates come from the Site Specific proxy.

Table 6-1: Example 6.2.1 prior model for states

V_s (m/s)	Probability from prior model
400	0.1
500	0.4
600	0.3
700	0.2

A field test is then carried out at the site, with the resulting V_{s30} being determined to be 600m/s (event E). However, the testing equipment is not perfect and has an associated error. Therefore, there is a probability of the resulting value being the accurate answer given the testing result (Table 6-2). This is the error distribution of the test (Section 6.3.3). If the test had resulted in a different value, this distribution may change. Note that for the example the test has been assumed to have results within the class B which would not generally be the case.

Table 6-2: Example 6.2.1. error distribution given a testing result of 600m/s for states

V_s (m/s)	Probability given the result was 600m/s
400	0.05
500	0.15
600	0.70
700	0.10

These values are input into Bayes Theorem, Equation 6.4 (Section 6.3.4). The denominator is equivalent to the probability of the test result (event E) occurring (Equation 6.3). This is determined through the multiplication of the prior model probabilities, A_i (Table 6-1), by the probability of the states given that event E is 600m/s (Table 6-2):

$$\begin{aligned}
 P(E) &= \sum_{i=1}^n P(E|A_i)P(A_i) \\
 P(E) &= (0.05)(0.1) + (0.15)(0.4) + (0.70)(0.3) + (0.10)(0.2) \\
 P(E) &= 0.295 \tag{6.5}
 \end{aligned}$$

The posterior model probabilities are then determined by varying the numerator. If the probability that A_i=600 is required given the result of the testing is 600m/s:

$$\begin{aligned}
 P(A_i|E) &= \frac{P(E|A_i)P(A_i)}{\sum_{i=1}^n P(E|A_i)P(A_i)} \\
 P(A_i|E) &= \frac{P(E|A_i)P(A_i)}{0.295} \tag{from [6.5]} \\
 P(A_i|E) &= \frac{(0.7)(0.3)}{0.295} \\
 P(A_i|E) &= 0.712 \tag{6.6}
 \end{aligned}$$

The posterior model is calculated (Table 6-3) as the probability of each of the states is updated given the testing result (as in Equation 6.6). Compared to the prior model probabilities, the distribution has shifted toward 600m/s being the most probable state. However, it is still possible that the other states are present. This would not be the case if the testing were perfect and had no error distribution. If a further testing result is carried out, the posterior model is now assumed to be the new prior model and

the process repeated.

Table 6-3: Posterior model given a testing result of 600m/s for states

V_s (m/s)	Probability
400	0.017
500	0.203
600	0.712
700	0.068

This is a highly simplified example used as an illustrative guide to the Bayes Theorem. In reality, it is unlikely that the EU (2004) class of the site would be known and the V_{s30} would be required to a higher accuracy than to the nearest 100m/s. In addition, the V_s is a continuous variable, but, in practice, it can be useful to work with discrete states and allow the resolution of these states to become small (far less than 100m/s).

However, though the application of this method can be simple, the inputs and resulting information can rapidly become complex. Therefore, each of the stages in this example is linked to the application of this method to the UK SGMS. Thus, this simplified example can give an overarching explanation to the method.

6.3 Application of Bayes Theorem to UK SGMS

In the application of Bayes Theorem to the UK SGMS, the states of being, A_i , are initially discussed (Section 6.3.1). Then the two inputs from each station are determined: the prior model (Section 6.3.2) and HVSR test results (Section 6.3.3.). These form the inputs to determining the posterior model, through the processing (Section 6.3.4). Each of these sections is linked to the simplified example (Section 6.2.1) for clarity. Tests are additionally inbuilt to the methodology (Section 6.4) such that the effect of the inputs can be determined in the results as well as the limitations (Section 6.5). The results of the application are then discussed (Section 6.6).

6.3.1 States

Bayes' Theorem can be used with discrete and continuous inputs. For the UK SGMS, the study aim is to evaluate one variable which itself is an average, as opposed to modelling the exact V_s throughout

the soil column. V_{s30} estimates are rarely recorded to an accuracy of more than an integer, because of the associated measurement errors. Consequently, a discrete model is formed with numerous values of V_s that could be used.

Determining the number of possible states to use is initially dependent on the accuracy required. This could be performed to a number of scales including the nearest 10m/s, 50m/s or 100m/s. However, states of V_s separated by 100m/s or more produced distributions that were not smooth (Figure 6-1). The distributions also did not necessarily retain the required shape of the models for the prior model or test results. Therefore, to prevent this error caused by large scale grouping of V_s values, the initial continuous distribution is discretised as lump probability mass into bins of width 2m/s.

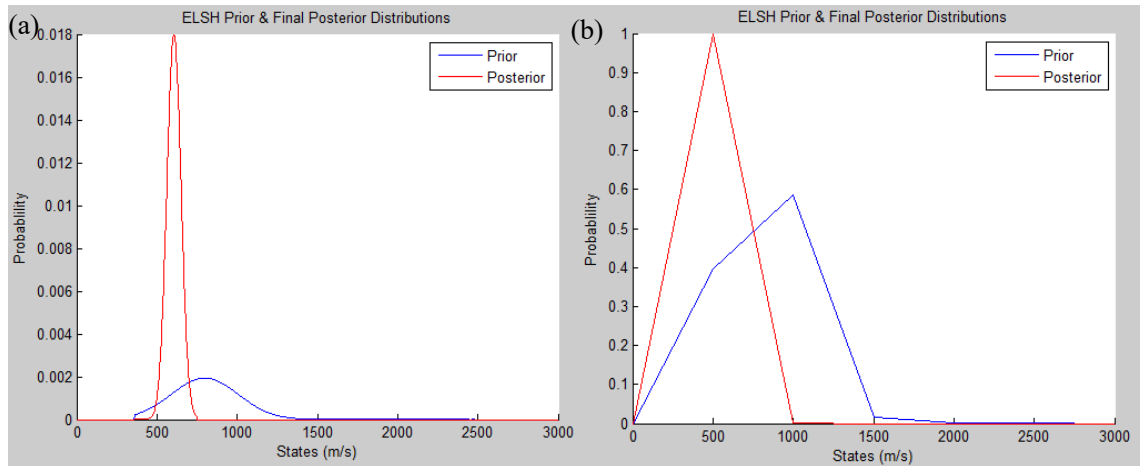


Figure 6-1: Prior and posterior models of Station ELSH with states every (a) 2m/s and (b) 500m/s. An extremely low value of states is used in (b) to illustrate the effect of high grouping on the models which appear much more certain in probability than they should be and have lost the distribution shape.

Possible V_s states are assumed to be between 0m/s and 3000m/s. The upper bound is restricted by the BGS model of the crustal V_s velocities for the UK as outlined in Edwards *et al.* (2008). This describes the first step change in V_s at 2.52km depth from a surface value of 2310m/s to 3410m/s (Edwards *et al.* 2008). At this depth, V_s is determined by the crustal rock which is homogenous compared to that at the surface. Therefore, a maximum of 3000m/s is developed as the likelihood of crustal rock velocities in the surface 30m is low and the highest V_{s30} value from the UK SGMS stations being 1600m/s. However, these values are insignificant as long as they ensure the full range of V_{s30} values expected within the models are included. The initial estimates from the Site Specific proxy had

produced prior estimates well within these ranges.

