New risk assessment approach to assessing interaction of trees with structures

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Abstract

Ground and structural responses to the presence of trees can be detrimental if their probable interactions are not duly considered. For example, trees growing in swelling/shrinking clays can lead to damage of buildings in the close proximity. Very often the problem is not identified until appreciable damage has occurred. Guidelines relating to acceptable distances of trees to buildings are available but these usually require specialist knowledge of trees. Current practices concerning tree protection and the associated subject of assessing potential structural damage from trees are reviewed and shortcomings identified. Following this, two new risk rating systems developed to facilitate the assessment of likelihood of damage to structures are described and explained. One covers damage occurring from the direct growth of tree roots and the other settlement/heave above shrinking/swelling clays. Both systems are intended to provide a basis for identifying situations where advice by tree specialists should be sought, ideally in advance of damage occurring. The former was tested by field surveys at several locations in and around London and the latter by well documented case studies. Both demonstrated that the systems have broad applications. This led to the development of a set of recommendations, in the form of an index chart, for when planting trees close to structures.

Keywords
Geotechnical Engineering; Building, Structures & Design; Foundations.

List of notation

H_1 hazard score that indicates the adequacy of space for air, water and food
E_H exposure factor
D_H depth factor
C_1 consequence score that indicates the likely level of damage
S_C structural factor
P_C proximity factor
R_1 risk score for assessing likelihood of physical damage due to unfavourable root growth
S_H species factor
HP_{HC} height-proximity factor
R_2 risk score for assessing likelihood of physical damage due to ground settlement in shrinkable soils

1. Introduction

Interaction of trees with man-made structures is complex and may occur as soon as new trees start growing in the close proximity to existing man-made structures or vice versa. Long-term interaction may involve fluctuations of soil moisture, causing shrinkage or swelling of soil and ground settlement or heave; or tree roots intruding into man-made structures, causing cracks or irreparable structural damage; or man-made structures bringing about changes to the environment and soil conditions that lead to a gradual deterioration of tree health (Biddle, 1998).

Ground and structural responses to the presence of trees can be detrimental if their probable interactions are not duly considered. The problem is very often not identified until appreciable damage has occurred. Laws, regulations and guidelines are in place but these usually require specialist knowledge of trees. This paper reviews current practices concerning the protection of trees and mitigation of potential structural damage from trees, identifying shortcomings. Following this, two new risk rating systems developed to facilitate the assessment of likelihood of damage to structures are described and explained. This led to the development of a set of recommendations for when planting trees close to structures in the form of an index chart that is designed so that it can be used by members of the general public.

2. Current practices concerning tree protection and mitigation of structural damage from trees

Statutory laws and regulations have been developed and implemented in the United Kingdom (UK) to protect existing trees against damage of all kinds, and to regulate planting of new trees in relation to urban development. An important aspect of law given in the UK is the Town and Country Planning Act (OPSI, 1990) requires that, except in certain circumstances, "*no work shall be carried out which will affect trees over a certain size which are situated in conservation areas*". Six weeks' notice of intent has to be given to the local authority in advance before the work is carried out. Having considered the case, the local authority may issue a tree preservation order, under this Act, to protect the trees. Should there be any breach of the planning conditions relating to tree protection in the course of work, the local authority can serve an "*enforcement notice*"; and if necessary this can be followed by a "*stop notice*". The Forestry Act (OPSI, 1967) requires a felling licence to be obtained for felling of trees with diameter exceeding a certain value or if the aggregate cubic content of the trees so felled exceeds a specified amount. There are other auxiliary laws and regulations to protect species of flora and fauna (e.g. The Conservation (Natural Habitats etc.) Regulations: OPSI, 1994) and to protect man-made structures from damage caused by tree growth relating in particular to ground movement due to swelling, shrinkage or freezing of the subsoil (Building Regulation: OPSI, 2000). Should any of these forms of legal protection be breached, substantial penalties can be imposed. Apart from statutory provisions, undesirable interaction of trees with man-made structures affecting third parties can result in disputes concerning damage or nuisances caused, giving rise to civil claims and litigation under common law.

While they set out a legal framework for protection of trees and structures, the statutory laws and regulations usually do not elaborate on how the legal requirements can be complied with. With a lack of knowledge and legal support, practitioners in industry therefore often find themselves in a state of confusion as to how to deal with trees and man-made structures in a professional and legitimate manner. In light of this, guidelines (e.g. BSI, 2005; ODPM, 2005; NJUG, 2007; NHBC, 2008) have been published in recent years by the joint efforts of various stakeholders, usually project clients, landscape planners, arborists, engineers and contractors, to assist those involved in this field to form reasonable and informed decisions.

3. Shortcomings in common practices

Practitioners in this field may study the laws and regulations related to tree damage and protection and make use of the references and guidelines to assess if physical damage to man-made structures is likely to occur. The references and guidelines, while useful to professionals and specialists working in this area, are however not presented in layman's terms and non-specialist individuals, e.g. landowners or estate management agents, might find them difficult to understand and follow.

The knowledge of trees and their interaction with man-made structures is at present very restrictive. While many trees are located in public places managed by local authorities, there are still large proportions falling within the boundary of private lots owned by management agencies or individual members of the general public. They are legally liable for damage or injury caused by trees on their land

and have a duty of care to prevent any foreseeable harm posed to third parties. They should take reasonable steps to assess trees within their land regularly and to manage them in a manner such that potential tree risk likely to cause harm or injury is kept at a reasonably practicable level. However, this liability can, at the present time, at best be discharged by seeking professional advice from any of the qualified tree management agencies available to the public. This is often easier said than done for an average household, for two reasons. First, the scale of work involved may be too small for a tree management agency to reap benefits of economy of scale. It would likely to be difficult to obtain a favourable agreement from a qualified tree management agency to take care of only a handful of trees. Second, the cost incurred in a single investigation might not be reasonably affordable.

To bridge this gap, information in relation to diagnosis of interaction of trees with man-made structures should indeed be more accessible to the general public. The potential capability of the general public to contribute to a pleasant environment for the co-existence of trees and human beings should indeed not be underestimated. As Biddle (1998) commented, it is only with a wide spread of knowledge across different levels in the hierarchy of the population that the prevention of damage from occurring in the first place is possible.

4. Proposed risk rating systems

4.1 Physical damage due to unfavourable root growth

4.1.1 Tree/structure survey form

Based on the review, together with field observations from a number of locations in London (Figure 1), Windsor and Cambridge, UK, a tree/structure survey form (Appendix 1) is developed to collate key tree/structure information for assessing the likelihood of tree roots causing physical damage to nearby man-made structures. The key information includes: maximum tree height at mature age; maximum canopy diameter at mature age; maximum trunk diameter at 1.5 m above ground level at mature age; planting conditions, i.e. in pits/trenches with soil exposed to air or in pits/trenches with soil covered by hard surface; area of soil exposed; extent of hard surface coverage; depth of pits/trenches; base clearance to structure(s); and physiological condition.

