

The post-yield behaviour of four Eocene-to-Jurassic UK stiff clays

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A detailed study is described of the post-yield behaviour of four medium-plasticity heavily over-consolidated UK stiff clays. Sub-layers of the stiff-to-hard Gault, Kimmeridge and Oxford clays were identified, sampled and tested; these, along with facies investigated in an earlier London Clay study, had broadly similar depositional histories. The intention in considering a spread of similar sediments from the Jurassic to the Eocene was to allow any strong effects of geological age, or burial depth, to be identified. A strongly fissured meso-structure was present in three of the four clays, which had a controlling influence on their effective shear strengths, considering that the representative element volume is of paramount importance in measuring the strengths of such soils. All four soils were brittle in shear and, when sheared to sufficient displacements, developed low residual shear strengths. The stiff clays were investigated further through comparisons between natural and reconstituted behaviour, using the latter to normalise the effective stress data for volume and also considering the clays' oedometer swell sensitivities. Normal compression tests, when normalised for void index, implied different degrees of 'structure' than undrained shear tests, showing that a more elaborate micro- and meso-fabric framework is needed to capture the behaviour of highly overconsolidated and aged geomaterials. This paper focuses on describing the study sites' geotechnical profiles and the stiff clays' yielding behaviours under one-dimensional compression and in triaxial compressive shear.

KEYWORDS: clays; fabric/structure of soils; laboratory tests; shear strength; soil classification; stress path

INTRODUCTION

A large proportion of the southern UK is underlain by stiff clays or mudrocks deposited from the Triassic (Mercia Mudstone) to the Eocene (London Clay); understanding their behaviour is of significant economic importance. The mechanics of some deposits have been investigated individually (particularly the London Clay (Hight *et al.*, 2007)), but a consistent and detailed comparative study employing modern techniques has yet to be presented.

Well-established frameworks exist that allow meaningful investigations to be made of the behaviour of natural stiff clays that address the effects of their structure (Burland, 1990; Cotecchia & Chandler, 2000). Detailed comparisons have been made within such frameworks of the effects of geological history on the behaviour of different units within the London Clay (Gasparre *et al.*, 2007), and also of the influence of weathering on an Italian stiff clay (Cafaro & Cotecchia, 2001). While there has been much research investigating the various effects of different forms of structure within these frameworks, including the effects of fissuring that is common in stiff plastic clays (see Vitone & Cotecchia, 2011), the important strata considered in this paper have received far less attention. There has also been no integrated study of how their structure and properties may vary with age and depth of burial. This paper considers these aspects by reporting detailed testing programmes on four UK stiff clays deposited between 50 and 160 million years before present (BP) that have broadly comparable

geological origins, mineralogies and post-depositional histories. Reliance is placed on published estimates of the stiff clays' ages and maximum burial depths.

The stiff clays investigated were the Gault, Kimmeridge and Oxford Clays, following a related study of the London Clay (Hight *et al.*, 2007). The authors' focus on age and burial depth required that other factors such as in-situ stress level, depositional heterogeneity, local geological structure and weathering should be isolated as far as possible. The sampling sites were chosen at midland locations where geological folding was not intense and coastal action absent. Weathering is usually unavoidable at 'greenfield' sites down to depths of several metres, so sampling was concentrated at similar depths of around 10 m. Comparisons were made with the London Clay (unit B2) from a similar depth at the Heathrow Terminal 5 site, where a full profile was established down to 50 m. It is recognised that Quaternary glacial and/or periglacial disturbance would have affected the sampling locations, which were probably covered by deep-rooted forests over much of the Holocene.

This paper focuses first on summarising the sites' geotechnical profiles. It examines how the meso- and micro-structures affect the four stiff clays' large strain yielding behaviour, as seen in oedometer and triaxial compression tests. Broader studies of the clays' geological histories and microstructures are summarised by Wilkinson (2011), while Gasparre *et al.* (2007), Nishimura *et al.* (2007), Hosseini Kamal (2012) and Brosse (2012) report on the clays' highly non-linear stiffness characteristics and marked anisotropy in mechanical behaviour. Ring shear tests on remoulded and intact samples are described by Cunliffe (2010) and Narayana (2010).

BACKGROUND: GEOLOGY, PRIOR WORK AND SAMPLING

Wilkinson (2011) summarises the geologic settings of, and information available for, the stiff clay sampling locations identified in Fig. 1. The depths of burial listed in Table 1

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Fig. 1. Sampling locations (after Wilkinson (2011); note: sampling locations are indicated with the stars)

derive from his literature review of relevant apatite fission track (e.g. Green, 1989) and stratigraphic reconstruction (e.g. Jackson & Fookes, 1974) studies. The two techniques clearly led to substantially different estimates for these strata. The tabulated ranges are generic guides that are compatible with geological age (the older sediments have deeper burial depths) rather than accurate site-specific assessments.

A summary of geotechnical data is given in Table 1 and profiles are presented in Figs 2–4 for the three new sites. Hight *et al.* (2007) and Gasparre *et al.* (2007) provide the equivalent London Clay information. Seismic cone penetration tests (CPTs) were carried out at each site. Also shown are profiles of index, strength and stiffness parameters, including those published for the same sites by other workers. Particle size distributions for the fines fraction, focusing on the depth of greatest interest, are shown in Fig. 5. Table 1 also lists key points regarding the four stiff clays' basic compositions, micro- and meso-fabrics, focusing on the depth ranges where testing was concentrated. In this context meso-fabric refers to the features that can be seen by eye in samples or trenches. No larger scale geological or tectonic features were logged at the three new sites. Table 1 also summarises the main mineral components of each soil; minor quantities of feldspars and pyrite were present in some cases. While there are variations in index properties, the most significant differences relate to organic contents, mineralogy and fabric. A trend can be seen in Table 1 for the in-

situ void ratio to reduce with increasing depth of burial. But the Kimmeridge Clay's void ratio was atypically low, reflecting its better grading, more numerous silt particles and highest proportion of quartz. Scanning electron microscopy (SEM) analyses revealed that the silt particles tended to limit the degree of the Kimmeridge Clay's micro-fabric orientation to the horizontal (Wilkinson, 2011).

Oxford Clay

The Oxford Clay was block-sampled from the base of a wide 10 m deep excavation near Elstow (Bedfordshire) to the south of Bedford. It is highly bedded, reflecting relatively quiet, shallow marine deposition (Hallam, 1975). A laboratory investigation of the stiffness behaviour was made at a nearby site by Hird & Pierpoint (1997), who reported recent chemical weathering of the clay down to about 3 m. The deeper soil is green-grey in colour, highly laminated and with the highest contents of illite and organic material of the four clays. Another important feature of the meso-fabric is the presence of horizontal shell layers. Parry (1972) and Burland *et al.* (1977) concluded that horizontal laminations present in the soil have a more important influence on mechanical behaviour than joints or fissures. The wide trench made to recover block samples revealed no significant fissure sets (see Fig. 6(a)), but highlighted again the important sets of sub-horizontal bedding laminations (Wilkinson, 2011).

Table 1. Summary characteristics of the stiff clays (mineralogy and micro-fabric data from Wilkinson (2011); London Clay data from Gasparre (2005)) (references: A, Jackson & Fookes (1974); B, Green *et al.* (2001); C, Lings *et al.* (1991); D, Chandler (2000))

Clay	Age: million years ago	Burial depth: m	In-situ void ratio	G_s	LL: % PL: % PI: %	Clay fraction: %/activity	Organic content: %	Bulk mineralogy: quartz: % clay minerals: % carbonate: %	Clay mineralogy: illite/smectite: % kaolinite: % chlorite: %	Microstructure	Mesostructure
Oxford Clay	Upper Jurassic 161–156	500 ^A –1130 ^B	0.60	2.46	66 34 32	45 0.71	10	25 58 13	82 16 2	Strong horizontal orientation of particles and shells	No significant fissuring but highly bedded. Horizontal shell beds.
Kimmeridge Clay	Upper Jurassic 156–151	410 ^A –1080 ^B	0.46	2.50	49 23 26	50 0.52	6	65 27 0	81 15 5	No strong preferred orientation due to presence of larger silt particles	Medium to high fissure intensity (typically 2–5 cm spacing) sub-horizontal and 40–60° to vertical.
Gault Clay	Lower Cretaceous 112–99	300 ^{AC} –870 ^B	0.67	2.59	74 28 46	57 0.81	1	26 41 32	89 10 2	No strong preferred orientation due to presence of larger micro-fossils	Medium to high fissuring intensity (spacing of 2–5 cm) sub-horizontal and sub-vertical with frequent zones of very high fissure intensity. Presence of nodules.
London Clay (unit B2c)	Eocene 56–49	200 ^D	0.82	2.65	66 29 37	47 0.79	1.5	37 NM* NM	87 11 3	Moderate particle orientation	Low to medium fissure intensity (spacing typically 5–20 cm) in sub-vertical and sub-horizontal directions.

* NM: Not measured.

SEM showed that the Oxford Clay was the only soil to have a very strong horizontally orientated clay particle micro-fabric (Wilkinson, 2011). The plasticity and in-situ water content trends are relatively steady with depth below 5 m, but there is more scatter in the bulk density. Profiles showing S_u trends from unconsolidated undrained triaxial compression tests on 100 mm samples (Arup & Partners, 2007) are presented in Fig. 2. The secant pressuremeter shear stiffnesses (measured in the horizontal G_{hh} mode at arbitrary cavity strains) scatter around or below the seismic CPT G_{vh} measurements made for the current study.

Kimmeridge Clay

Kimmeridge Clay is a major hydrocarbon source stratum for the North Sea. However, apart from limited high-pressure testing (Nygard *et al.*, 2004, 2006) for oil exploration studies, relatively little advanced laboratory research has been conducted to date. Kimmeridge Clay was sampled at Willow Brook Farm (Oxfordshire), south-west of Abingdon. Following seismic CPT testing, two 14 m deep, fully sampled boreholes were drilled with the Geobore 'S' wireline triple-tube rotary coring system, employing a natural polymer water-based drilling fluid. Coring and CPT testing identified a stronger and stiffer, cemented band at about 8 m that attested to variable depositional conditions within the profile. The Kimmeridge Clay originated as a shallow marine deposit, containing much eroded volcanic material within the upper, more silty part (Jeans *et al.*, 2000). Wilkinson's (2011) micro-fabric analysis identified no strong particle orientation.

Although no trenches were excavated or logged by the authors, rotary samples were split to observe the meso-fabric illustrated in Fig. 6(b). Relatively closely spaced fissures were noted at the 8–12 m depth of greatest interest, with one sub-horizontal set with around 50 mm spacings and a second set inclined at 40–60° to the vertical spaced at 20–50 mm. The discontinuities were slightly rough-to-smooth (D3–D4) and fresh (E1) within the classification scheme proposed by Vitone & Cotecchia (2011). The fissures have planar to curved (G1–G2) shapes with some intersections (H3), and a medium to high (I4–I5) intensity. The origins of the fissures are uncertain, but like the London Clay tested by Gasparre *et al.* (2007) they do not show any evidence of slickensiding or particle orientation due to shearing, and may have originated as tensile fractures. Their surface conditions therefore lead to different influences on the mass shear strength to the fissures reported by Vitone & Cotecchia (2011) that exhibit slickensiding and oriented residual shear-strength fabric.