6.3.2 Prior model

The Site Specific proxy results (Chapter 3) are used as the prior model information for each of the UK SGMS sites. The mean and standard deviation determined are employed as the parameters for a normal distribution. This type of distribution is chosen as it is open to alteration in shape during the Bayesian Updating, ensuring the final posterior model distribution is not assumed to have a specific shape. For example, if a normal distribution is initially assumed, during the processing this may change to a lognormal distribution shape for the final results. The accuracy of this assumption is trialled in the sensitivity testing (Section 6.4.5.).

During development of the process, it was determined that the prior model distributions should be truncated. Without truncation, rock sites with V_{s30} velocities over 1000m/s were including the possibility of having a V_{s30} of under 360m/s in the calculation due to the large uncertainties from the Site Specific proxy method. This is unrealistic and decreased the probability estimates unnecessarily. Therefore, sites are truncated to twice their expected standard deviation either side of the mean.

The overall range is discretised into bins of 2m/s and probability mass was computed by integrating the continuous probability distribution function over each bin. (Section 6.3.1). These discrete probabilities can then be used for separate states in Bayes Equation (Equation 6.4).

6.3.3 Testing results

The HVSR testing is carried out as a series of tests across the site, the Tromino instrument being moved after the completion of each measurement (Chapter 4). At the majority of the sites at least 11 tests are performed. This number can be reduced in processing by noise causing the results to be contaminated; the tests being carried out in a different geological formation to the station, but also on site; or general difficulties of testing conditions. However, unlike MASW, these tests are more confined around the station and a less open to changes across the site.

These HVSR tests results are used as a series of independent tests for each station. Each measurement is modelled as a separate test like event E with the associated error distribution. Therefore, the results are input sequentially with each test updating a prior model distribution to form a new posterior model. This posterior model then becomes the new prior model distribution for the subsequent test (Figure 6-3).

The result of each test is assumed to be unbiased, but with a 20% coefficient of variation. The manufacturers quote the measurement error at 20% of the final value (Micromed 2013). Therefore, initially 20% of the mean is assumed to be the standard deviation of each test forming the error distribution, but this is further tested in the sensitivity testing (Section 6.4). The distribution is truncated at 50% of the mean in order to prevent unfeasible results being considered in the calculation, similarly to the prior model distribution. Finally, each continuous test distribution is then discretised into specific probabilities to be used in the Bayes Theorem (Equation 6.4).

The assumption that the HVSR testing results are independent and unbiased is a limitation of this model. The results are unlikely to be unbiased as the HVSR results need to be interpreted alongside a geological profile to produce a V_s estimate. However, this testing is performed to give a qualification on the average HVSR value produced and its likely uncertainty. Therefore, the result continues to have value, but should be treated with caution (further discussed in Section 6.5).

6.3.4 Implementation

The Bayesian Updating for the UK SGSM is carried out using MATLAB (The MathWorks Inc. 2014) software, the scripts for which are included (Station Appendices 8.3). However, for clarity a flow chart of the processing is included (Figure 6-2) as well presenting the results in a series of figures (Figure 6-3).

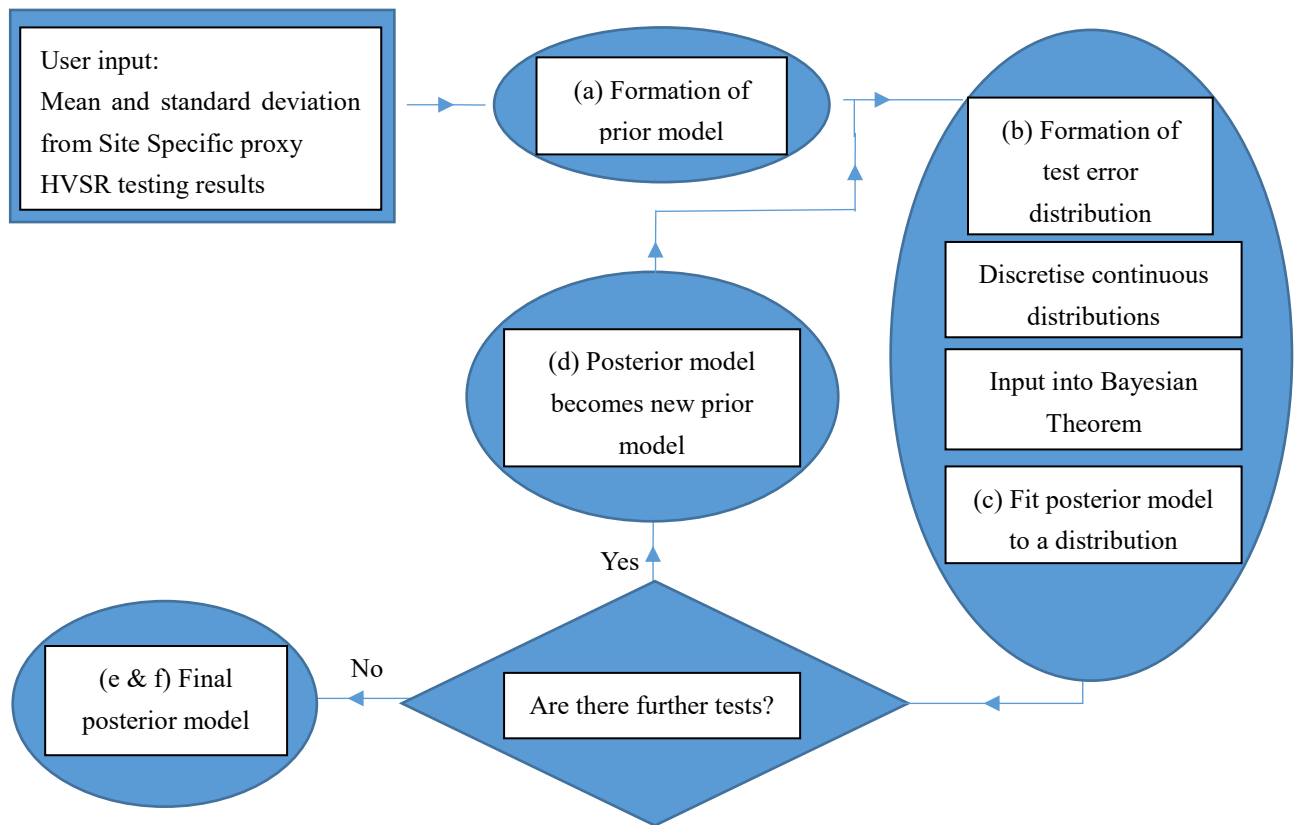


Figure 6-2: Flow chart illustrating process of Bayesian Updating for the UK SGSMS. The lettering relates to the results in Figure 6-4.