Definition of the terms above and guidelines for data collection are given at the back of the tree/structure survey form itself (Appendix 1, Part 1, Sheets 3 & 4). Within the form a deliberate intention is to include only key factual information that can be easily understood and managed by a non-specialist individual. Equally, estimation of the dimensions mentioned above 'at mature age' only needs to be approximate: the groupings given in the form (Sheet 1) have intentionally been set to be very broad. Identification of tree species, which is normally an essential item in tree surveys undertaken by specialist arborists, is therefore an optional item in this circumstance. The approach adopted here assumes that the material features of a tree, such as its physical dimensions, planting conditions and proximity to structures, are the fundamental causal factors resulting in physical damage to man-made structures.

Four ranges of values across the possible bandwidth of data for each of the items are adopted in Sheet 1 of the form (Appendix 1, Part 1). The idea of collecting exact and absolute figures for each of the items is in this case not necessary (and difficult to quantify realistically). While it is good practice to keep a survey form as informative as possible, one has to bear in mind the limited knowledge and technical skills usually possessed by an average individual as compared with specialist arborists: the purpose of the exercise is to provide a preliminary screening.

4.1.2 Risk rating system

The tree information collated is then analysed via a risk rating system. The rating system comprises three major parts: a hazard model; a consequence model; and a risk model.

(a) Hazard model

The hazard model examines the adequacy of surface area and depth of breathable soil for a given tree to acquire air, water and food. The adequacy of this space directly affects proper root growth. Unfavourable root growth would be highly likely to result in physical damage to nearby man-made structures.

Trees are first categorized into four hazard groups according to their maximum canopy diameter and trunk diameter at mature height (Appendix 1, Part 2, Item A, Sheet 1). Tree growth is a complex subject. There is no definite rule governing the growth behaviour of trees and the final outcome, such as root shape and extent, is always unpredictable, even for the same tree species, unless they are grown under strictly controlled conditions. It is however believed that trees with comparable physical dimensions would have similar demands for space that is necessary both for growth and food collection. As such, grouping trees of comparable sizes for analysis in this case is assumed to be both sensible and reasonable, and canopy diameter and trunk diameter are two basic tree features that are the most representative of the physical tree dimensions.

Each tree is then rated by two factors, the exposure factor (E_H) and the depth factor (D_H), according to the hazard group it belongs to. The exposure factor accounts for the adequacy of an exposed soil area for air, water and food while the depth factor looks into the adequacy of the soil depth for proper root growth.

Each hazard component, i.e. E_H and D_H, is assessed via a 4×4 hazard matrix (Appendix 1, Part 2, Items B & C, Sheet 1). A sliding scale of four ratings, i.e. 1, 3, 6, 10, is adopted to represent the scale of significance. "1" represents the most satisfactory condition while "10" the least. A logarithmic scale is chosen to give a sufficiently wide range of risk score so that a realistic classification of cases is possible. A summation of the two factors gives the hazard score (H_1) for a given tree that indicates the adequacy of space for air, water and food:

$$H_1 = E_H + D_H \qquad \text{(Eq. 1)}$$

(b) Consequence model

The consequence model examines the likelihood of damage that a given hazard scenario, i.e. unfavourable root growth in this case, may bring to nearby man-made structures.

Given the applied pressures from tree roots, the impact on man-made structures of different forms may vary. Light structures, or those with negligible lateral restraint, e.g. hard surfacing or paving, are the most vulnerable to displacement and damage. A more substantial structure or one with lateral restraint is more likely to resist the forces that tree roots can usually generate. The likely resistance as provided by various forms of structures should therefore be duly taken into account in the consequence model.

Biddle (1998) suggests that the closer the roots are to the tree trunk, the greater the exerting pressure they possess. As such, man-made structures that are close to the tree trunk would be subject to greater risk of physical damage caused by growing tree roots. The proximity of man-made structures to the tree trunk is therefore another crucial factor to be considered in the consequence model.

The likely resistance of structures of different forms to a given applied pressure from tree roots and their proximity to the tree trunk is expressed by the structural factor (S_C) and the proximity factor (P_C) respectively. The former is assessed via a 4×1 consequence matrix while the latter via a 4×4 consequence matrix (Appendix 1, Part 2, Items D & E, Sheet 2). The same sliding scale of four ratings, i.e. 1, 3, 6, 10, is adopted to represent the scale of significance. A summation of the two factors gives the consequence score (C_1) for a given tree that indicates the likely level of damage caused by the corresponding hazard scenario:

$$C_1 = S_C + P_C \qquad \text{(Eq. 2)}$$

(c) Risk model

The risk model combines the hazard model and the consequence model to calculate the risk of a given tree causing possible physical damage to nearby man-made structures.

Assuming that the two hazard components and the two consequence components have equal weighting, the risk score (R_1) is the mathematical sum of the four components:

$$R_1 = H_1 + C_1 = (E_H + D_H) + (S_C + P_C) \qquad \text{(Eq. 3)}$$

The risk score so obtained has a minimum value of 4 (i.e. exposure factor, E_H = 1; depth factor, D_H = 1; structural factor, S_C = 1; proximity factor, P_C = 1) and a maximum value of 40 (i.e. E_H = 10; D_H = 10; S_C = 10; P_C = 10). It can be readily deduced that the lower the score, the less likely there will be an adverse interaction of trees with man-made structures. For screening purpose, four risk classifications that specify the relative likelihood of adverse interaction of trees with man-made structures are defined (Table 1 and Appendix 1, Part 2, Item G, Sheet 3).

4.2 Physical damage due to ground settlement in shrinkable soils

Cutler & Richardson (1989) document abundant data collected in the Kew Tree Root Survey (1971-79) and supplementary information concerning the spread of roots from trees reported as having caused or contributed to damage to buildings. This provides a valuable source of information for a systematic diagnosis of the interaction of different tree species, particularly in clay soils, with buildings.

The tree data collated are summarized into a series of standardized, detailed and concise tree entries for 16 different tree species, which are found to be commonly associated with building damage in clay soils in the UK. The authors, however, did not synthesize various essential data to see if a global trend of behaviour can be observed, in particular, for the correlation of likelihood of damage with tree height and distance to the point of concern. An understanding of this relationship would help to develop a risk assessment framework for assessing the likelihood of hazard and damage a given tree may bring to a building. Therefore the opportunity is taken here to investigate this proposition.

(a) Hazard model

From the data collated by Cutler & Richardson (1989), it can be deduced that tree species and tree height are two key hazard elements for trees in shrinkable clay soils, which may result in building damage. On this basis, the hazard model given in Appendix 2 is therefore proposed, involving a species factor and a height factor (in reality this is simply the tree height as defined in Appendix 1, Part 1, Sheet 3).

The hazard module for determining the species factor (S_H) is formulated based on the observations discussed in Cutler & Richardson (1989). Cutler & Richardson (1989) identify tree species for which the proportion of trees reported to have caused damage to buildings is high and those for which the proportion is low. Because of this coarse classification, only a hazard module of two ratings can be developed, i.e. "1" for tree species with a high proportion of trees reported to have caused damage to buildings and "0" for those with a low proportion.

The hazard module for determining the height factor is combined with the consequence module for determining the proximity factor to give a combined height-proximity factor (HP_{HC}) because the two factors are strongly interrelated, as discussed below in the section on the consequence model.