Gault Clay

Gault Clay samples were retrieved from High Cross (Cambridgeshire), near Cambridge by both block sampling to 3 m from a trench and two Geobore S boreholes cored to 13 m depth. Standard and seismic CPT soundings were also made. The shallower block samples were drier than expected from earlier investigations (e.g. Coop, 1987) at the same site. The additional desiccation and weathering is interpreted as being due to tree re-growth over the last 25 years at the sampling area. The CPT trace presented in Fig. 4 represents the conditions applying many metres away from any substantial vegetation. The effects of weathering (after earlier tree removal) are evident in the reduced CPT cone resistances and sleeve frictions developed above about 6 m. Another CPT sounding close to both the trench and medium-sized trees showed higher resistances down to around 3 m, reflecting the effects of active tree roots, which were also evident from visual inspection and high suction test values in the block samples. The main laboratory testing programme

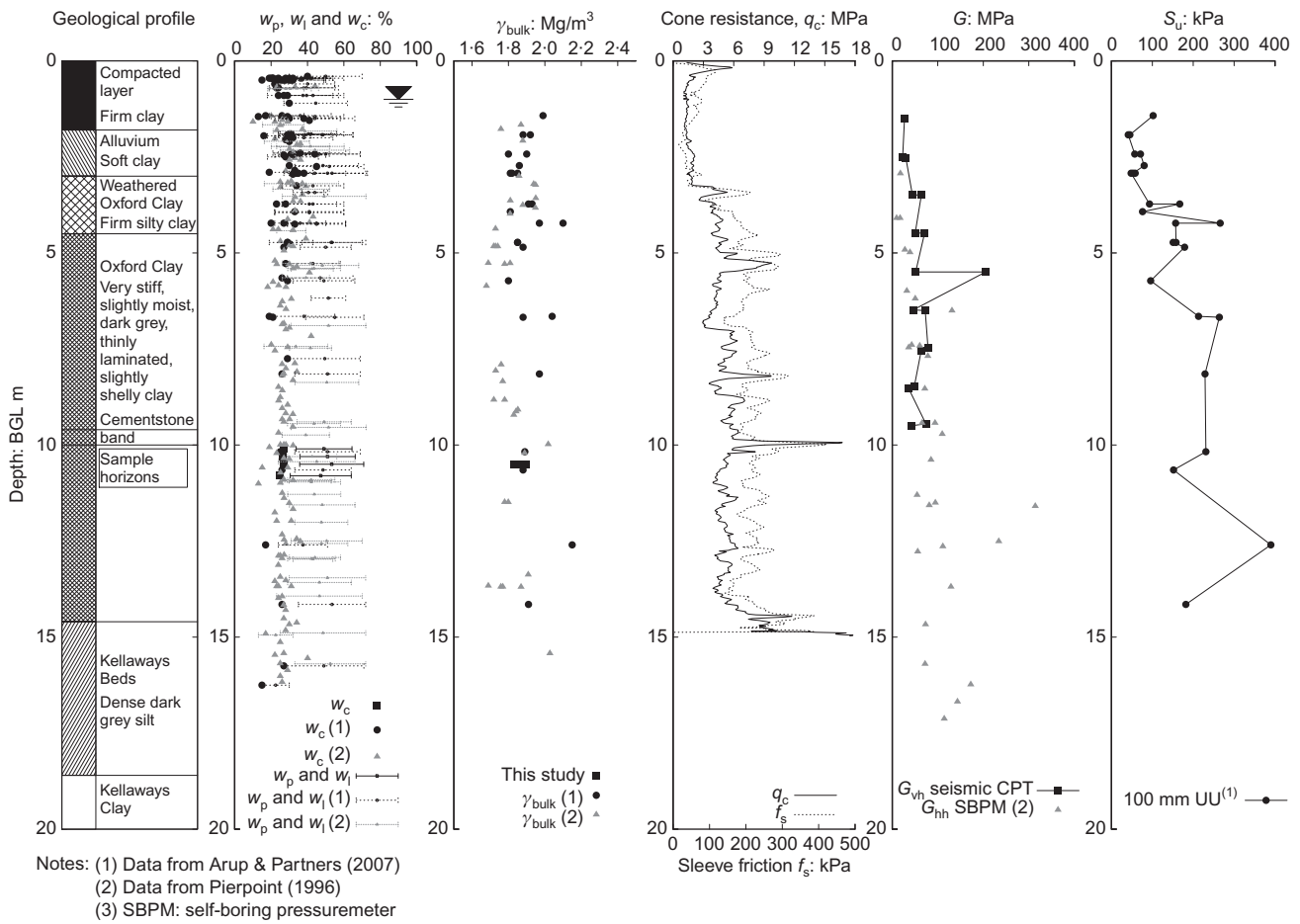


Fig. 2. Oxford Clay profile

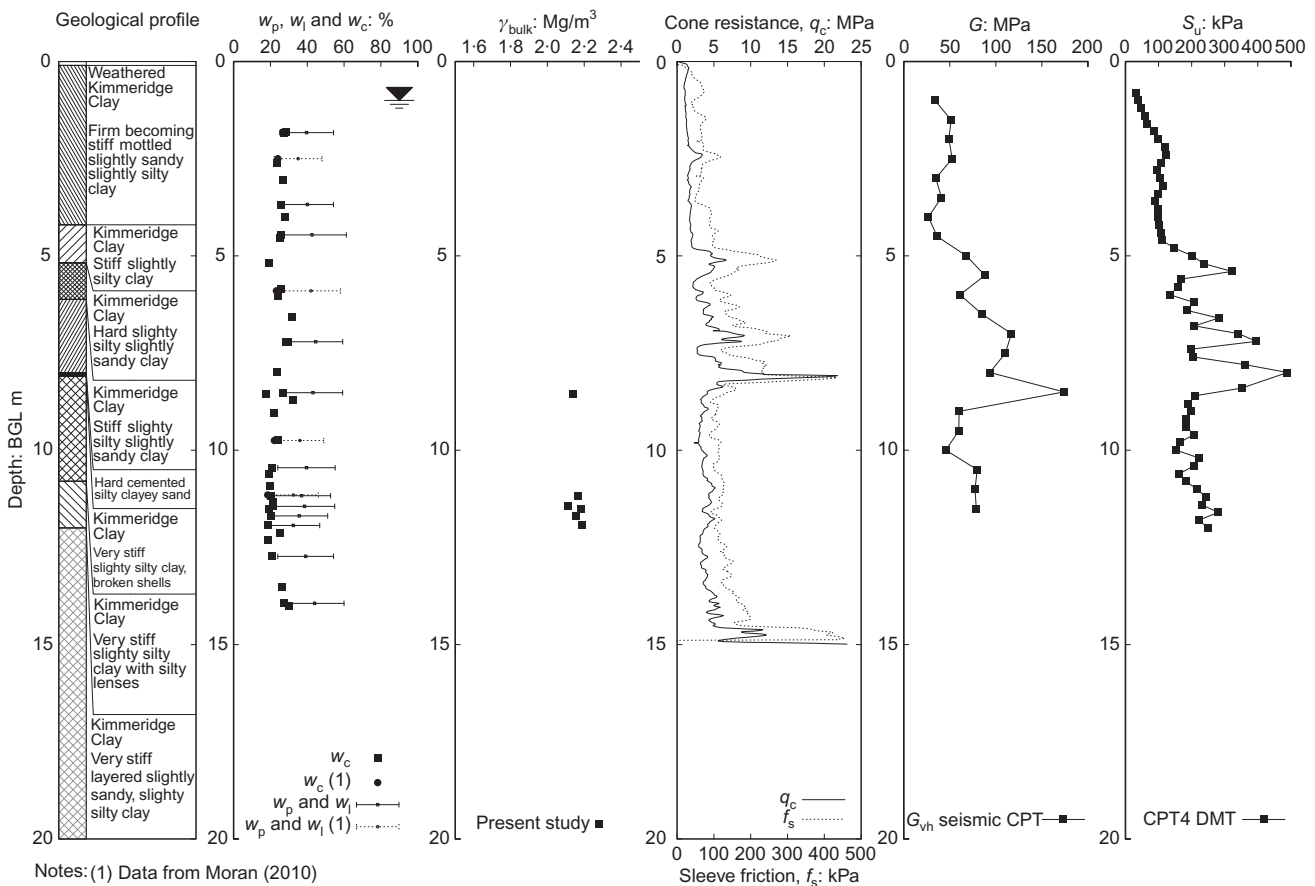


Fig. 3. Kimmeridge Clay profile

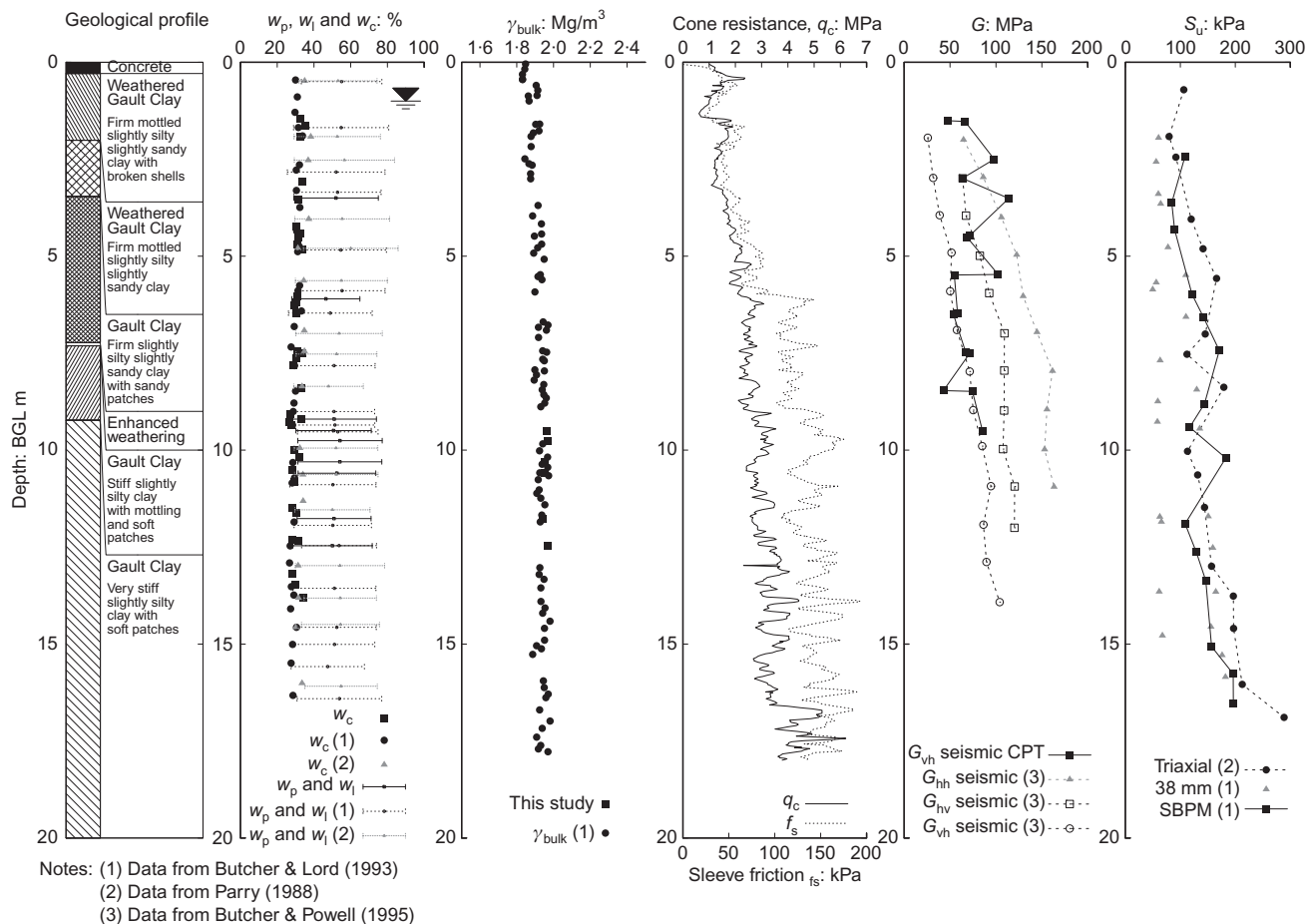


Fig. 4. Gault Clay profile

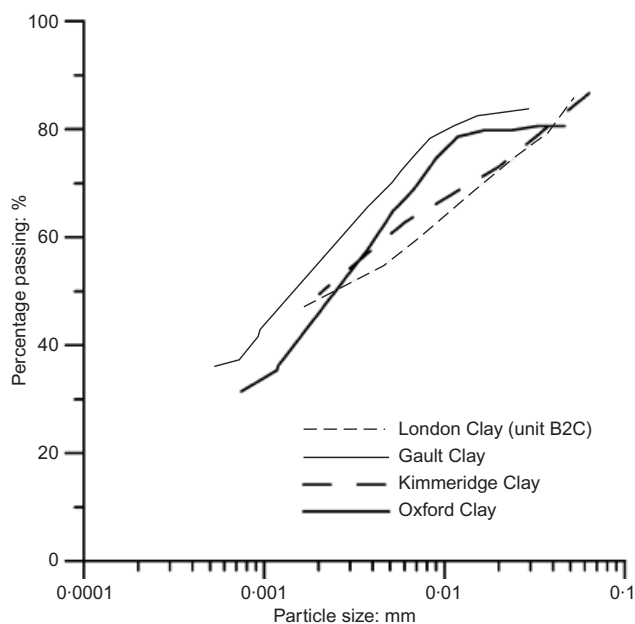


Fig. 5. Particle size distributions (London Clay data from Gasparre (2005))

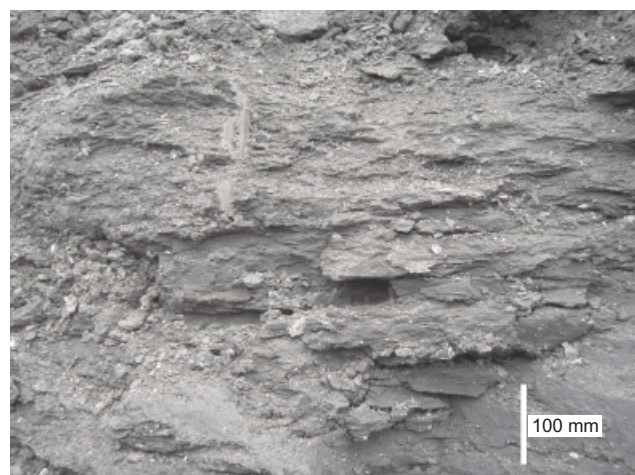
focused on testing the apparently unweathered rotary core samples from around 10 m depth.

The Gault Clay is also a marine deposit, originating from a deepening carbonate-rich muddy sea (Garrett & Barnes, 1984; Butcher & Lord, 1993) that left the clay with a

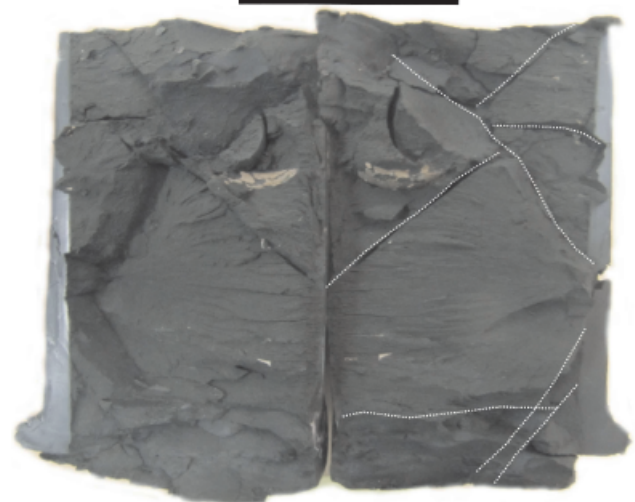
calcium carbonate content of about 30% (Ng, 1998); 200–400 m of chalk was deposited over the Gault that has since been eroded (Lings *et al.*, 1991). Along with the London Clay, it has the highest plasticity index, activity and swelling mineral content.

The clay appears grey below the recent depth of weathering, with closely spaced fissures. As with the Kimmeridge Clay, Wilkinson (2011) noted no strongly preferred particle orientation in his SEM analysis of the clay micro-fabric. The trench and rotary cores confirmed the observation by Butcher & Lord (1993) of two major fissure patterns with sub-horizontal and sub-vertical orientations, with spacings of about 20–50 mm, as can be seen in the split sample shown in Fig. 6(c). There were also frequent sections showing a fragmented soil matrix with fissures spaced every few millimetres. The fissure surfaces were similar to those of the Kimmeridge Clay, but their intensity was greater, classifying as medium to high (I4–I5) under the Vitone & Cotecchia (2011) scheme over much of the borehole and rising to very high intensity (I6) within the more heavily fractured sections. Butcher & Powell (1995) observed that brittleness and fissure intensity increase with depth over the range considered.

Figure 4 presents profiles with depth of laboratory and field undrained shear strength measurements and both geophysical G_{vh} and pressuremeter secant G_{hh} profiles. The seismic CPT data were taken in a sounding made close to trees. Desiccation and suction appears to have increased the G_{vh} values at the seismic CPT location down to about 6 m, as may be seen by comparison with the different traces obtained by downhole tests at another (non-vegetated) location by Butcher & Powell (1995). The S_u profiles for an un-vegetated location shown in Fig. 4 show moderate agreement



(a)
50 mm



(b)

50 mm



..... Fissures - - - Small fissure zone

(c)

Fig. 6. Photographs illustrating the meso-fabric of the soils: (a) trench cut in Oxford Clay; (b) split sample of Kimmeridge Clay (note: fissures have been highlighted); (c) split sample of Gault Clay (note: fissures have been highlighted, dashed zone indicates area of higher fissure intensity)

between traces from triaxial tests by Parry (1988) and self-boring pressuremeter (SBPM) tests by Butcher & Lord (1993). The latter's 38 mm diameter triaxial S_u test values are generally far lower.

APPARATUS AND PROCEDURES