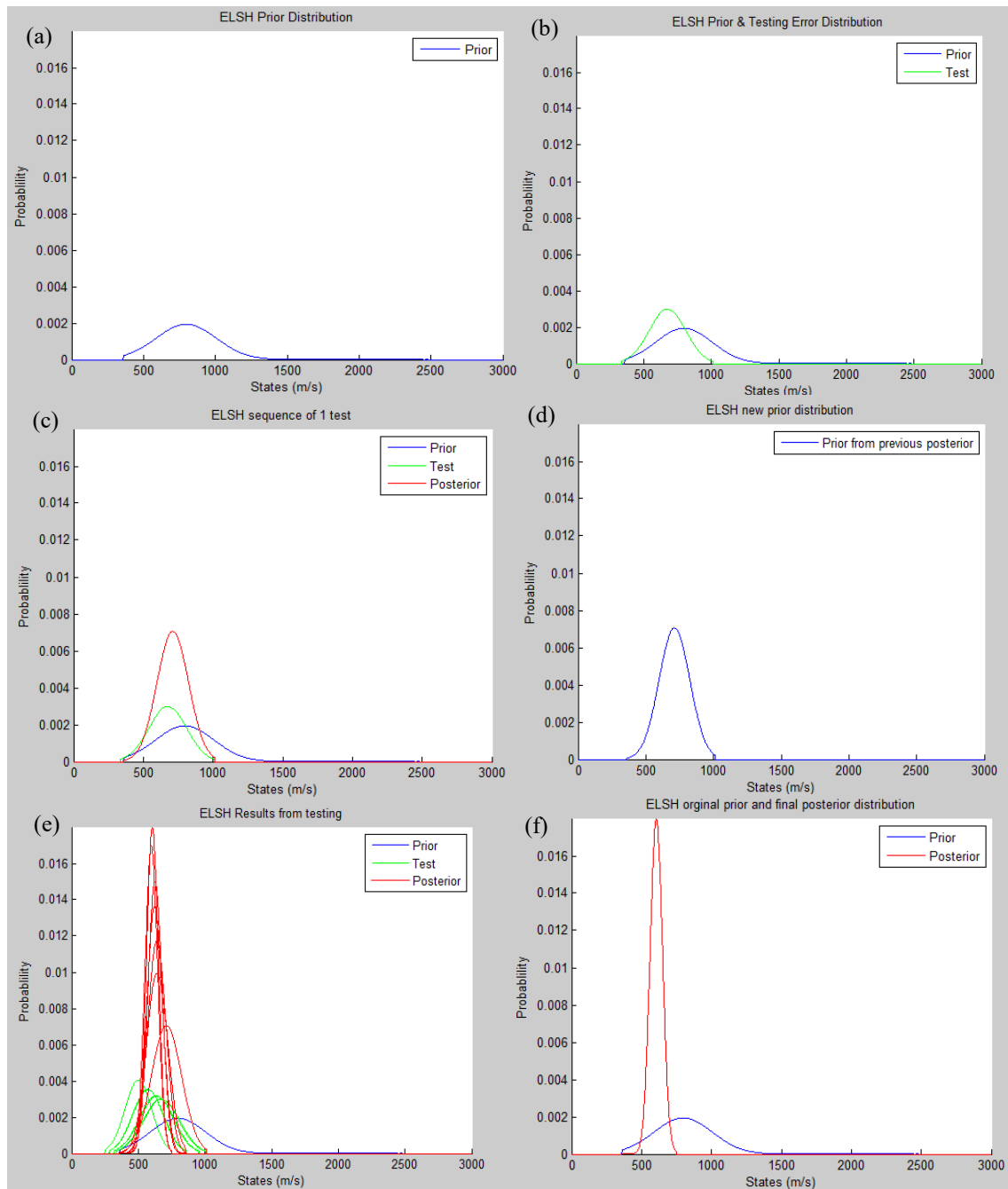


Figure 6-3: Results from specific stages of the Bayesian Updating process, related in Figure 6-2. Note (e) is a plot of all the tests and all the resulting posterior models distributions as the loop has progressed i.e. a series of (c), while (f) is the original prior model distribution and the final posterior model.

The results of these graphs can be challenging to display clearly if many tests have been performed. Therefore, the posterior models are summarised to its mean and standard deviation after each test result is calculated (Figure 6-4).

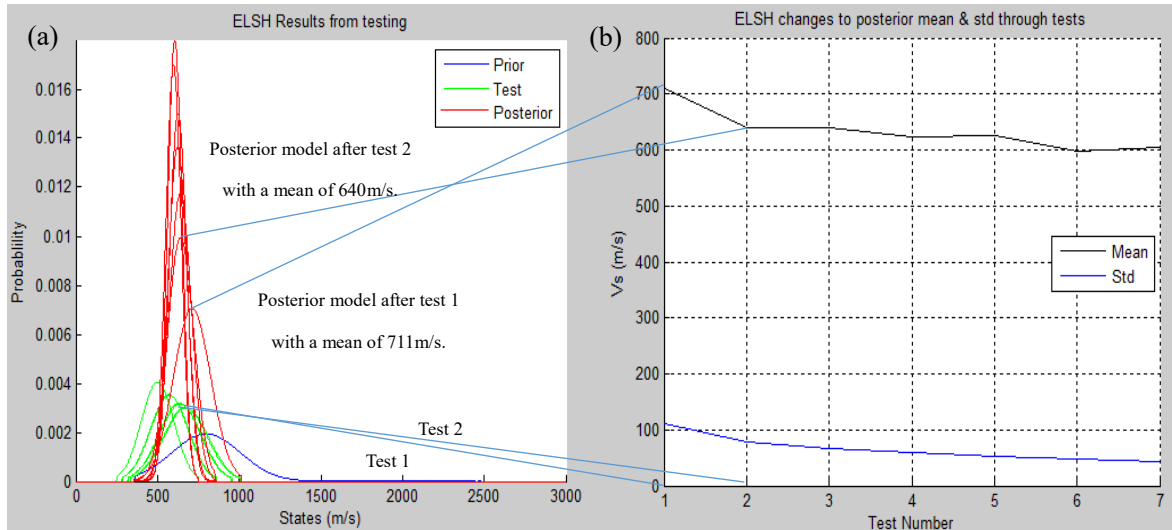


Figure 6-4: (a) Station ELSH results from testing as in Figure 6-2 (e). The changes caused in each posterior model is hard to determine in this layout. Therefore, the mean and standard deviation of each of the posterior models after each test is translated to (b). For example, after test number 1, the mean result from the initial posterior model is 711m/s which then changes after the second test is processed to 640m/s. The tests are ordered as they were measured in the HVSR testing.

6.4 Sensitivity testing

If a large number of test results are available for a site, initial decisions about the prior, such as its distribution type, mean and standard deviation are less significant to the final result. However, for small numbers of tests, or larger numbers of relatively inaccurate tests, then the prior model is more important as it may still influence the final result. To determine the extent of the prior and testing results influence, the input parameters for these distributions are examined in more detail.

This sensitivity testing aims to determine the effect of the user inputs and their relative magnitude of influence on the final results. This is important to determine whether the results would in fact converge to a single value with a sufficient number of tests despite the initial parameters, or if the initial inputs excessively determined the final output. In addition, the number of tests until the solution becomes

stable and becomes insensitive to further testing can also be determined. The five inputs considered are the prior mean and standard deviation as well as the input order of the testing results and the associated testing error. Finally, the distribution types for the prior and testing results are changed to lognormal to determine if the posterior is sensitive to this assumption. This is carried out alongside the processing of the UK SGMS (Section 6.6).

6.4.1 Prior model mean

The prior model distribution mean determines the initial starting point for the calculation. Therefore, if it is higher than subsequent test results, the overall trend will be a decrease in the mean value. Equally if the prior mean is lower than the test results, the trend will increase the mean value. However, the extent it is higher or lower than the actual value is critical. If the prior mean estimate is inaccurate, it may require many tests to converge towards the true value.