(b) Consequence model

The same considerations taken in developing the consequence model in Section 4.1.2 apply here as well (Appendix 1, Part 2, Sheet 2). The likely resistance of structures of different forms to a given amount of ground subsidence and their proximity to the tree trunk are two key causal factors leading to building damage and are expressed using the structural factor and the proximity factor respectively.

The same module for determining the structural factor (S_C) as explained in Section 4.1.2(b) is used. A separate consequence matrix for determining the proximity factor is however required as a different nature of consequence is being examined (i.e. shrinkable clay soils causing ground subsidence and consequently structural damage, which is different from tree roots causing physical damage to structures). The data collated by Cutler & Richardson (1989) are plotted in the form of maximum distance to the point of damage versus maximum tree height in Figure 2. Sixteen species of tree are considered and the maximum height refers to the maximum height to which that tree type can grow, for example the two species with the greatest maximum height are poplar and plane at 28 m and 30 m respectively. Cutler and Richardson collated data for each species in the form of the percentage of cases where damage occurred versus distance to the point of damage. These percentages can be cumulated and related to distance to the point of damage as shown in Table 2 for the poplar and plane cases. In Figure 2 for each species the distance to the point of damage for four cumulative percentages are plotted (50%, 75%, 90% & 100%). In the case of the poplar tree, for example, no damage was observed when the tree was more than 30 m

from the structure (100%); only 10% of cases of damage were observed when the tree was more than 20 m from the point of interest (90%) and so on. The lowest cumulative percentage considered and shown is 50% as beyond this level the distances are frequently relatively small and so there is greater uncertainty in accurately assessing whether the tree might cause damage. Figure 2 shows a clear correlation of likelihood of damage to buildings with maximum tree height and the distance to the point of damage. It is clear that the likelihood of damage increases with tree height (as shown by an increasing influence distance as tree height increases) but decreases with increasing distance to the point of concern (as indicated by a reducing percentage of cases as distance to damage increases). Because of this correlation, it is considered reasonable to combine the consequence matrix for determining the proximity factor, P_C, with the hazard module for determining the height factor to give the combined height-proximity factor (HP_{HC}). The ratings are defined by the four bands of likelihood of damage as shown in Figure 3, which indicate the scale of significance.

In view of the above finding, the following comments by Cutler & Richardson (1989) might be reconsidered: "*It is less clear how height and potential for root damage to buildings are related. For example, vigorous, semi-mature trees with a very active root system may be drawing on water from the soil more effectively and in greater quantities than taller, old trees well past their prime.*". The correlation is certainly representative as it is derived based on the data collated from several thousand tree samples in shrinkable clay soils which are commonly associated with building damage. It is therefore a good reference for assessing likelihood of damage to buildings for trees at their mature age. Having this as a basis, an adjustment module may be included to take into account the fact that demand for water may vary with tree age. By applying risk management techniques and principles, height and potential for root damage to buildings can certainly be related.

(c) Risk model

The risk model combines the hazard model and the consequence model to calculate the risk of a given tree in shrinkable clay soils causing possible damage to nearby man-made structures due to ground subsidence.

Assuming that the hazard and consequence components have equal weighting, the risk score (R_2) is equal to:

$$R_2 = S_H \times (S_c + HP_{HC}) \qquad \text{(Eq. 4)}$$

The risk score so obtained has a minimum value of 0 (i.e. species factor, $S_H = 0$) and a maximum value of 20 (i.e. $S_H = 1$; structural factor, $S_C = 10$; height-proximity factor, $HP_{HC} = 10$). Similarly, the lower the score, the less likely there will be an adverse interaction of trees with man-made structures. As in Section 4.1(c), four risk classifications that specify the relative likelihood of adverse interaction of trees with man-made structures are defined (Table 3 and Appendix 2, Part 1, Item E, Sheet 2).

5. Calibration

5.1 Physical damage due to unfavourable root growth

As each problem has its own particular characteristics, it is prudent to calibrate the models so as to test out the assumptions made, in particular, in this case, the reasonableness of the sliding scale and the risk classifications adopted. The calibration is done in two ways: (a) field calibration and (b) calibration with the BRE category of damage (Burland, 1995).

5.1.1 Field calibration

The tree/structure survey form and the hazard, consequence and risk models were put to test in the field. A total of 30 trees randomly selected from a number of places in London, Windsor and Cambridge, UK were surveyed in July 2009. The locations of the field work in London are shown in Figure 1. Only one sample each at Windsor and Cambridge was taken and therefore, their locations are not indicated in Figure 1. The following summarizes the key tree information.

(a) No trees belong to Group 1, 15 trees (50%) to Group 2, 11 trees (37%) to Group 3 and 4 trees (13%) to Group 4 (see Appendix 1, Part 2, Sheet 1 for quantification of groups).

(b) 25 trees (83%) have soil cover while 5 trees (17%) are covered by hard surface. Their distribution within each tree group is shown in Table 4.

(c) 10 trees (33%) affect both pavement and man-made structures, 12 trees (40%) affect pavement only while 8 trees (27%) affect man-made structures only. Their distribution within each tree group is shown in Table 4.

Key observations from the field calibration are discussed below.

(a) Man-made structure - Pavement

- There are in total 22 trees affecting pavements.
- Among the 11 nos. of trees with obvious destructive behaviour, i.e. with tree roots causing physical damage to pavements, 100% of them have risk score ranging between 20 and 40. All fall into the risk class of "LIKELY" or "VERY LIKELY", which means adverse interaction of trees with man-made structures is "likely" and "very likely". The risk scores match well with the field observations.
- Among the 11 nos. of trees without obvious destructive behaviour, i.e. tree roots causing physical damage to pavements have not been observed, about 90% of them (i.e. 10 nos.) have risk score ranging between 4 and < 20. They fall into the risk class of "UNLIKELY" OR "VERY UNLIKELY", which means adverse interaction of trees with man-made structures is "unlikely" and "very unlikely". The risk scores match well with the field observations.
- There is however one case that has a risk score of 20, which falls marginally into the risk class of "LIKELY", but has no obvious destructive behaviour observed. The risk assessment framework identifies it as a case in which obvious destructive behaviour should have occurred, as there is not sufficient space for root growth with respect to the tree size and the pavement is too close to the tree trunk. The discrepancy between the risk assessment result and the field observation may be due to the fact that the expected destructive behaviour may have yet to surface or may have occurred and been repaired. For either case, it is recommended that in order to avoid physical damage to the pavement, the exposed soil area of the tree should be enlarged to > 1.0 × 1.0 m^2. The risk scores would then fall to 18 and to the risk classification of "UNLIKELY".

(b) Man-made structure - Other structures

- There are in total 18 trees affecting man-made structures other than pavements
- Among the 10 nos. of trees with obvious destructive behaviour, i.e. with tree roots causing physical damage to other structures, e.g. brick wall and planter, 100% of them have risk score ranging between 20 and 30. All fall into the risk class of "LIKELY", which means adverse interaction of trees with man-made structures is likely. The risk scores match well with the field observations.
- Among the 8 nos. of trees without obvious destructive behaviour, i.e. tree roots causing physical damage to other structures have not been observed, 100% of them have risk score ranging between 6 and 19. They fall into the risk class of "UNLIKELY" OR "VERY UNLIKELY", which means adverse interaction of trees with man-made structures is "unlikely" and "very unlikely". The risk scores match well with the field observations.