Triaxial apparatus employed for the testing summarised in Table 2 included hydraulic Imperial College stress path cells for cell pressures up to 800 kPa and a 5 MPa high-pressure cell. Specimens were all tested with 2:1 height to diameter ratios. The high-pressure apparatus required 50 mm diameter specimens, while the other cells tested 38 or 100 mm diameter specimens. The research was not specifically designed to investigate the effect of the representative element volumes (REV's), although larger sizes were preferred for investigations of natural samples' strengths, aiming with the two fissured clays (Kimmeridge and Gault) to approach REV's as closely as was possible with the core available. The extended times required for drained stiffness probing tests on 100 mm diameter samples led to smaller sizes being adopted to study the (highly non-linear and anisotropic) stiffness behaviour. The shear strength data from the latter tests have been included to enable some commentary on the potential effects of specimen size. The reconstituted clay specimens all had 38 mm diameters.

The apparatus employed local strain measurement and bender elements, although the small strain stiffness behaviour will be discussed in later papers. Each apparatus had either linear variable differential transducer (LVDT) (Cuccovillo & Coop, 1997) or inclinometer (Jardine *et al.*, 1984) local axial strain measuring systems. Most apparatus were fitted with LVDT radial strain measuring devices and bender elements, either platen-mounted or with a lateral T-configuration similar to that of Pennington *et al.* (1997). Most employed mid-height pore pressure transducers.

Intact samples were carefully trimmed, maintaining a humid environment and covering exposed surfaces with cling-film to limit drying. Trimmings were mixed with water to form smooth pastes with liquidity indices of 1.3, from which reconstituted samples were formed and compressed in two sizes of consolidometer. For the Oxford and Gault Clays 230 mm diameter 'cakes' were prepared, from which the test specimens were hand trimmed. The more limited Kimmeridge Clay supply led to the use of 38 or 50 mm diameter floating ring consolidometers. Slurry samples were placed directly into standard oedometer rings at the start of the compression tests on reconstituted samples.

Testing started by applying a cell pressure greater than the in-situ effective stress to induce a positive pore pressure. Measurements on multiple samples of the initial mean effective stress allowed the in-situ p' and K_0 to be estimated, after making an allowance for the effect of deviator stress release and noting the in-situ vertical effective stress. Saturation to achieve B values exceeding 0.95 followed. Specimens were then compressed or swelled isotropically to the target p' . Most were sheared from isotropic effective stress conditions to establish shear strength envelopes. However, multiple shear tests were also conducted from nominally in-situ stress conditions, which were reached by applying drained constant p' paths leading to the target ($K_0 > 1$) q values. The in-situ stress states appeared to be close to passive failure and the constant p' paths were monitored and halted if the axial or volumetric strains reached either 0.5% or 1% respectively to minimise any premature destruction. Further details of the anisotropic re-consolidation procedures followed will again be given in companion papers on stiffness behaviour and shear strength anisotropy, where the recompression paths had a more significant influence. A

Table 2. Summary of undrained triaxial compression tests conducted on isotropically consolidated samples

Stiff clay type	Test	Sample type	Sample size: mm	p'_0 : kPa	q : kPa
Oxford Clay	R1	Reconstituted	38	600	0
	R2	Reconstituted	38	600	0
	R3	Reconstituted	38	50	0
	R4	Reconstituted	50	1000	0
	R5	Reconstituted	38	310	0
	N1	Natural B*	38	350	0
	N2	Natural B	38	500	0
	N3	Natural B	38	590	0
	N4	Natural B	38	650	0
	N5	Natural B	50	1300	0
Kimmeridge Clay	R1	Reconstituted	38	500	0
	R2	Reconstituted	38	100	0
	R3	Reconstituted	38	166	0
	N1	Natural R†	100	185	-95
	N2	Natural R	100	215	-170
	N3	Natural R	100	200	-105
	N4	Natural R	100	500	0
	N5	Natural R	38	1000	0
Gault Clay	R1	Reconstituted	38	500	0
	R2	Reconstituted	38	100	0
	R3	Reconstituted	38	166	0
	N1	Natural R	38	160	-83
	N2	Natural B	38	70	0
	N3	Natural R	100	125	-60
	N4	Natural B	100	142	-46
	N5	Natural R	100	250	0
	N6	Natural R	100	350	0
	N7	Natural R	38	1000	0
London Clay From Gasparre (2005)	R1	Reconstituted	38	317	0
	R2	Reconstituted	38	200	0
	R3	Reconstituted	38	30	0
	N1	Natural	50	3500	0
	N2	Natural	100	125	0
	N3	Natural	100	260	-86
	N4	Natural	38	275	0
	N5	Natural	38	1123	247

* B: Block sample.