For each of the stations, the value of the prior mean is increased and decreased by 50% and 25%. The resulting values of the final mean posterior models were examined (Figure 6-6). The difference in the final results is determined to see if all the resulting posterior model mean result had become stable. This would indicate if the results are insensitive to the prior mean. A further examination of how many tests were required for the results converged within 10%, 5% and 1% of each other. This is performed to see if the full number of tests performed with the HVSR were actually required. Finally, the posterior

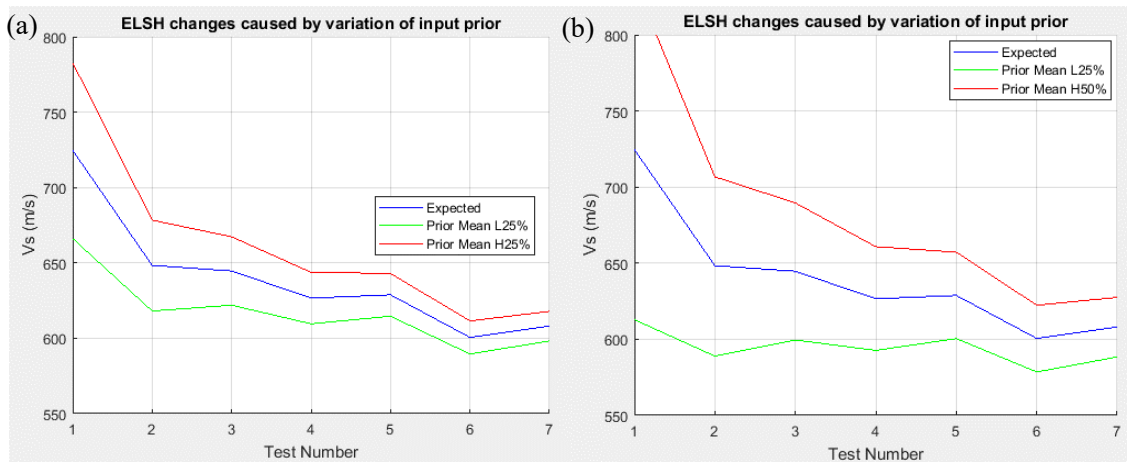


Figure 6-5: Variation in posterior model means for each updated test when the prior model mean is increased/decreased from the expected by (a) 25% and (b) 50%.

standard deviation is also examined to see if the difference in the mean of the prior distribution had any effect.

For example, increasing or decreasing the mean at Station ELSH by 25% caused a 0.3% difference in the final posterior model mean after seven tests (Figure 6-6). While 50% change in the mean caused a final difference of 3%. For the 25% change, one test was required to bring the posterior model means within 10% and two tests to bring the means within 5% of each other. While for the 50% change two tests were required to be within 10% and four to be within 5%.

6.4.2 Prior model standard deviation

The second input into the prior model is the standard deviation. This controls the susceptibility of the prior model distribution to change by the testing. If the prior standard deviation is small, the probability the prior model is correct is assumed to be higher. Therefore, the prior distribution will be more resistant to change via the testing results. Conversely, if the standard deviation is large, the testing results have more influence.

Similarly to the prior model mean tests, the sites are tested with 50% higher and lower prior standard deviation to the original (Figure 6-6). They are then monitored to see the effect on the final posterior model. The efficiency of the tests is also considered to determine how many are required before the posterior model means converged with 10%, 5% and 1% percent of each other.

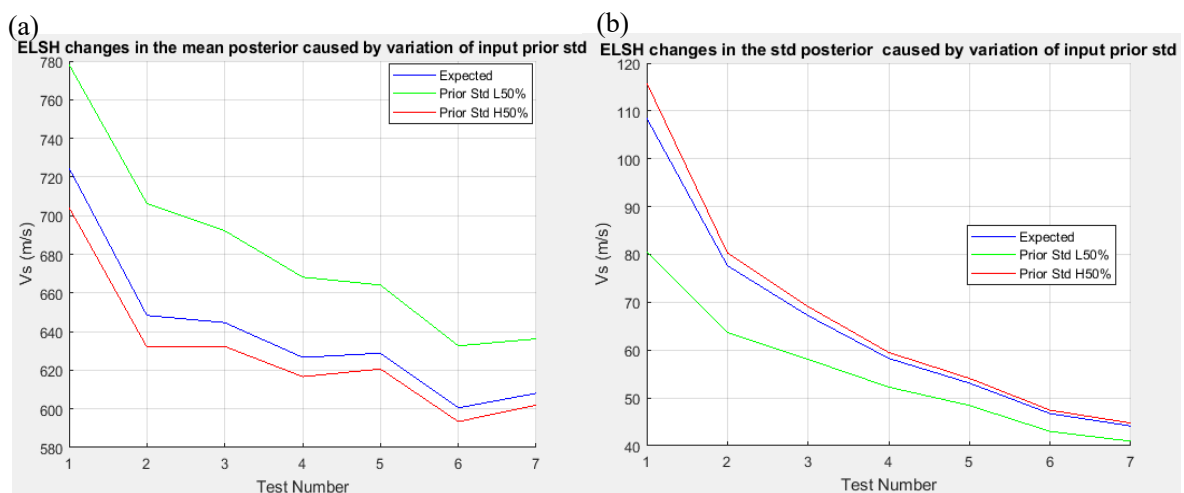


Figure 6-6: Variation in posterior model (a) means and (b) standard deviation for each updated test when the prior model standard deviation is increased/decreased from the expected by 50%.

For Station ELSH as the final mean is below the prior mean, reducing the standard deviation results in a higher final mean as the test results have less impact and only converging within 10% the original results after 5 tests (Figure 6-6). While increasing the standard deviation changes the initial results dramatically as the first test has a high impact, but the mean is closer with the final result of the expected standard deviation.

6.4.3 Order of testing results

The order in which the HVSR testing measurements are input into the processing can affect the final mean posterior results. For example, if all tests of lower value are applied initially, the mean of the posterior model will appear lower and then sharply increase if a higher testing result is included. Thus, the influence of the input order is bounded by sorting the results into descending and ascending order.