5.1.2 Calibration with the BRE category of damage

The models and the risk classification can also be calibrated with the BRE category of damage (Burland, 1995) for cases involving physical damage to walls using field measurement of crack width (Table 5) as a primary factor, while taking into account other relevant observations. Key observations are discussed below.

(a) The models and the risk classification give results that are comparable with the BRE category of damage and correctly differentiate cases with and without physical damage to walls.

(b) All cases in the risk class of "LIKELY" have the BRE category of damage of at least "1 - VERY SLIGHT". Other cases in the risk class of "VERY UNLIKELY" or "UNLIKELY" have the BRE category of damage of "0 - NEGLIGIBLE".

(c) The risk score increases with the severity of damage as exemplified in the crack width measured.

(d) Marginal cases in the risk class of "LIKELY" with score around 20 are observed to link with the category of damage of "1 - VERY SLIGHT" and "2 - SLIGHT". Cases with higher risk score in the risk class of "LIKELY" correspond to the "3 - MODERATE" category of damage.

(e) It is predicted that cases in the risk class of "VERY LIKELY" would match up with the "4 - SEVERE" and "5 - VERY SEVERE" categories of damage.

5.2 Physical damage due to ground settlement in shrinkable soils

No field work has been carried out in this case due to the scope of the project, but four case studies documented in Biddle (1998) are reviewed and used as test cases for model calibration. Key information is summarized in Table 6.

The findings indicate that all cases with building damage caused by ground settlement in shrinkable clay soils have risk scores above 10, i.e. adverse interaction of trees with man-made structures is either "LIKELY" or "VERY LIKELY" (Appendix 2, Part 1, Item E, Sheet 2). The risk scores match well with the field observations.

Despite this, the following limitations of the risk assessment framework should be noted.

(a) The hazard and consequence models are formulated based on a limited amount of processed tree data, which is taken as the best estimate.

(b) There was no opportunity to review the raw data. It is not know how the data had been processed and any uncertainties involved cannot be reasonably accounted for.

The calibration of the risk assessment modules is not sufficiently rigorous, with only four case studies reviewed. For wider application, the method needs more substantiated validation.

6. Recommendations

Based on the observations from the field work, a set of recommendations with regard to the proper planting of trees of different sizes close to man-made structures is developed. These are summarized in the Tree Planting Index Chart (Figure 4). The diagram provides a good practice guide, in layman's terms and style, to plant a tree of certain size so that potential physical damage to nearby man-made structures is minimized. A member of the public may find it useful when they plan to plant a tree in their front or back garden or when one would like to have a quick check of the conditions of a tree with regard to its capability to cause physical damage to nearby man-made structures.

Even without the above chart, the general public should be reassured that most of the time, assessing and mitigating damage from tree is somehow intuitive and requires only common sense. Figure 5 shows some innovative ideas of blending developments pleasantly with trees, which may involve little or no technical/engineering input. With an impartial pursuit of innovative ideas, building a green society along with advanced capital development is achievable.

7. Conclusions

Trees are an important asset to the environment and everyone on earth has a duty of care to preserve the healthy growth of trees. However, knowledge and skills of tree protection are generally restricted to a small class of professionals, such as arborists, landscape planners, architects, engineers and contractors. The level of understanding of the subject is nonetheless not uniform across different professions. Their communication links are also not active and strong. This often leads to a lack of appreciation of each other's design concerns and requirements, bringing about undesirable consequences on trees and man-made structures.

There is plenty of scope for improvement within this field and the practices involving the protection of trees and assessing potential damage from trees on man-made structures. In particular, wide participation of the general public in the process of tree planting, protection and preservation should be encouraged. Increasing the spread of knowledge across all levels within the population would help prevent damage occurring in the first place.

Two new rating systems for application by the general public to assess the likelihood of physical damage to structures due to direct growth of tree roots and ground settlement in shrinkable clay soils are developed. They are deliberately designed to operate on simple measurable tree data so that they can be easily managed by members of the general public. It is demonstrated that the rating systems work satisfactorily for various tree species within and around London, UK. This led to the development of a set of recommendations for planting trees close to structures in the form of an index chart that is designed for the use of members of the general public. Given its robustness, the systems have scope for broad application elsewhere.

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Table 1 - Risk classification for cases of physical damage due to unfavourable root growth.

Risk score	Risk classification	Description
< 10	VERY UNLIKELY	Adverse interaction of trees with man-made structures is VERY UNLIKELY.
10 - < 20	UNLIKELY	Adverse interaction of trees with man-made structures is UNLIKELY.
20 - < 30	LIKELY	Adverse interaction of trees with man-made structures is LIKELY.
30 - 40	VERY LIKELY	Adverse interaction of trees with man-made structures is VERY LIKELY.

Table 2 - Example of data on proportion of cases of damage occurring within certain bands of distance from the tress species on shrinkable clay soils.

(a) Poplar (maximum tree height = 28 m)

Cases of damage (%)	Cumulative cases of damage (%)	Maximum distance from damage (m)
0	100	> 30
10	100	30
15	90	20
25	75	15
25	50	11
25	25	7

(b) Plane (maximum tree height = 30 m)

Cases of damage (%)	Cumulative cases of damage (%)	Maximum distance from damage (m)
0	100	> 15
10	100	15
15	90	10
25	75	8
25	50	6
25	25	4

Table 3 - Risk classification for cases of physical damage due to ground settlement in shrinkable soils.

Risk score	Risk classification	Description
< 5	VERY UNLIKELY	Adverse interaction of trees with man-made structures is VERY UNLIKELY.
5 - < 10	UNLIKELY	Adverse interaction of trees with man-made structures is UNLIKELY.
10 - < 15	LIKELY	Adverse interaction of trees with man-made structures is LIKELY.
15 - 20	VERY LIKELY	Adverse interaction of trees with man-made structures is VERY LIKELY.

Table 4 - Summary of key tree information from the tree survey.

		Tree Group				Total
		Group 1	Group 2	Group 3	Group 4	
Exposure condition	**Soil cover**	0	13	8	4	25
	Hard surfacing		2	3	0	5
	Total	0	15	11	4	30
Structures affected	**Pavement and other man-made structures**	0	5	3	4	12
	Pavement only	0	5	5	0	10
	Other man-made structures only	0	5	3	0	8
	Total	0	15	11	4	30

Table 5 - Risk scores against the BRE category of damage.

Tree no.	Measured crack width (mm)	Category of damage	Risk score
17-BM05	3	2	20
18-BM06	1	1	20
13-BM01	6	3	26
19-BM07	7	3	26
22-W01	10	3	27

Table 6 - Key information from case studies for model calibration (Biddle, 1998).