† R: Rotary sample.

right cylinder area correction was generally applied during shearing, although the approach of Chandler (1966) was applied when a single shear plane could be identified post-peak. Depending on the type of test and type of specimen, the void ratios were calculated using the initial and final water contents, along with the initial bulk and dry unit weights. Generally two or three methods were applied and averages are reported; void ratios scattered around ± 0.02 for otherwise similar samples.

COMPRESSION BEHAVIOUR

Oedometer tests were conducted by standard staged loading on samples with 20 mm initial heights. For tests with maximum vertical stresses of less than about 17 MPa, a 50 mm diameter ring was used, but 38 mm diameter rings were adopted for higher pressure tests (up to 30 MPa). Typical compression trends for reconstituted and natural samples are presented in Figs 7(a) and 7(b) for each soil. Isotropic compression was also carried out on 38 mm diameter reconstituted samples in triaxial cells, applying a typical stress rate of 5 kPa/h. The latter exceeded those required for full dissipation of excess pore pressures and regular constant stress hold points were programmed to allow for full pore pressure dissipation and some creep (the vertical sections of the paths on Fig. 8). Fig. 8 shows

the intrinsic isotropic normal compression lines interpreted from the final points established from the latter 'hold' points.

Figures 7(a) and 7(b) concentrate on samples from around 10 m depth and only one test for the reconstituted soil and one for a natural sample are shown for each clay for clarity. The compression parameters summarised in Table 3 are based on all the data available and also on both the triaxial and oedometer data, ensuring that $\lambda^* = C_c^*/2.303$ for consistency and assuming parallel critical state and normal compression lines. It is not clear why the relative vertical positions of the oedometer intrinsic compression line (ICL) and triaxial critical state lines (CSLs) differ from those expected classically, as was also the case in the London Clay experiments reported by Gasparre *et al.* (2007). The values of C_c^* that may be derived from Fig. 7 may therefore vary slightly, but the discrepancies are less than 2%, with the exception of the London Clay for which it is about 5%.

The intrinsic normal compression parameters of most clays correlate with their plasticity indices or liquid limits (Burland, 1990). In the present tests the most plastic, Gault, clay presented as expected the uppermost ICL and the least plastic, Kimmeridge, the lowermost. However, the semi-logarithmic compression line gradients C_c^* or λ^* and swelling lines C_s^* or κ^* correlated less systematically with plasticity index.

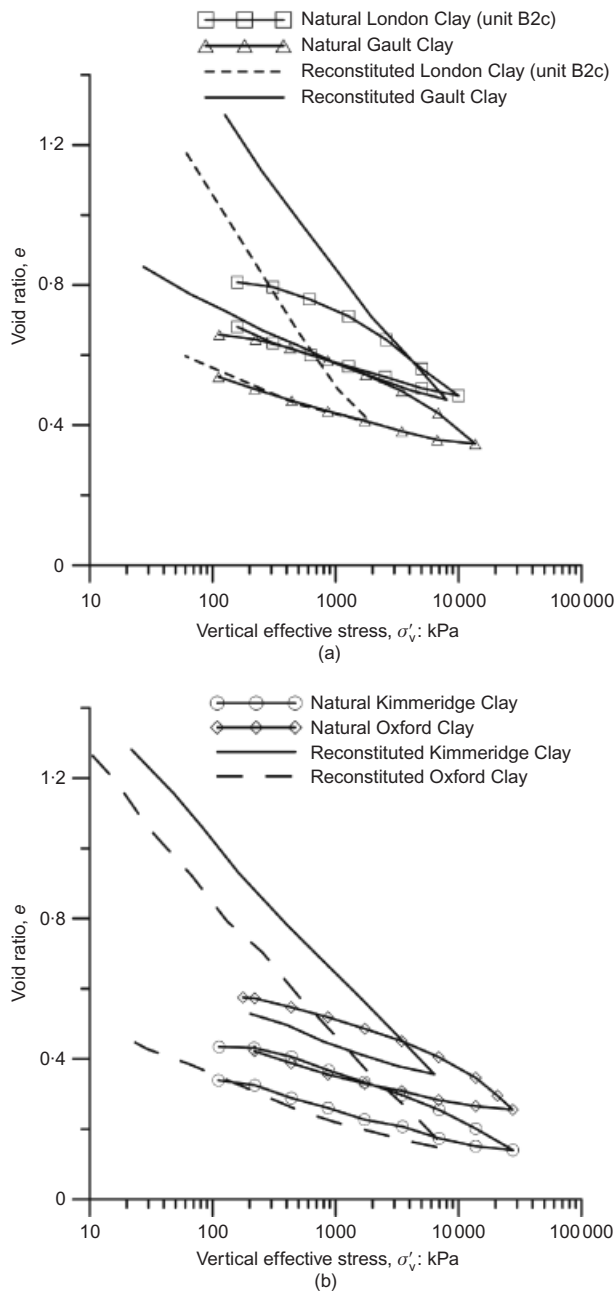


Fig. 7. Oedometer compression curves for all four soils, concentrating on samples from around 10 m depth with only one test per stiff clay shown for clarity (London Clay data from Gasparre *et al.* (2007)): (a) London Clay and Gault Clay; (b) Kimmeridge Clay and Oxford Clay

The natural samples' oedometer log-linear compression curves all curve gently downwards at higher pressures, as with London Clay (Gasparre *et al.*, 2007), giving no single clear yield point. The intact soils' 'normal' compression indices C_c , were assessed by fitting straight lines to the curves' final sections, although in each case the paths do not seem to have reached a constant value of C_c at even the highest stresses reached. The initial state reflects the in-situ void ratio, which is controlled predominantly by depth of burial, grading and plasticity. The Kimmeridge Clay has the lowest in-situ void ratio largely as a result of its lower plasticity; this is also reflected in its lower intact compressibility.

Values of C_s^* and C_s were derived by fitting straight lines to the swelling paths of the reconstituted and natural soils. The ratios of swell sensitivity C_s^*/C_s (Schmertmann, 1969) are low for all the soils, implying weak effects of structure,

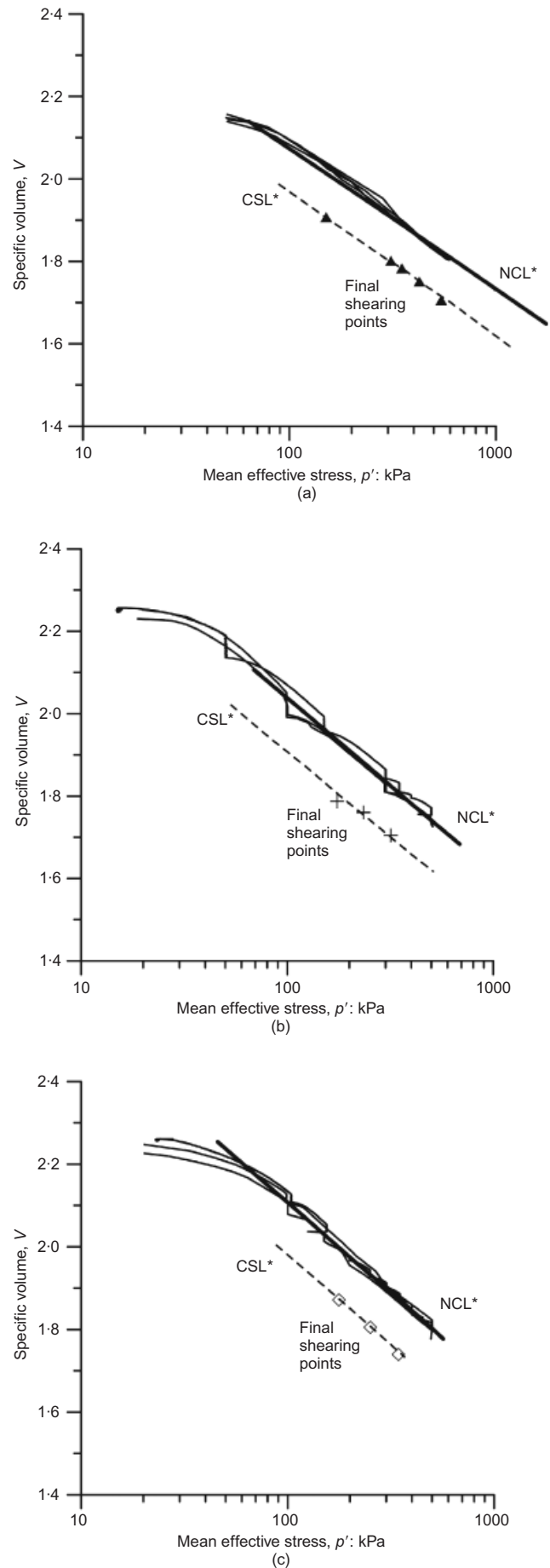


Fig. 8. Isotropic compression and critical state data for reconstituted samples of three of the studied soils: (a) Oxford Clay; (b) Kimmeridge Clay; (c) Gault Clay

Table 3. Summary of compression and strength parameters (London Clay data from Gasparre (2005))

Stiff clay	N^*	Γ^*	λ^*	κ^*	C_c^*	C_s^*	C_c	C_s	C_s^*/C_s	ϕ'_{cs}	ϕ'_r
Oxford Clay	2.85	2.77	0.169	0.036	0.390	0.104	0.216	0.076	1.37	24.9°	10°
Kimmeridge Clay	2.80	2.51	0.164	0.047	0.377	0.128	0.160	0.091	1.40	21.8°	7°
Gault Clay	2.99	2.85	0.215	0.040	0.496	0.168	0.221	0.095	1.77	24.8°	10°
London Clay (unit B2c)	2.95	2.85	0.168	0.069	0.522	0.144	0.254	0.106	1.36	21.3°	12°

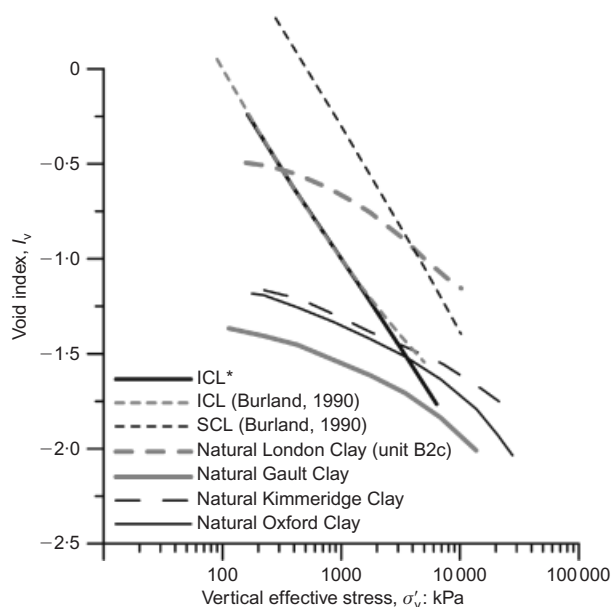
and the C_s values and C_s^* values tend to be higher in the two more plastic soils. The values of C_s^*/C_s in Table 3 have been calculated from the swelling lines (such as those in Fig. 7) established by unloading just after the initial steepening of the compression curves. It is possible that there had already been some destructuration at this point, but tests on Oxford Clay at stresses up to 27.6 MPa, which is well beyond the possible past maximum stress, indicated that the ratio did not change greatly with further increases of stress level, so the degree of 'structure' that the ratio represents was not easily broken down by compression.