Therefore, the results are sorted into ascending and descending order as well as several random orders to determine when the posterior mean come within 10% and 5% of each other (Figure 6-7). This test is particularly important for heterogeneous sites, as the testing results can be highly variable. For Station ELSH, the ascending and descending results came within 10% of each other after 5 tests

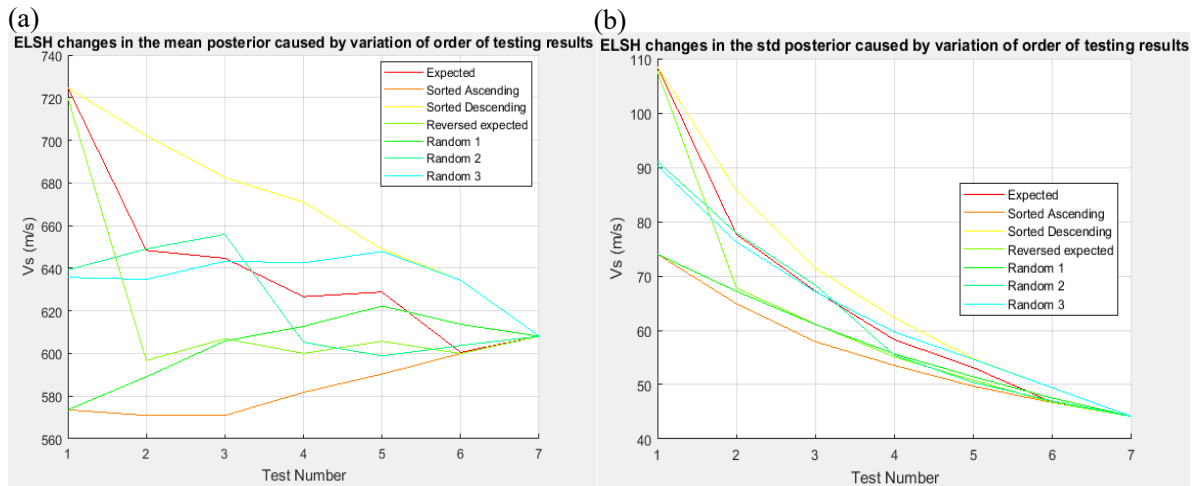


Figure 6-7: Variation in posterior model (a) means and (b) standard deviation for each updated test when the order of input of the test results is changed.

6.4.4 Error of tests

The effect of the error associated with each of the tests is also tested. This determines the power of each test on influencing the prior distribution. If a test has a low error associated with it the strength of the test to change the prior model is higher. This is important for heterogeneous sites with low error associated with them, as the strength of the test is high, but the variability of the final result is also high. Therefore, the posterior model mean may vary significantly and no become stable.

The tests were trialled with 50% larger and smaller error to that quoted by the manufacturer to determine if the final posterior is significantly changed (Figure 6-8). At Station ELSH, a test with 50% lower error than expected only requires one test to halve the prior standard deviation while the expected error and 50% larger require two tests

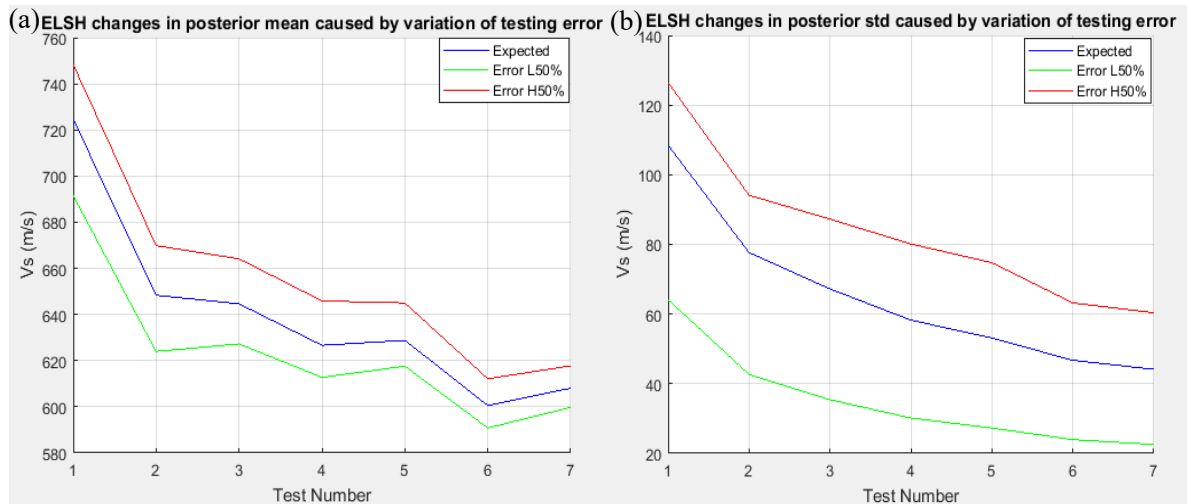


Figure 6-8: Variation in posterior model (a) means and (b) standard deviation for each updated test when the error associated with each test is increased/decreased 50%.

6.4.5 Sensitivity to input distribution

Finally sensitivity of the posterior model to the assumption of normality of the input distributions is trialled. A lognormal distribution could be a better representation of the V_s velocity, particularly as this is the model assumed in the Toro (1994) modelling for the V_s profiles (Chapter 3). In addition, if the original prior and test normal distributions are measured for skewness, many of the models show values significantly greater than two. Thus, indicating a significant positive skew and making a

lognormal distribution an appropriate choice.

The input distributions for the prior and test results are changed from normal distribution to lognormal (Figure 6-10). The parameters for the lognormal distribution are formulated using a limit-state function (Nowak & Collins, 2013):

$$\sigma_{\ln V_{s30}}^2 = \ln \left[1 + \left(\frac{\sigma_{V_{s30}}}{\mu_{V_{s30}}} \right)^2 \right] \quad [6.7]$$

$$\mu_{\ln V_{s30}} = \ln \mu_{V_{s30}} - \frac{1}{2} \sigma_{\ln V_{s30}}^2 \quad [6.8]$$

where $\sigma_{V_{s30}}$ is the standard deviation and $\mu_{V_{s30}}$ is the mean of the V_{s30} estimate, while $\sigma_{\ln V_{s30}}$ is the standard deviation and $\mu_{\ln V_{s30}}$ is the mean for the lognormal distribution.

The results are then examined for difference in shape and position from the original posterior estimate. For example, at Station ELSH, the resulting posterior from the lognormal distribution inputs seems similar to the original (Figure 6-10). When considered as lognormal the posterior estimate mean is $591\text{m/s} \pm 42$. The difference between this and the normal distribution is 3%.

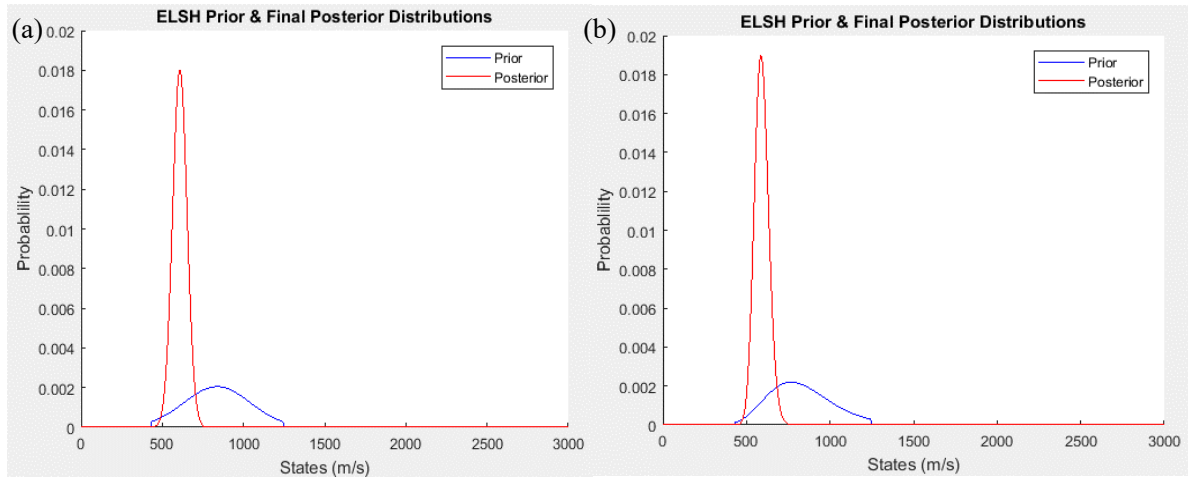


Figure 6-9: (a) Normal distribution modelling and (b) lognormal distribution modelling of the input prior distribution and the final posterior distribution after the testing results have been used in the updating.