Case study no.	Tree species	Average tree height (m)	Type of structures affected	Average distance to damage (m)
5	Poplar	23.5	Brick partition walls	12.5
6	Horse chestnut Oak	14.5	Brick flank and partition walls	6.5
7	Oak	21.0	Brick flank and partition walls	13.0
8	Lime	20.0	Brick flank and partition walls	5.5

List of figures

Figure 1. Map showing locations of field observations in London, UK.

Figure 2. Correlation of likelihood of damage with tree height and distance of tree from the potential location of damage.

Figure 3. Height-proximity ratings.

Figure 4. Tree planting index chart: (a) tree group chart; (b) planting chart (1); (c) planting chart (2).

Figure 5. Innovative ideas for planting trees.

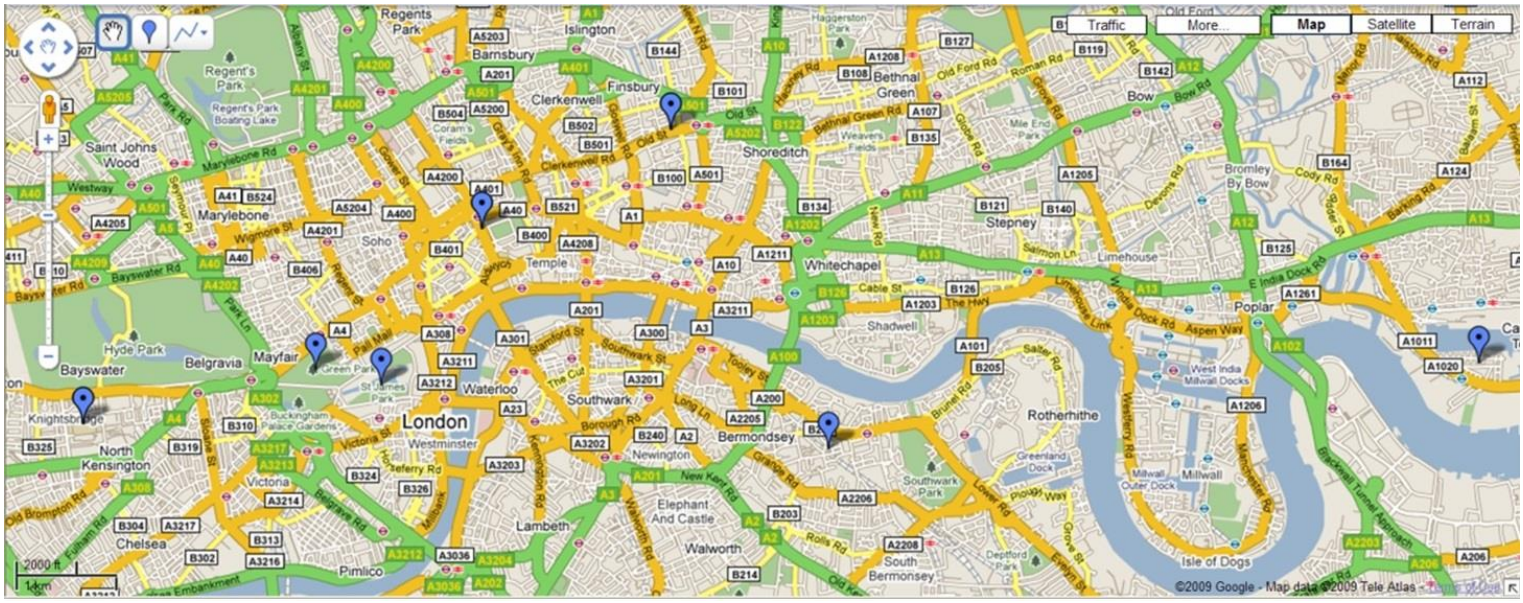
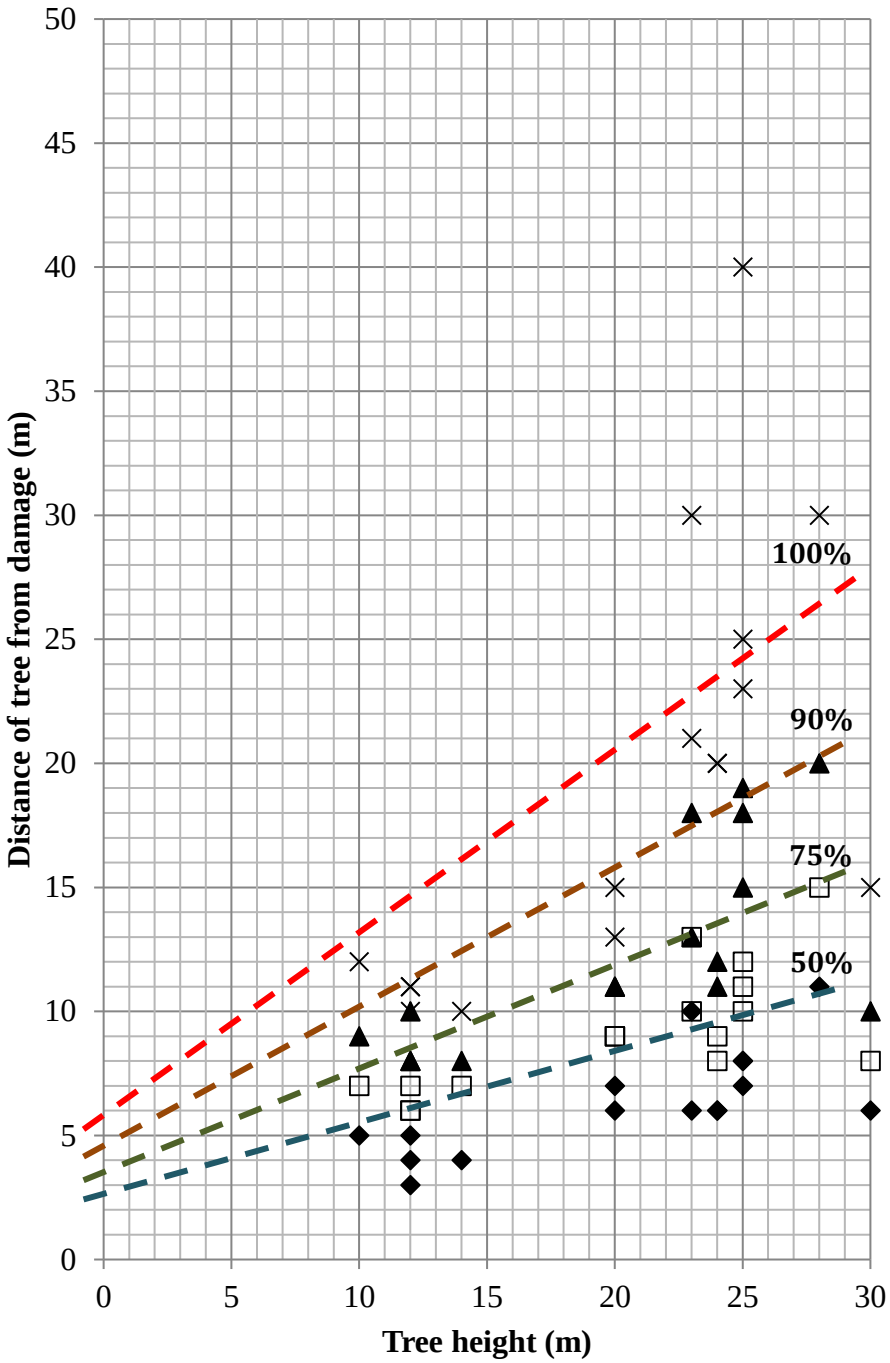
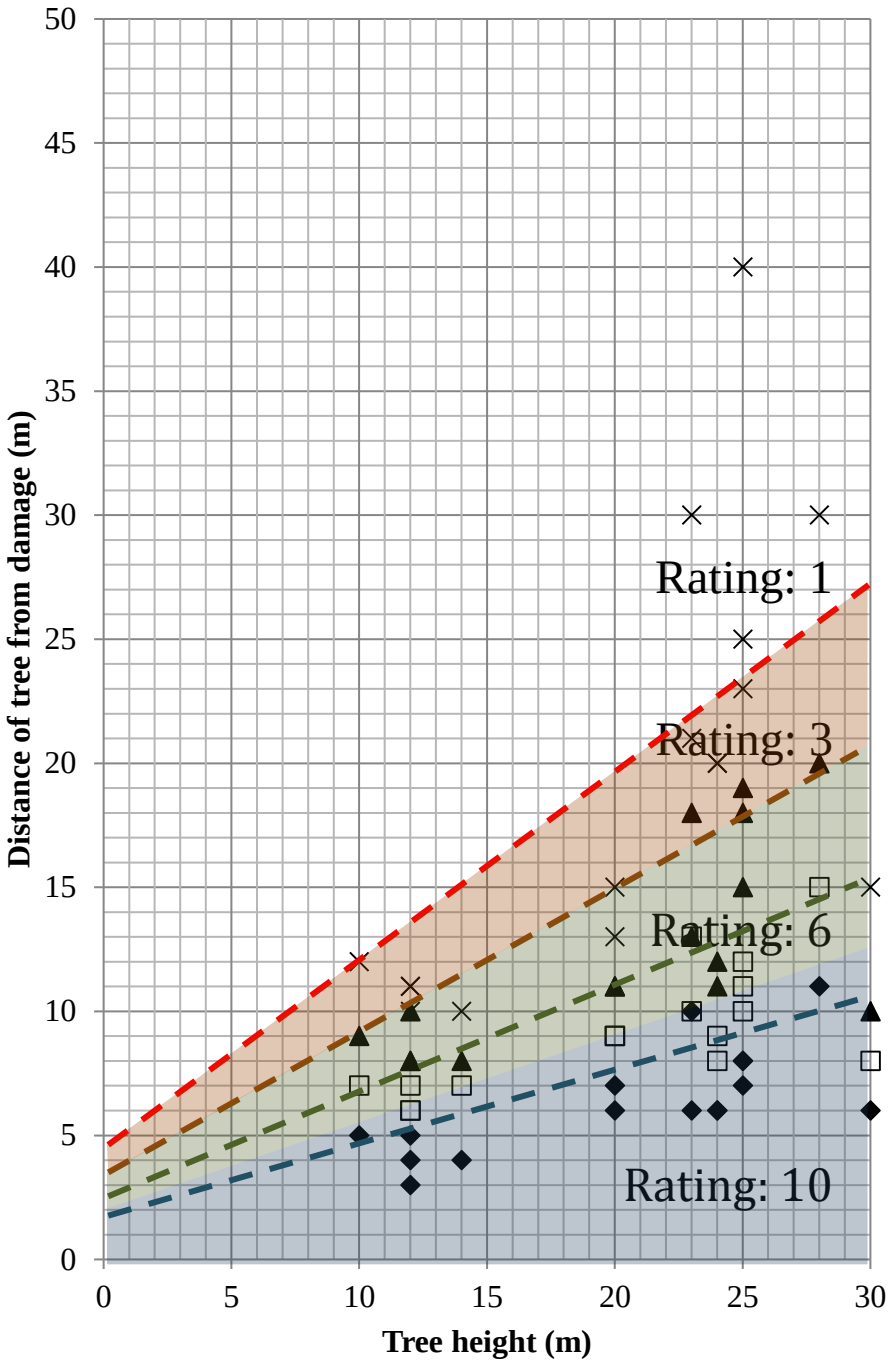