In Fig. 9 the oedometer compression curves have been normalised using void index (Burland, 1990)

$$I_v = \frac{e - e_{100}^*}{e_{100}^* - e_{1000}^*} \quad (1)$$

where e is the current void ratio and e_{100}^* and e_{1000}^* are the void ratios on the intrinsic, ICL, at 100 and 1000 kPa. Only the compression paths are shown for clarity. Burland (1990) proposed that the ICL should be curved over an extended vertical effective stress range, and his line is shown in Fig. 9. A simplified log-linear interpretation has been made for the normalisation of the triaxial test data, but this is only applied over a smaller stress range and so the discrepancies would be small. Also shown is the single sedimentation compression line (SCL) proposed by Burland (1990) for intact normally consolidated clays of medium sensitivity. Apart from the Gault Clay, the general trend on Fig. 9 is for the initial I_v values to stack in terms of age and depths of burial, although the generic depths of burial given in Table 1 may not account for local variations.

Applying the void index and sensitivity framework reasoning to the present stiff clays, the logarithmic offsets

**Fig. 9. Normalised oedometer compression curves (London Clay data from Gasparre *et al.* (2007))**

between their (poorly defined) yield points and intrinsic compression curves (that is their 'oedometer sensitivities') tend to reduce with age and burial depth, as had been observed for other clays by Cotecchia & Chandler (2000). The evident trend for the degree to which the natural samples' paths cross the ICL to reduce with decreasing initial I_v was also seen in equivalent tests on several various units of the London Clay (Gasparre *et al.*, 2007). Gasparre & Coop (2008) note that this apparent reduction of the effects of structure conflicts with the trends for the deeper sediments to show 'stronger' structure under shear loading, and so it may be simply an artefact of the I_v normalisation. As discussed below, the shear data are affected by both micro-fabric structure and meso-fabric features. However, it is difficult to discern any effect of meso-fabric on the compression behaviour.

In their extension of the sensitivity framework for fissured clays Vitone & Cotecchia (2011) proposed that specimens with a high to very high fissuring intensity (I5–I6) would yield before reaching the ICL, while unfissured (intact) clays would yield outside the ICL. In both cases post-yield compression was expected to involve convergence towards the ICL. Here, most of the soils (which exhibited fissuring intensities ranging from moderate I4–I5 to absent in the Oxford clay) traced paths that extended to the right of the ICL. The soils tested from high I_v values tended to cross the SCL, while for the soil with the lowest I_v value, Gault Clay, it is not clear whether the curve for the natural soil would cross the ICL, especially if the curvature of Burland's (1990) ICL is extended to higher pressures. The gradual yielding behaviour of the four soils is quite similar, but their relative locations on the I_v plot seem simply to be a function of their initial values of I_v rather than any fundamental difference in their behaviour.

The Kimmeridge Clay shows the same feature as was previously noted for the London Clay by Gasparre *et al.* (2007) for the compression path of the natural soil to diverge from the ICL even at the highest pressures reached. This behaviour contrasts with that expected for clays with lower fissuring intensities within the sensitivity framework of Cotecchia & Chandler (2000), for which a clear yield point is expected defining the maximum ratio of stresses on the compression path of the natural specimen and on the ICL at the same void ratio. For the Oxford Clay, the compression curve diverges from the ICL up to about 10 MPa. Whether or not there is such a yield point and subsequent convergence at even higher pressures would depend on how its ICL curves at stresses greater than the 6.4 MPa reached in the test carried out on the reconstituted soil and also greater than the 4 MPa considered originally by Burland (1990) in defining the ICL. For the Gault Clay tests at several tens of MPa would be required even to determine if the ICL was ever crossed.

SHEARING IN TRIAXIAL COMPRESSION

Stress–strain data and shear strength envelopes

Stress–strain curves and effective stress paths are shown in Figs 10 and 11 from tests on both natural and reconsti-

tuted samples of each clay. In comparing natural and reconstituted specimens, it should be recalled that the latter are either normally compressed, or less heavily overconsolidated, than the high yield stress ratio (YSR) intact specimens.

The summary of shearing parameters for reconstituted samples given in Table 3 emphasises the potential brittleness of the clays and also indicates critical state and residual angles of shearing resistance, ϕ'_{cs} and ϕ'_r that do not correlate well with plasticity index. The least plastic Kimmeridge Clay has poorer shear strength parameters than the far more plastic Gault Clay. The critical states from the tests on reconstituted specimens are indicated on Fig. 8, and CSLs interpreted that are parallel to the isotropic compression lines.

The peak shear strength envelopes developed from the tests on natural sample tests given in Fig. 11 do not appear to correlate with geological age, burial depth or in-situ void ratio. Indeed, intact specimens (those unaffected by fissures) of the youngest, London, clay show a higher envelope than is the case for either Gault or Kimmeridge Clay. The intact (unfissured) Oxford specimens' peak shear strengths lie further above its critical state envelope than the other (fissured) stiff clays' natural sample peaks, leading to greater post-peak stress-strain brittleness for Oxford Clay (Fig. 10). Post-rupture strength analyses were made of all samples that failed on a single shear plane (Burland, 1990). As with London Clay (Gasparre *et al.*, 2007) the post-rupture and critical state ϕ' angles were similar in tests conducted around the in-situ effective stress levels, while the post-rupture angles tended to be smaller at higher stresses, perhaps due to some earlier particle re-orientation.

The key differences in the natural samples' peak shear strength envelopes are interpreted as being due to meso-fabric variations, in particular the influence of the fissuring in the Gault, Kimmeridge and London Clays. In each case the fissures were matt-surfaced with either one or two preferred orientations. They had not sustained sufficient prior shear displacements or particle orientation and could represent tensile fractures. The analysis by Gasparre *et al.* (2007) of the effective shear strengths mobilised on pre-existing fissures showed that they were broadly compatible with the intact (unfissured) samples' post-rupture or critical state strengths. The Kimmeridge and Gault Clays' fissures led to large reductions in their triaxial compression shear strengths, leading to much less brittle stress-strain behaviour than with the Oxford Clay (Fig. 10) and reducing their peak strengths in comparison with the Oxford Clay, which has no significant fissuring.

The intact rotary cores experienced contact with the water-based natural polymer mud during drilling. All softened material was carefully stripped from the samples as soon as they were recovered. The suctions measured on Kimmeridge clay core suctions fell close to the estimated in-situ mean effective stresses $p'_{in-situ}$ suggesting good sampling quality. However, the more intensively fissured Gault Clay cores showed abnormally low suctions that amounted to less than half $p'_{in-situ}$, indicating that they imbibed more water during sampling. Comparisons between the effective shear strengths of rotary and block samples of Gault Clay, taken from the same relatively shallow depths and re-consolidated to the same effective stresses, indicate that the suction losses had little or no permanent effect on the rotary cores' yielding behaviour, as demonstrated in Fig. 12.

The effect of sample size was investigated for London Clay by Marsland (1971) and for a variety of fissured clays by Vitone *et al.* (2009). Marsland found a continuous drop in mean strength with increasing sample size, although the differences between the mean specimen strength for a given sample size and that at the REV reduced to about 30% once

the ratio of specimen diameter to discontinuity spacing exceeded unity. Gasparre's London Clay samples showed low-to-medium-intensity (I3–I4) fissuring, implying an REV requirement that could not be met with her 100 mm diameter specimens; considerable scatter might therefore have been expected in her shear strength data. However, Gasparre *et al.* (2007) found a broadly bi-polar pattern, rather than random scatter. Two consistent envelopes could be defined: one for intact strengths (those uninfluenced by fissures) and one for specimens that contained fissures oriented such that they could contribute to the failure mechanism (Fig. 11(d)). While sample size effects and REV limits were not investigated comprehensively in the present study, tests were carried out on specimens with 38, 50 and 100 mm diameters; the upper limit being the Kimmeridge and Gault Clays' rotary core size.

No size effect was expected with the apparently unfissured Oxford Clay under triaxial compression and the limited data presented in Fig. 11(a) are compatible with this assumption. The tests on fissured Kimmeridge Clay plotted in Fig. 11(b) indicate no clear sample size effect. The 100 mm specimen results cluster around the chosen peak strength envelope (note that there are three tests at the in-situ stress level). The lack of scatter between 100 mm specimen tests conducted at the in-situ stress level suggest that these results may have approached REV values. The 38 mm diameter Kimmeridge specimens (whose diameter-to-fissure-spacing ratios approached unity) fell below the REV limits and could be expected to develop both more scatter and higher mean strengths than the 100 mm tests, although this was not evident in the limited population of tests completed. The Gault Clay triaxial tests also showed no clear trend with specimen size. Noting that fissuring in the Gault Clay was at least as intense as that in the Kimmeridge Clay, it is possible that even some 38 mm diameter Gault Clay specimens approached the REV requirement.