6.5 Limitations of the method

There are two issues with the series HVSR test measurements being assumed to be independent. Firstly, the majority of the tests at each site have been carried out on the same day and processed by

the same operator. There is some subjectivity in this technique, particularly during the fitting of the V_s profiles given the indeterminacy of the solution (Chapter 4). The second issue is that the testing results have been modelled on the prior information and therefore have some interdependency.

Both the interdependency and bias have been reduced through validation of the technique. Nevertheless, these limitations are important to be considered during the Bayesian Updating. The main aim of the updating is to reduce the uncertainty surrounding the V_{s30} parameters. If the standard deviation is excessively decreased not taking into account the limitations of interdependency, the results may become unreliable. This is particularly significant at sites with high heterogeneity, where there a certain level of variability in the results may be inherent to the site. However, it is still worthwhile determining how many results are actually necessary on site to decrease the cost of the testing. This will also highlight the efficiency of the method used (Chapter 4).

6.6 Results

All UK SGMS previously studied are processed using the Bayesian Updating, except Station MCH1 which had no V_{s30} results from the HVSR testing (Chapter 4 Section 4.5.1). These are summarised (Table 6-4), but discussed in further detailed in the Station Appendix.

The average standard deviation after the Bayesian Updating is 53m/s. This is reduced 145% from the average, original, prior model standard deviation of 361m/s. To halve the original standard deviation an average of 1.2 tests is required with only Stations ELSH and WACR requiring two or more tests. Notably, those sites that are heterogeneous generally had high initial standard deviations and so were easier to decrease.

When the Bayesian Updating results are compared to the standard mean of the HVSR results for each of the stations, the results are on average 3% different. This indicates the results had little dependence on the prior inputs and were mainly influenced by the HVSR tests. Only two stations had a larger difference than 5% between the two measures: Stations CCA1 & JDG. The posterior model means are also generally lower than the average HVSR, possibly as the results are less swayed by anomalous,

higher, single results like the HVSR means. In addition, the standard deviation of the posterior model results is on average 48% lower than the mean of the HVSR tests, with four stations having over 50% difference.

Only two stations showed significant remaining influence of the prior distributions: Stations JDG and SWN1. For Station JDG, this likely is caused by a lack of tests, only five being deemed acceptable to use after difficult testing conditions and so was expected. This is not the case for Station SWN1 which had 11 tests. However, the prior model mean and the testing results had a large separation indicating a need to revisit the prior assumptions (Chapter 3 & Chapter 5). Therefore, the Bayesian Updating is valuable to highlight stations where more testing is required even if the average number of tests has already been performed or stations where the prior assumptions may not have been correct.

For the remaining stations, seven tests are required on average to cause insensitivity of the results to the user inputs. This number increased, particularly for heterogeneous stations including Station WLF1 which required 10 tests and Station CCA1 which required 15. However, this does indicate that the testing method has been sufficient in the majority of cases for the results to become insensitive to the prior inputs. In addition, an average of 79% of the tests are used for each site indicating an efficient method.

The main input parameter susceptible to sensitivity is the order the testing results are input. This could cause large variations in the final test result if a reduced number of tests are used. This affected all of the stations and seemed to be the main parameter that bounded the sensitivity. The testing error affected 9 of the 14 stations, which is indicative of the posterior distribution becoming more reliant on the HVSR results. The prior mean affects 6 of the stations, possibly indicating poorer correlations between the testing results and Site Specific proxy and including Stations JDG and SWN1. The remaining parameters: prior model standard deviation and input distributions affected around a third of the stations.

Table 6-4: Summary of results for Bayesian Updating of the UK SGMS. (Note: Station MCH1 is not included as no results were obtained in the HVSR testing).

Station	Prior Distribution (m/s)	HVSR Results (m/s)	Bayesian Updating (m/s)	Difference HVSR/ Bayesian (%)	Number of tests used	Number tests for STD to half	Number of tests until insensitive	Main sensitivity (Primary/secondary)
CCA1	812 ± 611	950 ± 186	887 ± 44	6.9	17	1	15	Order of tests/prior std
ELSH	838 ± 204	610 ± 63	608 ± 44	0.3	7	2	6	Test error/order of tests
FOEL	864 ± 488	780 ± 63	791 ± 59	1.4	7	1	6	Test error/order of tests (sensitive to input distribution)
GDLE	912 ± 511	645 ± 61	637 ± 56	1.2	5	1	4	Order of tests/ test error
HPK	911 ± 337	685 ± 85	668 ± 38	2.5	12	1	9	Order of tests/Prior mean
HTL	948 ± 503	950 ± 118	911 ± 61	4.2	9	1	6	Order of tests/ prior std
JDG	1084 ± 284	1220 ± 400	1376 ± 118	12.0	5	1	4 (However, still reliant on prior)	Order of tests/ prior mean & std (sensitive to input distribution)
LBWR	720 ± 260	650 ± 75	639 ± 38	1.7	11	1	8	Order of tests/ test error
LMK	599 ± 201	487 ± 34	485 ± 34	0.4	8	1	7	Order of tests/ test error (sensitive to input distribution)
OLDB	379 ± 155	360 ± 20	358 ± 25	0.6	8	1	5	Order of tests/ test error and prior mean (sensitive to input distribution)
SWN1	867 ± 197	550 ± 29	551 ± 32	0.2	11	1	9 (However, still reliant on prior)	Prior mean/ order of tests & prior std
WACR	798 ± 336	850 ± 106	823 ± 70	3.2	5	3	3	Order of tests/prior mean & testing error
WLF1	1093 ± 293	885 ± 75	876 ± 46	1.0	14	1	10	Order of tests/prior mean & testing error
WPS	1115 ± 680	1100 ± 146	1066 ± 71	3.1	9	1	9	Order of tests/ test error

6.7 Conclusion

A method of Bayesian Updating is developed for determining a V_{s30} at a site in order to understand more fully the associated uncertainty with each test. The calculations have shown that one to two tests are normally sufficient to halve the initial standard deviation at a site. This again shows the value of even relatively uncertain testing to estimate the site response.

Though some bias exists due to the limitations of the HVSR, the uncertainty estimates are reduced. The mean estimates are also likely improved as they are not as affected by single anomalous results as a mean of the HVSR results would be. In addition, the importance of the input parameters is highlighted, particularly the input order of the testing results which affected all of the stations. In future applications of the Bayesian Updating to V_{s30} estimates, the testing results could be used to form an overall sample distribution and update the prior as a summarised result, which would reduce both the effect of the testing order and bias within the results.

The technique indicated stations where the results may still be dependent on the Site Specific proxy estimate as well as sites where the correlation between the HVSR and the proxy results was not as strong. Moreover, it showed the significance for the HVSR method of performing at least seven tests or more on site to reduce the sensitivity of the results to the initially assumed V_{s30} . This also highlights the efficiency of the testing method used (Chapter 4) as 79% of the test measurements carried out were used for the result. Though, HVSR testing has a relatively high measurement error and so requires more tests measurements, other testing techniques may require more tests than expected for the sensitivity of the results to be reduced.