Figure 1. Map showing locations of field observations in London, UK.



Note: Distance of tree from damage is the shortest distance measured between the tree trunk of the tree that causes damage and the most obvious damage on the structure. The data shown are the maximum values obtained for the individual species.

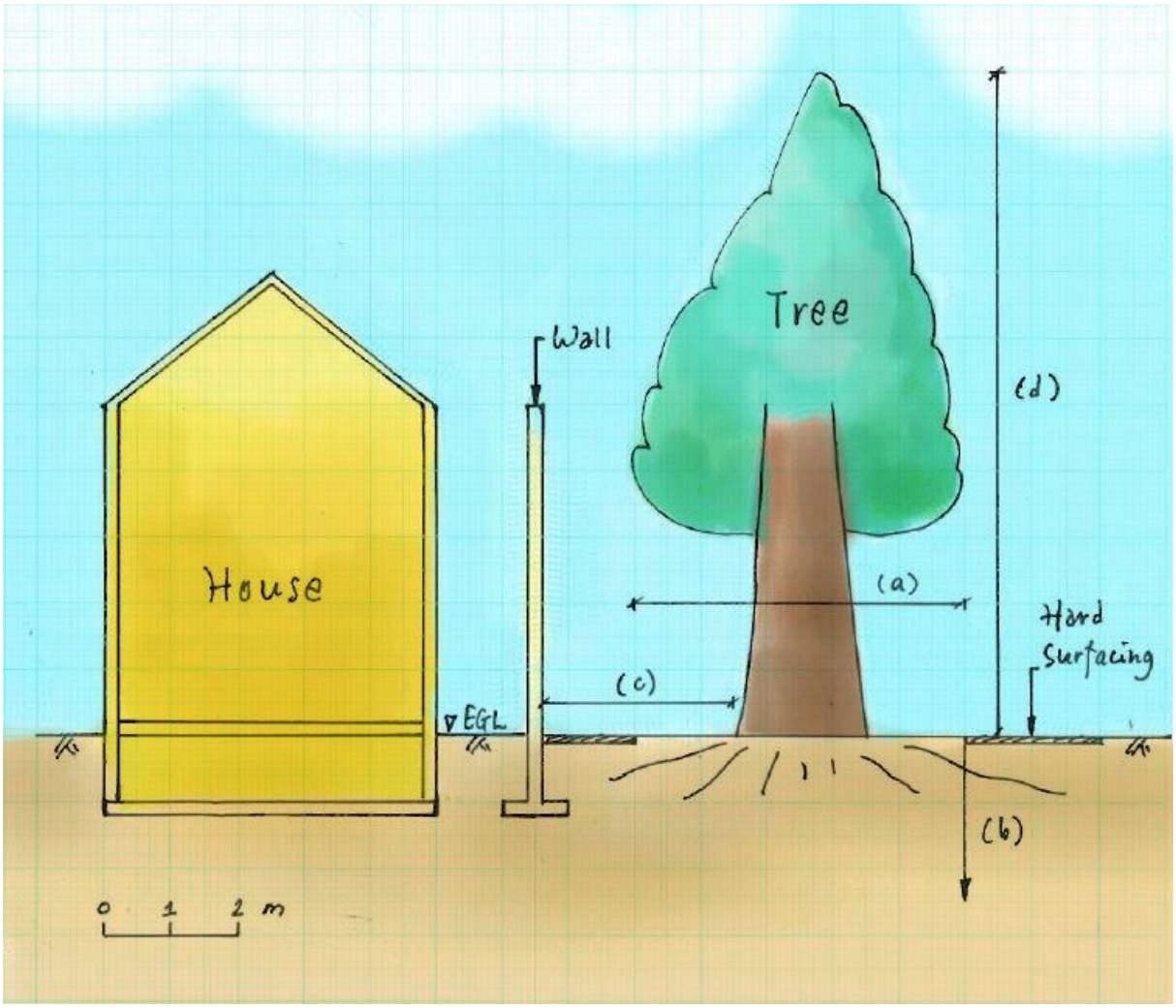
Figure 2. Correlation of likelihood of damage with tree height and distance of tree from the potential location of damage.