Normalised shearing data

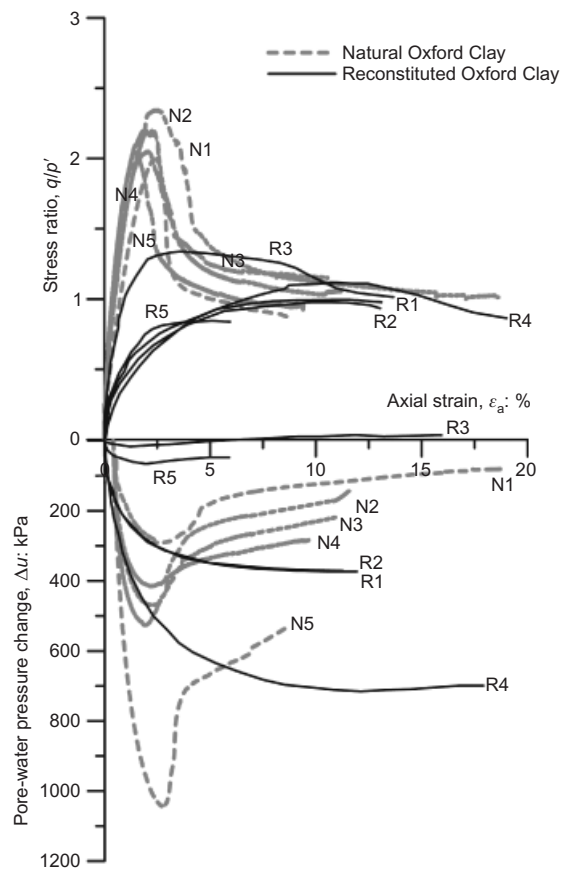
The shearing data have been normalised using equivalent pressures defined on the intrinsic isotropic normal compression lines, p_e^*

$$p_e^* = \exp \left(\frac{N^* - v}{\lambda^*} \right) \quad (2)$$

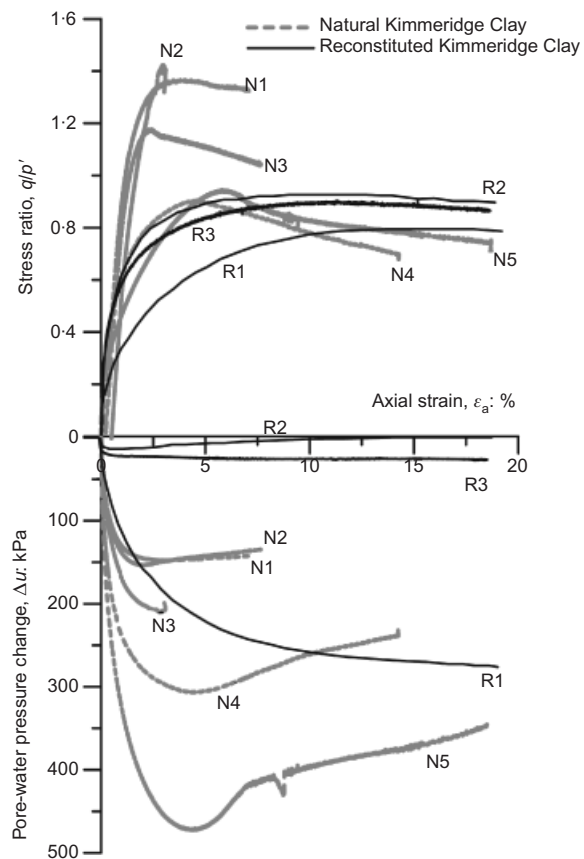
where v is the current specific volume. To remove the effects of the different angles of shearing resistance on the data, the q' axis has further been normalised by the critical state line gradient, M . The resulting stress paths for the reconstituted soils are shown in Fig. 13 along with the intrinsic local (isotropic) boundary surfaces (LBS*, see Zdravkovic & Jardine (2001)) that have been chosen to encompass the paths.

In Fig. 14 the normalised shearing data for intact specimens of each of the clays are compared to their LBS*. For the Oxford Clay there is a clear effect of structure with an intact boundary surface that falls far above the LBS*. Similar positive effects of the microstructure on the strength, in the absence of the effects of a fissured meso-fabric have been seen by, for example, Coop *et al.* (1995) and Cotecchia & Chandler (2000).

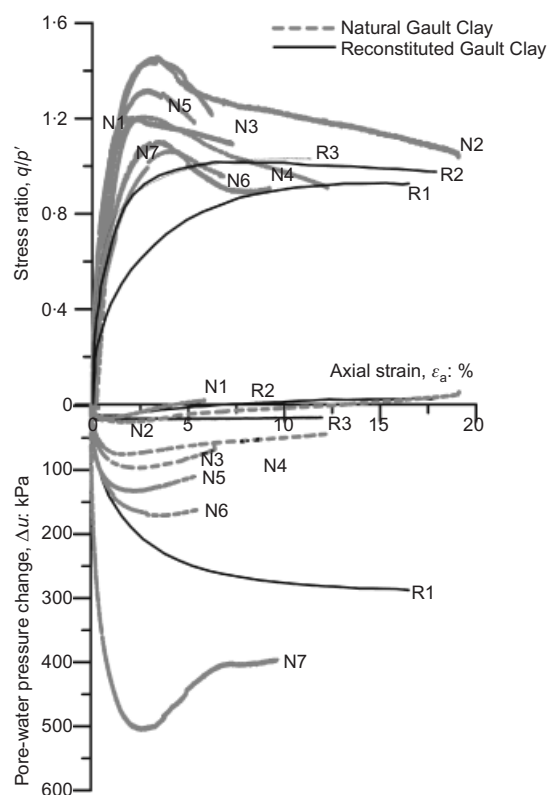
For the London Clay, Gasparre *et al.* (2007) found that the intact boundary surface again plots significantly above the LBS*, provided the specimen's strength is not affected by fissures, but below it when it was. This effect of widely spaced but favourably orientated fissures in the London Clay is distinctly different to that observed for the Kimmeridge and Gault clays for which a closer fissure spacing led to a



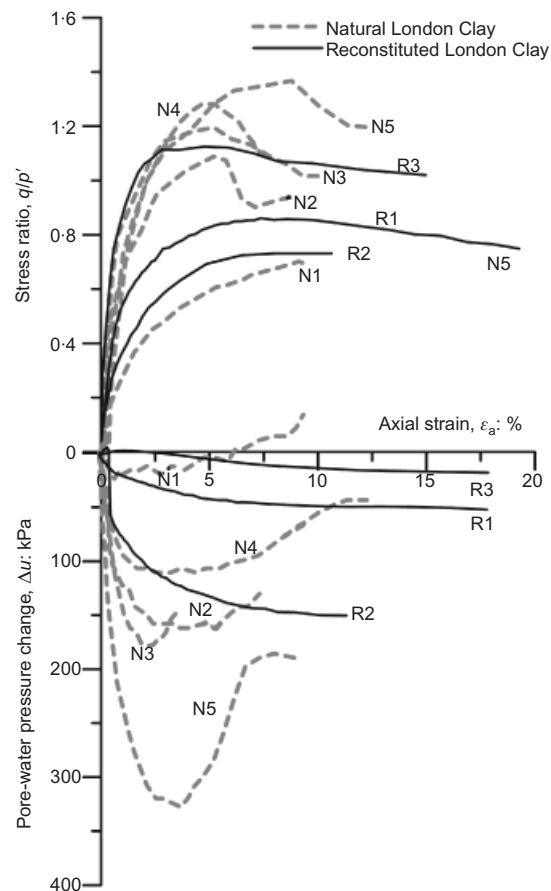
(a)



(b)



(c)



(d)

Fig. 10. Stress-strain behaviour for undrained shearing of the natural and reconstituted soils: (a) Oxford Clay; (b) Kimmeridge Clay; (c) Gault Clay; (d) London Clay (unit B2, redrawn from data in Gasparre *et al.* (2007))

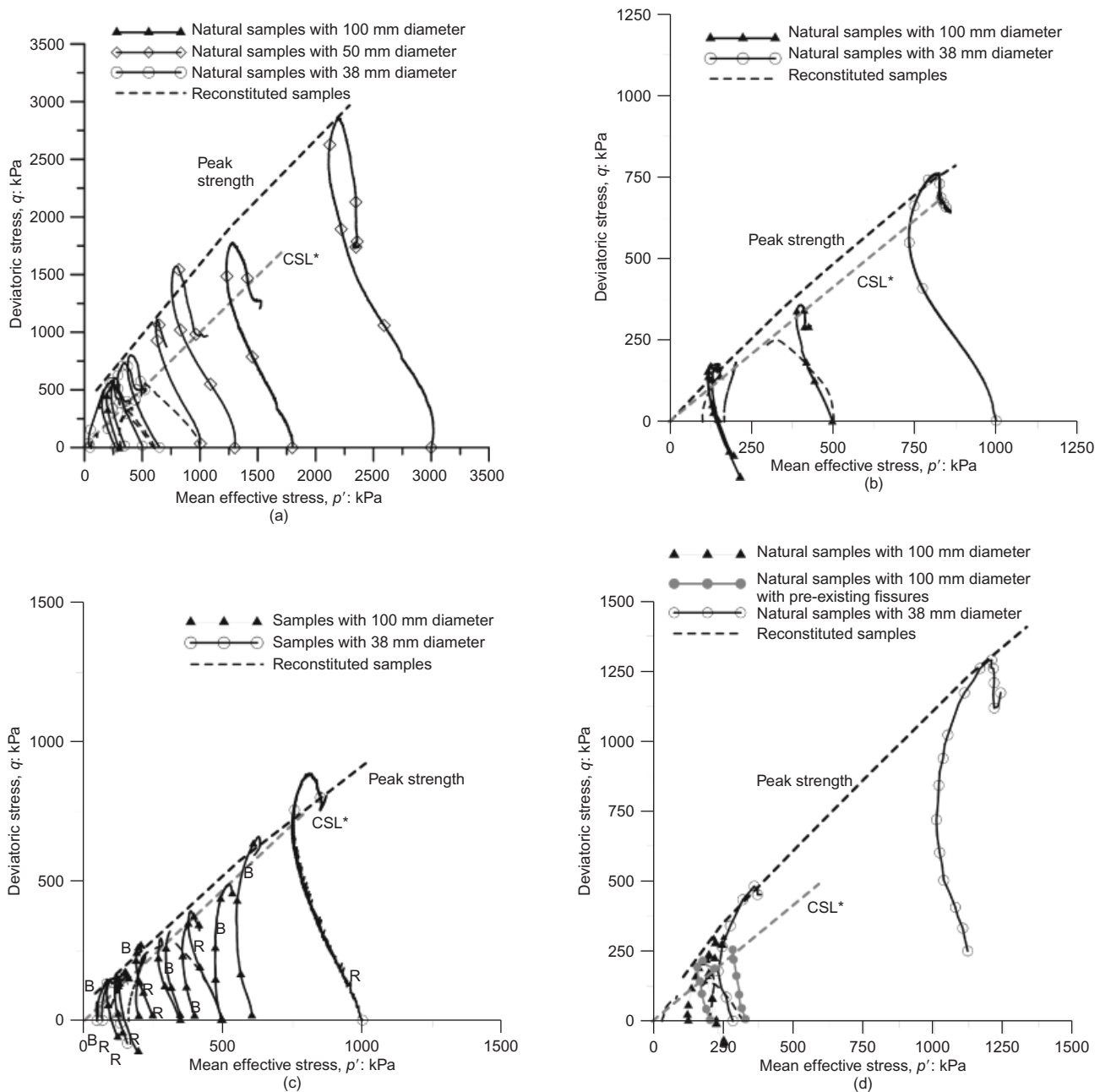


Fig. 11. Effective stress paths for intact and reconstituted samples of all four clays: (a) Oxford Clay; (b) Kimmeridge Clay; (c) Gault Clay; (d) London Clay (unit B2, redrawn from data in Gasparre *et al.* (2007))

more pseudo-continuum type of behaviour, including the fissures as part of the fabric. Since most specimens were tested at sizes relatively close to the REV, there is only one failure envelope for each. For these soils there is again a 'negative' effect of mesostructure on strength, as for the London Clay affected by fissures, with the intact boundary surfaces below the LBS*. Similar effects were noted for high fissuring intensity by Fearon & Coop (2002) and Vitone & Cotecchia (2011), although for their scaly clays the heavily sheared and slickensided nature of the scale surfaces meant that the peak strengths of the natural soil could be reduced significantly below the critical state strength of the reconstituted soil, whereas the effect of the matt surfaced fissures found in these soils is less pronounced and the peak strengths generally remain above ϕ'_{cs} . Strain localisation dominated the post-peak behaviour with a brittle progressive decay towards post-rupture strengths at similar stress ratios to the intrinsic critical state.