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CHAPTER 7

Conclusions

7.1 Summary of research

For low seismicity regions, it is generally necessary to import and adjust ground motion models developed for other regions. One of the key adjustments is to account for the specific features of the velocity profile and damping in the target region, *i.e.*, the UK. A good constraint on the target velocity profile and damping aids the accuracy of this calibration and prevents a significant amount of uncertainty being associated with this part of the model. This uncertainty can have a significant role in the overall hazard computations and the more that the target profile can be constrained, the less uncertainty needs to be considered.

However, due to a low perception of the risk, insufficient funds are often available for the costly testing techniques used in high seismicity regions. This prohibits the use of current, customary testing methods for significant networks such as the UK SGMS. Consequently, there are fewer previous *in situ* measurements that can be used to calibrate the region-specific proxy methods from high seismicity regions. Thus, it was established that new methods are required to improve the uncertainty associated with site amplification in low seismicity regions.

Initially, parameters used to represent site amplification were reviewed, with the prevalence of the V_{s30} velocity being significant. It does have specific disadvantages (Mulargia & Castellaro 2009), but, in the absence of a fully characterised site, it continues to be the universally used parameter (Kamai *et al.* 2016). However, the relationship between V_{sz} profiles and geology is not commonly studied. Most advances in this relationship have come through the progression of proxy methods to determine V_{s30} velocity.

The Global V_s Database aims to allow a better examination of the relationship between V_s velocity and geology. The original database compiled in the study by Campbell (2014) co-supervised by the author, has been extended by the addition of two large datasets and industry data. The aim was to double the number of

records while maintaining the quality of the data and to include a higher portion of igneous and metamorphic rocks. This would ensure the comparison with UK geology. The database was analysed to determine controlling factors between geology and V_s velocity focussing on origin, depth and age. Depth was demonstrated to be an influencing factor as well as grain size in soils, but further analysis is required into further parameters.

The subsequent review of the current proxy methods for determining V_{s30} velocity showed they can prove insufficient for specific sites as they aim to cover broad regions quickly (Wald *et al.* 2008). They are also generally calibrated using data from regions of high seismicity and so are most applicable to the regions from which this data has come. In addition, they depend on sufficiently numerous previous *in situ* measurements to be able to correlate with one defining parameter. Thus, these are not considered suitable for the UK SGMS as little or no regional V_s testing is available.

Therefore, a Site Specific proxy method is created. This aims to provide a framework for engineers to determine a rigorous V_{s30} estimate for a site with initially little to no site-specific data. This is carried out through the formation of a geological model, comparison of the model through similarity of geological facies to the Global V_s Database and the combining the uncertainty of the two models using an adapted version of the Toro (1995) equations. The adapted equations are calibrated to the known geological profile preventing unfeasible profiles being considered. The Site Specific proxy does have limitations, particularly in terms of finding sufficient previous *in situ* invasive testing and so producing a large the final uncertainty associated with the results.

However, the Site Specific proxy also provides a defensible initial V_s profile. Most other proxy methods produce only a V_{s30} value. This can be hard to justify if the calibration or calculations behind the value are not explicitly explained, particularly in terms of the uncertainty associated with them. While the Site Specific proxy requires more input, the ability to understand the assumptions that form the profile provide a significant advantage when aiming to classify specific sites.

In situ testing was required to validate the results of the Site Specific proxy method. All of the *in situ* testing methods have significantly less uncertainty and are generally more accurate than proxy methods. Therefore, direct testing is preferred for characterisation. However, in both low and high seismicity regions, the cost of the methods is found to be prohibitive particularly over several sites. The expense of a test was one of the main limitations in this research as well as time on site and the complexity of processing.

Given these limitations, three methods were chosen after having considered the numerous other possibilities. The first, HVSR, is a compromise between the expense of the test and its accuracy. The SCPT and MASW methods are used as supplementary tests. This is not only to offset the concerns about the indeterminacy of the HVSR method, but also to determine its bias in combination with the geological models in Site Specific proxy method. Therefore, the HVSR technique was used in a series of validation tests to ensure its accuracy and reliability.

All of the 15 UK SGMS considered were tested using the HVSR method as well as SCPT and MASW at three sites. The HVSR results compared well with to the Site Specific proxy method, but did not correlate a simplistic version of the Topographical proxy method (Wald & Allen 2007; USGS 2013). Thus, the V_{s30} profiles for the UK are seen to be diverse and highly site specific.

Finally, a method of Bayesian Updating is developed for refining a V_{s30} velocity at a site in order to understand more fully the associated uncertainty with each test. The calculations have shown that one to two tests are normally sufficient to halve the initial standard deviation suggested by the Site Specific proxy method at a site.

7.2 Analysis of findings

From the Global V_s database, it was determined that depth is an important influence on V_s , but rock type, age and origin correlations were not strong. Thus, it is expected that there are other significant controlling factors. The relationships predicting V_s as a function of the parameters trialled have a large amount of scatter.

This may be linked to factors such as weathering and fracturing, but this requires further investigation.

For soil, grain size was seen to be a controlling factor. However, this highlights the main challenge of determining the controlling geological factors on V_s velocity. Many geological parameters are measures for more fundamental factors or are highly inter-correlated. For example, although grain size appears to be a fundamental parameter, it is also highly related to void ratio and could be a representation of cementation.

The Site Specific proxy method used the results of the Global V_s database to constrain V_s profiles for the geological models determined in the site investigations. When the two models were combined in the adapted Toro (1995) equations, the proxy results had inconsistent V_{s30} classifications for the 15 stations than expected from comparison with the EC8 site class descriptions. Many of the stations, expected to be on hard rock, are found to be on the boundary between soft and hard rock. Several soil sites were also expected to be significantly stiffer. Two sites did have unexpectedly high estimates, but the recognition of this demonstrated the increased awareness created by determining the geological model.

The HVSR method was chosen to be the main testing method for the UK SGMS in order to determine the accuracy of the Site Specific proxy method. However, the HVSR itself has specific limitations which were initially tested to be able to more accurately determine the V_s profiles for the UK SGMS. During this validation, it has been shown that HVSR testing can be successful in characterising sites alongside the Site Specific proxy method as well as at sites of known geology or previously tested sites. However, the strength of any impedance contrasts between the strata is fundamental to the successful characterisation of the site using this technique.

The HVSR method also requires caution when used in environments with velocity reversals and is limited in accuracy for the first meter of the ground surface. In addition, the testing can be better referenced if carried out at a previous borehole record nearby to the site. While, accounting for what level of detail can be detected by the instrument is important in determining sufficient spacing at each site. High amplitude, narrowly banded anthropogenic noise is a fundamental limitation of the method, but, for the rurally based UK SGSM,

this was not an issue. The method also performs well against HVSR records from earthquake data. Therefore, it is seen as a sufficient primary method of characterisation, if properly constrained with the depth of the first stratum.