Cumulative percentage of individual species: ◆50% □75% ▲90% ×100%

Note: Distance of tree from damage is the shortest distance measured between the tree trunk of the tree that causes damage and the most obvious damage on the structure. The data shown are the maximum values obtained for the individual species.

Figure 3. Height-proximity ratings.



(a) Tree group chart

		Maximum actual/estimated stem diameter (mm)			
		< 150	**150 – < 300**	**300 – < 600**	**≥ 600**
Maximum actual/estimated canopy diameter (m)	**< 2**	G1	G1	G2	G2
	2 - < 4	G1	G2	G2	G3
	4 - < 8	G2	G2	G3	G3
	≥ 8	G2	G3	G3	G4

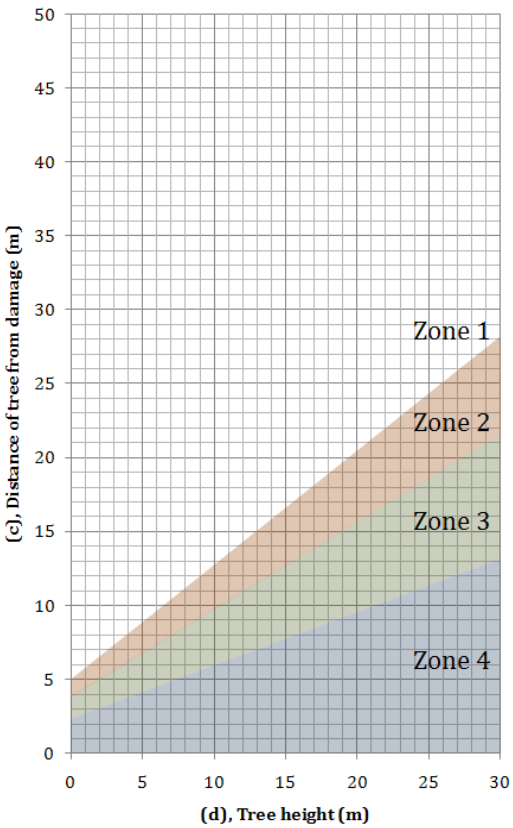
Figure 4. Tree planting index chart (sheet 1 of 2).

(b) Planting chart (1)
- to avoid physical damage directly caused by root growth

Tree group	(a) Exposed soil area (m^2)	(b) Depth of suitable planting soils, (b) (m)	(c) Proximity to structures other than pavements (m)			
			VL*	L*	S*	VS*
G1	1.0 × 1.0	1.5	1.5	1.5	1.5	1.5
G2	1.5 × 1.5	1.5	2.5	2.5	1.5	1.5
G3	2.5 × 2.5	2.0	3.5	3.5	2.5	1.5
G4	3.5 × 3.5	2.0	3.5	3.5	2.5	1.5

(c) Planting chart (2)
- to avoid physical damage caused by ground settlement in shrinkable clay soils

Structure type	Planting zone
VL*	1
L*	2
S*	3
VS*	3



Notes:
*VL - Very light structures without lateral restraint, e.g. asphalt/brick pavement or low brick wall; L - Light structures without lateral restraint, e.g. high brick wall; S - Substantial structures with lateral restraint, e.g. concrete parapet wall; VS - Very substantial structures with lateral restraint, e.g. concrete building wall.

Figure 4. Tree planting index chart (sheet 2 of 2).



Figure 5. Innovative ideas for planting trees.

Diagnosis of Interaction of Trees with Man-made Structures
Part 1 - Tree/Structure Survey Form (Sheet 1 of 4)
(Please put a "×" in the appropriate boxes.)

Location					**Tree no.**		
					Date		
Tree type (see Note 1)							
Maximum actual/estimated tree height at mature age (see Note 2)							
< 5 m		**5 m - < 10 m**		**10 m - < 20 m**		**≥ 20 m**	
Maximum actual/estimated canopy diameter at mature age (see Note 3)							
< 2 m		**2 m - < 4 m**		**4 m - < 8 m**		**≥ 8 m**	
Maximum actual/estimated stem diameter at 1.5 m above ground level at mature age							
< 150 mm		**150 mm – < 300 mm**		**300 mm - < 600 mm**		**≥ 600 mm**	
In pits/trenches; soil exposed to air (see Note 4)				**In pits/trenches; soil covered by hard surface** (see Note 5)			
Area of soil exposed				**Extent of hard surface coverage**			
< 1.0 × 1.0 m²				**≤ Full coverage**			
< 2.0 × 2.0 m²				**< ¾ coverage**			
< 3.0 × 3.0 m²				**< Half coverage**			
≥ 3.0 × 3.0 m²				**< ¼ coverage**			
Depth of pits/trenches (see Note 6)							
< 0.5 m		**0.5 m - < 1.0 m**		**1.0 m - < 2.0 m**		**≥ 2.0 m**	
Base clearance to structure (see Note 7)							
				Pavement		**Other structures**	
Any one side is < 1.0 m							
Any one side is < 2.0 m							
Any one side is < 3.0 m							
Four sides are > 3.0 m							
Physiological condition (see Note 8)							
Excellent		**Good**		**Fair**		**Poor**	
Remarks							

Diagnosis of Interaction of Trees with Man-made Structures
Part 1 - Tree/Structure Survey Form (Sheet 2 of 4)

Sketch/ photograph record

Diagnosis of Interaction of Trees with Man-made Structures
Part 1 - Tree/Structure Survey Form (Sheet 3 of 4)

Notes:

(1) This item is optional.

(2) This should be the maximum height of crown clearance above existing ground level as shown by the green measurement line in Figure S1.