Comparison between the intact failure envelopes of the London Clay and Oxford Clay confirms a clear increase in strength with age and burial depth. However, this is not carried forward for the other two stiff clays, where meso-fabric features override any microstructural influences of age or burial depth; see Fig. 11. Constructing the wet side of the LBS would require testing with confining stresses in tens of MPa. A unique boundary surface could only be interpreted if the compression paths became either parallel to the intrinsic normal compression line or converged with it. As discussed above, there is little evidence of either trend from the oedometer tests on the Kimmeridge and London clays throughout the stress range tested, or for the Oxford Clay up to 10 MPa. Whether such trends could be detected at even higher pressures for the Oxford Clay or for the Gault Clay would depend largely on the degree of curvature of their ICLs at extremely high pressures, but at such stress levels the type of normalisation of shearing data that has been used

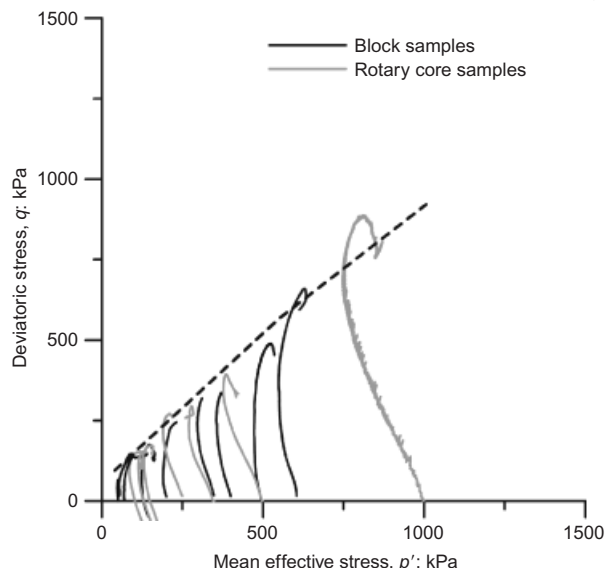


Fig. 12. Effects of sampling on the shear strength for Gault Clay

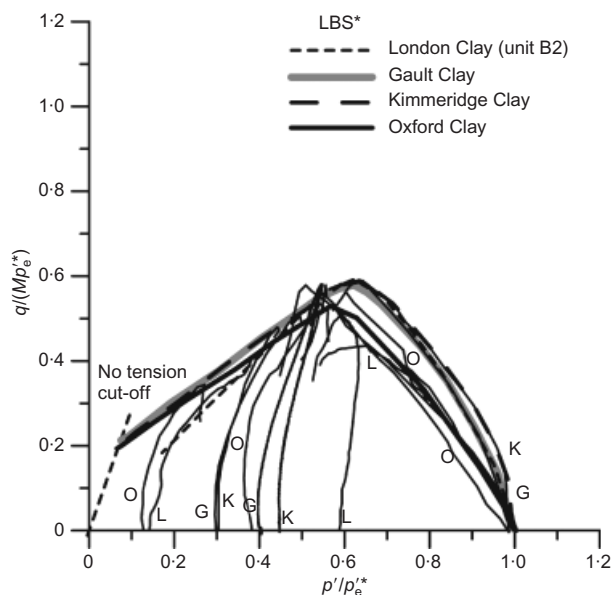


Fig. 13. Intrinsic state boundary surfaces (LBS*) for all four soils

here may in any case become invalid as the CSL, as well as the one-dimensional and isotropic ICLs, must all curve towards an asymptote at zero voids ratio ($v = 1$).

The gradual and progressive yielding seen in the compression data (Fig. 9) differs from the sharp yielding anticipated in the sensitivity framework of Cotecchia & Chandler (2000). The large volume strains developed prior to any possible stable surface emerging could be expected to alter the soil structure very significantly. Any boundary surface interpreted from such tests would therefore be incompatible with that obtained by shearing samples (after imposing minimal volume strains) on the dry side. Vitone & Cotecchia (2011) extended the sensitivity framework to consider clays with high to very high fissure intensity (I5–I6), locating boundary surfaces from both shearing and compression tests on natural samples that plotted inside the intrinsic state boundary surface. The less intensively fissured and un-sheared natural clays reported here (with I3–I5) showed a similar, but less pronounced ‘negative’ effect of mesostructure in shear tests conducted on the ‘dry side’ of critical state. However, as noted above, their isotropic or K_0 com-

pression paths could extend well beyond the intrinsic surfaces. Further shear testing at higher stress levels could reveal further information on the transition between these two styles of behaviour.

SUMMARY AND CONCLUSIONS

This paper considers four, medium plasticity, heavily over-consolidated stiff clays from the UK of Jurassic to Eocene origins with the aims of: (a) adding to the characterisation of strata that affect important UK infrastructure assets and (b) identifying any strong effects of geological age, or burial depth on structure and mechanical behaviour. The selected strata were deposited in broadly similar environments and their sampling locations and sampling depths were chosen to reduce potential local effects of post-depositional weathering, glacial or tree action and tectonic disturbance.

The geotechnical profiles of the sampling sites were outlined before reviewing the yielding behaviour seen in consistent suites of consolidation and triaxial compressive shear tests, considering high-quality natural and reconstituted samples. The stiff clays’ geology, microstructure and highly anisotropic non-linear stiffness and shear strength characteristics are outlined in parallel cited studies. The principal conclusions to emerge from this paper are given below.

- The sediments’ variations in composition and mineralogy were relatively minor. The effects of variable disturbance by erosion, glacial, periglacial or tree activity were reduced by selecting midland sites and concentrating on testing high-quality samples taken from around 10 m depths.
- The mechanical properties showed no clear correlation with their Eocene to Jurassic ages or variable burial depths.
- The most important controlling factor on the clays’ behaviour was their mesostructure.
- The Oxford Clay units tested had clear bedding features, but no fissures, and developed markedly higher triaxial compression shear strengths and post-peak brittleness; the peak triaxial shear strengths of natural samples of the three other stiff clays were strongly affected by their fissure intensity. All four soils were markedly brittle in shear.
- Differences were found between the behaviour of the clays and existing frameworks for structure in clays. Void index normalisation of the oedometer compression tests led to the potentially misleading suggestion that the effects of structure reduced with increasing age, which conflicted with the conclusion drawn from the shearing tests.
- A more elaborate micro- and meso-fabric framework appears necessary to describe the structure and behaviour of highly overconsolidated and aged geomaterials.

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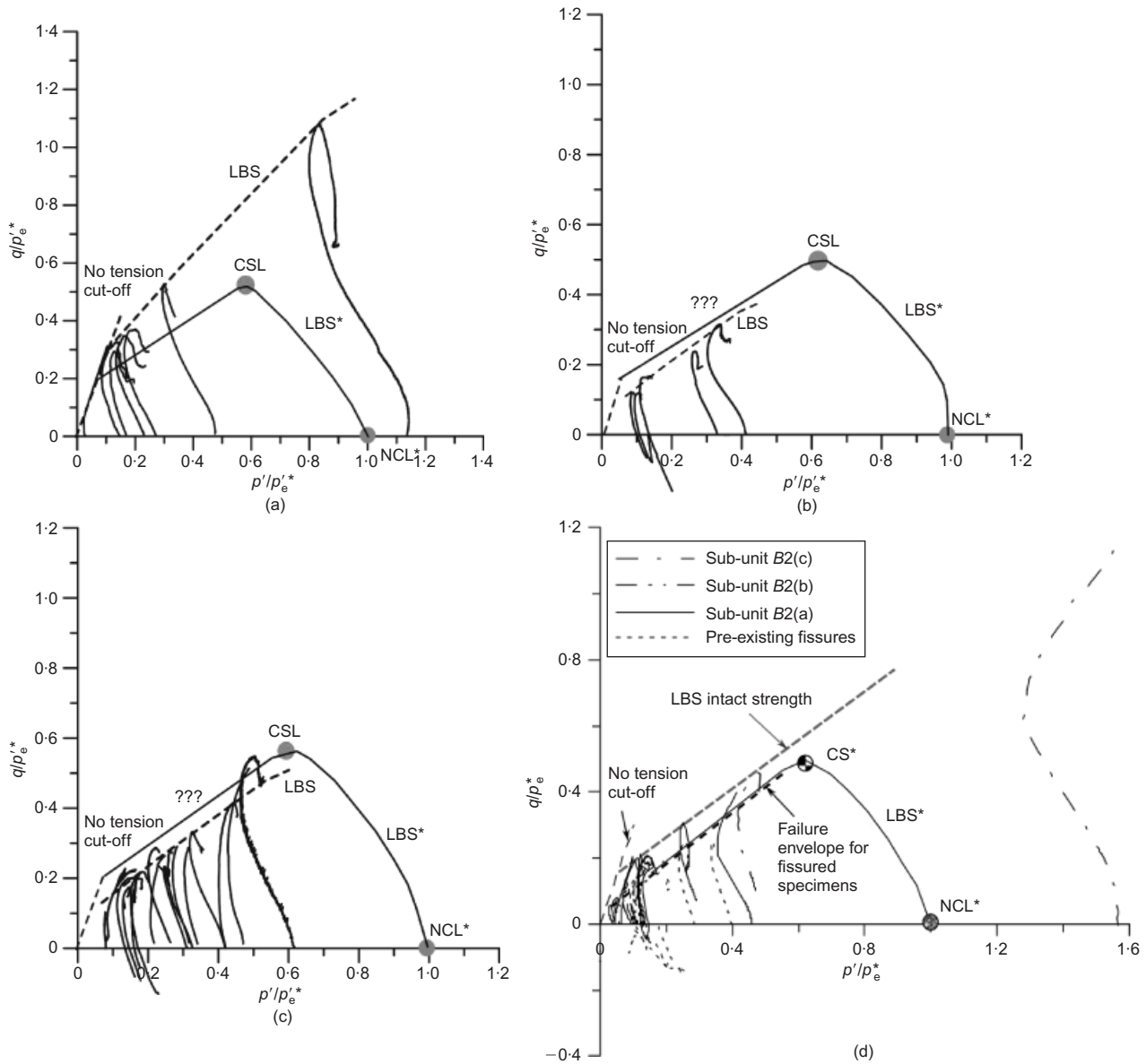


Fig. 14. Normalised stress paths for intact samples compared to LBS*: (a) Oxford Clay; (b) Kimmeridge Clay; (c) Gault Clay; (d) London Clay (redrawn from data in Gasparre *et al.* (2007))

their site investigation report at The Wixams, Bedford and Imperial College technicians Alain Bolsher, Steve Ackerly and Graham Keefe. They would also like to thank Dr S. Wilkinson and Professor F. Cotecchia for their invaluable help in preparing the paper.