The HVSR testing results compared well with the expected values from the Site Specific proxy method. A total of 14 out of 15 stations were correctly categorised in the Eurocode 8 (2004) site classes, with the one incorrectly classed being recognised during the application of the Site Specific proxy. In addition, the HVSR results allowed a significant reduction in standard deviation that could be achieved compared to the proxy method. Thus, seven stations could be redefined into a single Eurocode 8 (EU 2004) class from an overlapping class. This improvement highlights the importance of the testing to developing the certainty of results. Therefore, as the HVSR has proven to be an economic test with easily validated results, it is recommended to be combined with the Site Specific proxy method where possible to improve the uncertainty associated with the proxy results.

The testing results were also compared to previous assessment based a simplistic version of the Topographical proxy method (Wald & Allen 2007; USGS 2013). Both of these methods classified over half the stations incorrectly, though it should be noted the Topographical proxy is aimed to be a first order estimate (Wald & Allen 2007). This has significance for the design of sensitive structures that have used previous estimates from these methods.

Stations in the North East of England are determined to have a lower V_{s30} velocity than would have been expected given their location on hillsides formed of sedimentary rock. This is thought to have been caused by the bedrock being of younger age than apparently similar stations in Wales. While stations situated on chalk are determined to have a consistent response, especially in the HVSR cross-sections. The significance of these results is wide ranging. One is the effect on the latest GMPEs for the UK. These currently assume on average zero amplification across the network. The HVSR results indicate that this may not be the case.

Bayesian Updating was used to develop a better understanding of the uncertainty associated with the final

V_{s30} results for the UK SGMS. Though some bias exists due to the limitations of the HVSR, the uncertainty estimates are reduced. The mean estimates improved in the Bayesian method as they are not as strongly influenced by anomalous results as a mean average from the HVSR results would be. In addition, the importance of the input parameters is highlighted, particularly the input order of the testing results which affected all of the stations. In future applications of the Bayesian Updating to V_{s30} estimates, the testing results could be used to form an overall sample distribution and update the prior as a summarised result, which would reduce both the effect of the testing order and bias within the results.

The Bayesian technique indicated stations where the results may continue to depend highly on the prior distribution and further testing would be of value in reducing uncertainty. Moreover, it showed the significance for the HVSR method of performing at least seven tests or more on site to reduce the sensitivity of the results to the initially assumed V_{s30} velocity. This also highlights the efficiency of the testing method used as 83% of the test measurements performed were used for the result to become stable.

It is noted that HVSR testing has a relatively high measurement error in comparison with invasive tests and so requires more test measurements than, for example, downhole testing. However, other testing techniques may also require more tests than expected for the sensitivity of the results to be reduced. This could have high ramifications in terms of cost where drilling even two boreholes per site could rapidly make the testing unfeasible, while comparatively the main cost in performing repeat HVSR tests is the labour. In addition, seven HVSR tests could be carried out in one half day, while a downhole test would be likely to require at least two days to complete.

Finally, the results of the Bayesian Updating showed the combination of the Site Specific proxy method and the HVSR testing could significantly reduce the uncertainty at a site in an economical way. However, caution is taken with the reduced Bayesian results due to the interdependence of the test results and as many of the stations are in highly heterogeneous environments. Therefore, reducing the uncertainty from the HVSR average may no longer represent the site which in itself may have an inherent variability.

Thus, the benefits of this research include a clear and justifiable method for intraplate regions to infer the necessary site characteristics to account for site effects. As application of this method, the characterisation of the V_{s30} for over half the UK SGMS has been performed. This study has also led to the development of Global V_s database highlighting the uncertainty associated with V_s profiles when correlated with commonly used parameters such as depth and grain size. The widely used Toro (1995) method has been modified to reflect the considered layer thickness within the site profiles and then the results updated with the Bayesian Theorem throughout the testing process.

7.3 Relevance to initial aims

The research had a dual aim (Chapter 1 Section 1.4): to create a geologically rigorous method to determine site amplification in areas with little data and to use this method to characterise the ground conditions under UK strong ground motion stations. In order to achieve this, the Site Specific proxy method is based specifically on geological modelling and the results/relationships from the Global V_s Database. The proxy method has been used to characterise out for 15 of the 24 stations across the UK. Reducing the number of stations characterised ensured the quality of the method and that sufficient validation could still be performed within the limited time.

In addition, to develop this method the current practices for determining site amplification were reviewed. This included proxy methods as well as invasive and non-invasive testing. The Global V_s Database was created in collaboration with Campbell (2014) and subsequently extended to twice the original number of V_s tests. Finally, uncertainty in V_s velocity estimation has been accounted for in the initial estimation through the randomisation of results. In addition, the final uncertainty is considered in the Bayesian Updating of this initial estimate from *in situ* testing. Therefore, this research has achieved its aims given the restricted time available.

7.4 Recommendations for further work

If further time and resource were available, the following tasks would be carried out. These are listed by significance to the scope of this research:

- Complete the investigation of the remaining nine UK SGMS and the other weak motion seismic stations across the UK. This could be achieved economically by combining the Site Specific proxy method and HVSR testing. This characterisation would then allow prioritisation for invasive testing at sites that are more challenging or those with unexpected V_s velocity profiles. This would include stations such as those in the North of England. Any invasive results could then be included in the Bayesian Updating to observe the effect on the proxy results (Chapter 6).
- Add further V_s profile recordings to the Global V_s Database, particularly with those containing data on rock weathering and fracturing (Chapter 2). This would enable further investigation of the proficiency of the factors assumed to be controlling in the Site Specific proxy method. Not all the sources found have been added to the database and further information is included in Appendix 2-4. In addition, the regression analysis could be performed on this data to separate the influence of known controlling factors.
- Couple controlling factors from the Global V_s database to the equations in the adapted Toro modelling, if any of the relationships between the geological parameters and V_s velocity are determined (Chapter 2). This may improve the accuracy of the randomisation and produce more realistic profiles.
- Analyse further the testing results from several of the HVSR and MASW methods. For example, the grids carried out for the HVSR validation could be modelled in 3D, rather than 2D cross-sections (Chapter 4). Similarly, all of the MASW results have been assumed to be 1D, but could be converted to 2D. This may provide more detailed information about the sites tested or the capabilities of the

testing methods.

- Compare HVSR results from *in situ* testing with H/V results from UK stations recordings. This would determine the differences found through the different method styles especially in terms of the significance of length of recording. The shorter *in situ* recordings are known to be limited in frequencies greater than 0.1Hz Those less than 0.1Hz may be important for site amplification and more easily retrieved from the UK stations which record constantly.
- Compare the HVSR results with UK earthquake recordings for the stations. This was not attempted during this research as those records available were found to have narrow frequency ranges and limit the results for the spectral comparisons (Chapter 5). However, this should be carried out with any future recordings.
- Use the V_s profiles determined to produce transfer functions for each site. This would allow the comparison of assumed station influence to Fourier Amplitude Spectra inversions with that determined from the HVSR results. This would aid the improvement of GMPEs for the UK, allow further investigation of the UK attenuation structure and/or influence the expected Fourier Amplitude Spectra parameters such as stress drop and geometric spreading.
- Further investigate the relationship of chalk with the HVSR method. This method produced similar results for the different facies of chalk despite the large differences between the sites (Chapter 5). This relationship should be investigated to determine if chalk could be more easily classified through passive methods.
- Investigate the differences between the Eurocode 8 and NERHP spectra. The full consequences for design or PSHA could be better understood, particularly as these codes are often compared.

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