NOTATION

B	coefficient of saturation
C_c	intact compression index
C_c^*	intrinsic compression index
C_s	intact swelling index
C_s^*	intrinsic swelling index
e	void ratio
e_{100}^*	void ratio on the intrinsic compression line for 100 kPa vertical pressure
e_{1000}^*	void ratio on the intrinsic compression line for 1000 kPa vertical pressure
f_s	sleeve friction
G_{hh}	shear modulus in horizontal plane
G_{hv}, G_{vh}	shear moduli in vertical plane
I_v	void index

M	ratio q/p' at critical state in compression
p'	mean effective stress
p_e^*	equivalent pressure, p' , on the isotropic intrinsic compression line at the same V
p_0'	initial mean effective stress
Q	deviatoric stress
q_c	cone resistance
S_s	swell sensitivity
S_u	undrained strength
w_c	water content
w_l	liquid limit
w_p	plastic limit
V	specific volume
γ	unit weight
γ_{bulk}	bulk unit weight
Δu	pore-water pressure change
ε_a	axial strain
κ^*	gradient of intrinsic swelling line in $V:\ln p'$ space
σ_v'	vertical effective stress
ϕ_{cs}'	critical state angle of shearing resistance
ϕ_r'	residual angle of shearing resistance
$*$	effective stress parameters applying to reconstituted clay

REFERENCES

- Arup & Partners (2007). *Factual report: Ground investigation at The Wixams, Bedford*. London, UK: Arup & Partners.
- Brosse, A. (2012). *Study of the anisotropy of three British mudrocks using a hollow cylinder apparatus*. PhD thesis, Imperial College London, UK.
- Burland, J. B. (1990). On the compressibility and shear strength of natural soils. *Géotechnique* **40**, No. 3, 329–378, <http://dx.doi.org/10.1680/geot.1990.40.3.329>.
- Burland, J. B., Longworth, T. I. & Moore, J. F. A. (1977). A study of ground movement and progressive failure caused by a deep excavation in Oxford Clay. *Géotechnique* **27**, No. 4, 557–591, <http://dx.doi.org/10.1680/geot.1977.27.4.557>.
- Butcher, A. & Lord, J. (1993). Engineering properties of the Gault Clay in and around Cambridge, UK. *Proceedings of international symposium on geotechnical engineering of hard soils-soft rocks*, Athens, Greece, pp. 405–416. Rotterdam, the Netherlands: Balkema.
- Butcher, A. P. & Powell, J. M. M. (1995). The effects of geological history on the dynamic stiffness in soils. *Proceedings of the 11th European conference on soil mechanics and foundation engineering*, Copenhagen, Denmark, vol. 1, pp. 1.27–1.36. Lyngby, Denmark: Danish Geotechnical Society.
- Cafaro, F. & Cotecchia, F. (2001). Structure degradation and changes in the mechanical behaviour of a stiff clay due to weathering. *Géotechnique* **51**, No. 5, 441–453, <http://dx.doi.org/10.1680/geot.2001.51.5.441>.
- Chandler, R. J. (1966). The measurement of residual strength in triaxial compression. *Géotechnique* **16**, No. 3, 181–186, <http://dx.doi.org/10.1680/geot.1966.16.3.181>.
- Chandler, R. J. (2000). Clay sediments in depositional basins: the geotechnical cycle. *Q. J. Engng Geol. Hydrogeol.* **33**, No. 1, 7–39.
- Coop, M. R. (1987). *The axial capacity of driven piles in clay*. DPhil thesis, University of Oxford, UK.
- Coop, M. R., Atkinson, J. H. & Taylor, R. N. (1995). Strength, yielding and stiffness in structured and unstructured soils. In *Proceedings of the 11th European conference on soil mechanics and foundation engineering*, Copenhagen, Denmark, pp. 1.55–1.62. Lyngby, Denmark: Danish Geotechnical Society.
- Cotecchia, F. & Chandler, R. J. (2000). A general framework for the mechanical behaviour of clay. *Géotechnique* **50**, No. 4, 431–447, <http://dx.doi.org/10.1680/geot.2000.50.4.431>.
- Cuccovillo, T. & Coop, M. R. (1997). The measurement of local axial strains in triaxial tests using LVDTs. *Géotechnique* **47**, No. 1, 167–171, <http://dx.doi.org/10.1680/geot.1997.47.1.167>.
- Cunliffe, D. (2010). *A study of the brittle behaviour of intact UK mudrocks in shear*. Master's thesis, Imperial College London, UK.
- Fearon, R. E. & Coop, M. R. (2002). The influence of landsliding on the behaviour of a structurally complex clay. *Q. J. Engng. Geol. Hydrogeol.* **35**, No. 1, 25–32.
- Gao, Y. (2009). *Investigation of the transitional behaviour of clays*. Master's thesis, Imperial College London, UK.
- Garrett, C. & Barnes, S. J. (1984). The design and performance of the Dunton Green retaining wall. *Géotechnique* **34**, No. 4, 533–548, <http://dx.doi.org/10.1680/geot.1984.34.4.533>.
- Gasparre, A. (2005). *Advanced laboratory characterisation of London clay*. PhD thesis, Imperial College London, UK.
- Gasparre, A. & Coop, M. R. (2008). The quantification of the effects of structure on the compression of a stiff clay. *Canadian Geotech. J.* **45**, No. 9, 1324–1334.
- Gasparre, A., Nishimura, S., Coop, M. R. & Jardine, R. J. (2007). The influence of structure on the behaviour of London Clay. *Géotechnique* **57**, No. 1, 19–31, <http://dx.doi.org/10.1680/geot.2007.57.1.19>.
- Green, P. F. (1989). Thermal and tectonic history of the East Midlands shelf (onshore UK) and surrounding regions assessed by apatite fission track analysis. *J. Geological Soc.* **146**, No. 5, 773–775.
- Green, P. F., Thompson, K. & Hudson, J. D. (2001). Recognition of tectonic events in undeformed regions: contrasting results from the Midland Platform and East Midland Shelf, Central England, London. *J. Geological Soc.* **158**, No. 1, 59–73.
- Hallam, A. (1975). *Jurassic environments*. Cambridge, UK: Cambridge University Press.
- Hight, D. W., Gasparre, A., Nishimura, S., Minh, N. A., Jardine, R. J. & Coop, M. R. (2007). The influence of structure on the behaviour of London Clay. *Géotechnique* **57**, No. 1, 3–18, <http://dx.doi.org/10.1680/geot.2007.57.1.3>.
- Hird, C. C. & Pierpoint, N. D. (1997). Stiffness determination and deformation analysis for a trial excavation in Oxford Clay. *Géotechnique* **47**, No. 3, 665–691, <http://dx.doi.org/10.1680/geot.1997.47.3.665>.
- Hosseini Kamal, R. (2012). *Experimental study of the geotechnical properties of UK mudrocks*. PhD thesis, Imperial College London, UK.
- Jackson, J. O. & Fookes, P. G. (1974). Relationship of the estimated former burial depth of Lower Oxford Clay to some soil properties. *Q. J. Engng Geol.* **7**, No. 2, 137–179.
- Jardine, R. J., Symes, M. J. & Burland, J. B. (1984). The measurement of soil stiffness in the triaxial apparatus. *Géotechnique* **34**, No. 3, 323–340, <http://dx.doi.org/10.1680/geot.1984.34.3.323>.
- Jeans, C. V., Wray, D. S., Merriman, R. J. & Fisher, M. J. (2000). Volcanic clays in Jurassic and Cretaceous strata of England and the North Sea Basin. *Clay Miner.* **35**, No. 1, 25–55.
- Lings, M., Nash, D., Ng, C. & Boyce, M. (1991). Observed behaviour of a deep excavation in Gault Clay: a preliminary appraisal. *Proceedings of the 10th European conference on soil mechanics and foundation engineering*, Florence, Italy, vol. 2, pp. 467–470. Rotterdam, the Netherlands: Balkema.
- Marsland, A. (1971). The shear strength of stiff fissured clays. In *Stress-strain behaviour of soils, the Roscoe memorial conference*, pp. 59–68. Cambridge, UK: Cambridge University Press.
- Moran, P. (2010). *Obtaining the intrinsic parameters of stiff clays to evaluate the effects of structure*. Master's thesis, Imperial College London, UK.
- Narayana, M. (2010). *A study of the residual shear strength characteristics of remoulded UK mudrocks*. Master's thesis, Imperial College London, UK.
- Ng, C. W. W. (1998). Observed performance of multipropped excavation in stiff clay. *J. Geotech. Geoenviron. Engng* **124**, No. 9, 889–905.
- Nishimura, S., Minh, N. A. & Jardine, R. J. (2007). Shear strength anisotropy of natural London Clay. *Géotechnique* **57**, No. 1, 49–62, <http://dx.doi.org/10.1680/geot.2007.57.1.49>.
- Nygard, R., Gutierrez, M., Gautam, R. & Hoeg, K. (2004). Compaction behaviour of argillaceous sediments as function of diagenesis. *Marine and Petroleum Geol.* **21**, No. 3, 349–362.
- Nygard, R., Gutierrez, M., Bratli, R. K. & Hoeg, K. (2006). Brittle-ductile transition, shear failure and leakage in shales and mudrocks. *Marine and Petroleum Geol.* **23**, No. 2, 201–212.
- Parry, R. H. G. (1972). Some properties of heavily overconsolidated Oxford Clay at a site near Bedford. *Géotechnique* **22**, No. 3, 485–507, <http://dx.doi.org/10.1680/geot.1972.22.3.485>.
- Parry, R. (1988). Short-term slipping of a shallow excavation in Gault clay. *Proc. Instn Civ. Engrs Part 1 – Design and Construction* **84**, No. 2, 337–353.
- Pennington, D. S., Nash, D. F. T. & Lings, M. L. (1997). Anisotropy of G_0 shear stiffness in Gault clay. *Géotechnique* **47**, No. 3, 391–398, <http://dx.doi.org/10.1680/geot.1997.47.3.391>.
- Pierpoint, N. D. (1996). *The prediction and back analysis of excavation behaviour in Oxford Clay*. PhD thesis, University of Sheffield, UK.
- Schmertmann, J. H. (1969). Swell sensitivity. *Géotechnique* **19**, No. 4, 530–533, <http://dx.doi.org/10.1680/geot.1969.19.4.530>.
- Vitone, C. & Cotecchia, F. (2011). The influence of intense fissuring on the mechanical behaviour of clays. *Géotechnique* **61**, No. 12, 1003–1018, <http://dx.doi.org/10.1680/geot.9.P005>.
- Vitone, C., Cotecchia, F., Desrues, J. & Viggiani, G. (2009). An approach to the interpretation of the mechanical behaviour of intensely fissured clays. *Soils Found.* **49**, No. 3, 355–368.
- Wilkinson, S. (2011). *The microstructure of UK mudrocks*. PhD thesis, Imperial College London, UK.
- Zdravkovic, L. & Jardine, R. J. (2001). The effect on anisotropy of rotating the principal stress axes during consolidation. *Géotechnique* **51**, No. 1, 69–83, <http://dx.doi.org/10.1680/geot.2001.51.1.69>.