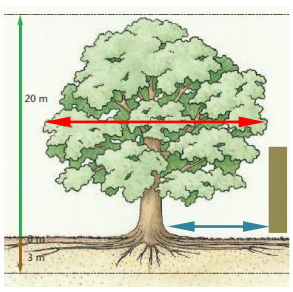


Figure S1

(3) This should be the maximum lateral spread of branches as shown by the red measurement line in Figure S1.

(4) This refers to the tree planting condition as shown in Figure S2 or otherwise similar. If the extent of the exposed soil is not in the shape of a square, an equivalent length of a square may be considered. For example, if the extent of the exposed soil is circular in shape which has a diameter of 2 m, the area is 3.14 m^2. The equivalent length of a square is 1.77 m. A "×" should therefore be put in the box next to "≤ 2.0 × 2.0 m^2".



Figure S2

(5) This refers to the tree planting condition as shown in Figure S3 or otherwise similar.



Figure S3

(6) This may not be obvious for existing trees that have already been planted below ground. Judgment should be made based on circumstantial evidence.

(7) This should be the clearance between the bottom of tree trunk and the outer boundary of man-made structure as shown by the blue measurement line in Figure S1. If trees are planted in pits, this may be taken as the clearance between the bottom of a tree trunk and the outer boundary of the pit.

Diagnosis of Interaction of Trees with Man-made Structures
Part 1 - Tree/Structure Survey Form (Sheet 4 of 4)

(8) The following figures provide a reference to the classification of physiological condition:



Excellent



Good



Fair



Poor

Diagnosis of Interaction of Trees with Man-made Structures
Part 2 - Tree/Structure Risk Assessment Form (Sheet 1 of 3)

(A) Tree groups

		Maximum actual/estimated stem diameter			
		< 150 mm	150 mm – < 300 mm	300 mm – < 600 mm	≥ 600 mm
Maximum actual/estimated canopy diameter	< 2 m	G1	G1	G2	G2
	2 m - < 4 m	G1	G2	G2	G3
	4 m - < 8 m	G2	G2	G3	G3
	≥ 8 m	G2	G3	G3	G4

(B) Determination of exposure factor

(i) In pits/trenches, with soil exposed to air

		Area of soil exposed			
		< 1.0 × 1.0 m²	< 2.0 × 2.0 m²	< 3.0 × 3.0 m²	≥ 3.0 × 3.0 m²
Tree group	G1	1	1	1	1
	G2	3	1	1	1
	G3	6	3	1	1
	G4	10	6	3	1

(ii) In pits/trenches, with soil covered by hard surface

		Extent of hard surface coverage			
		≤ Full coverage	< ¾ coverage	< Half coverage	< ¼ coverage
Tree group	G1	10	10	6	3
	G2	10	10	6	6
	G3	10	10	10	6
	G4	10	10	10	6

(C) Determination of depth factor

		Depth of pits/trenches			
		< 0.5 m	0.5 m - < 1.0 m	1.0 m - < 2.0 m	≥ 2.0 m
Tree group	G1	6	3	1	1
	G2	6	3	1	1
	G3	10	6	3	1
	G4	10	6	3	1

Diagnosis of Interaction of Trees with Man-made Structures
Part 2 - Tree/Structure Risk Assessment Form (Sheet 2 of 3)

(D) Determination of structural factor

Structures	**Without lateral restraint**	**Very light (e.g. asphalt/brick pavement or low brick wall)**	10
		Light (e.g. high brick wall)	6
	With lateral restraint	**Substantial (e.g. concrete parapet wall)**	3
		Very substantial (e.g. concrete building wall)	1

(E) Determination of proximity factor

		Base clearance			
		Any one side is < 1.0 m	**Any one side is < 2.0 m**	**Any one side is < 3.0 m**	**Four sides are > 3.0 m**
Tree group	**G1**	3	1	1	1
	G2	6	3	1	1
	G3	10	6	3	1
	G4	10	6	3	1

(F) Calculation of risk score

Risk score = (Exposure factor + Depth factor) + (Structural factor + Proximity factor)

For pavement:

Exposure factor	
Depth factor	
Structural factor	
Proximity factor	
Risk score	

For other structures:

Exposure factor	
Depth factor	
Structural factor	
Proximity factor	
Risk score	

Diagnosis of Interaction of Trees with Man-made Structures
Part 2 - Tree/Structure Risk Assessment Form (Sheet 3 of 3)

(G) Evaluation of risk score

Risk score	Risk classification		Description
< 10	Very unlikely		Adverse interaction of trees with man-made structures is very unlikely.
10 - < 20	Unlikely		Adverse interaction of trees with man-made structures is unlikely.
20 - < 30	Likely		Adverse interaction of trees with man-made structures is likely.
30 - 40	Very likely		Adverse interaction of trees with man-made structures is very likely.

(H) Remarks

Diagnosis of Interaction of Trees with Man-made Structures
Part 2 - Tree/Structure Risk Assessment Form (Sheet 1 of 2)

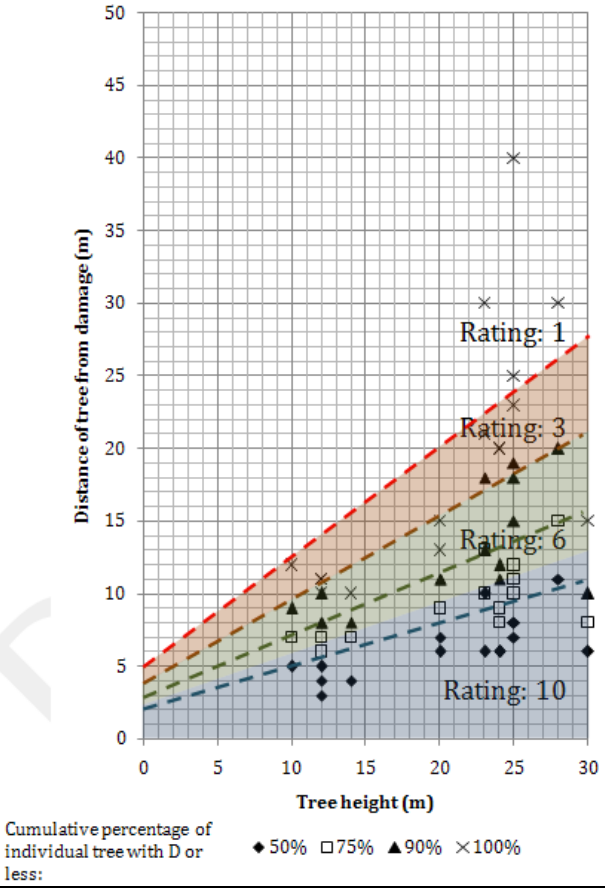
(I) Determination of species factor

Tree species	**Apple, Pear, Ash, Beech, Birch, Cherry, Plum, Damson, etc., Elm, False acacia, Hawthorn, Horse chestnut, Lime, Oak, Plane, Poplar, Rowan, Service tree, White beam, Sycamore, Maple, Willow**	1
	Other species	0

(J) Determination of structural factor

Structures	**Without lateral restraint**	**Very light (e.g. asphalt/brick pavement or low brick wall)**	10
		Light (e.g. high brick wall)	6
	With lateral restraint	**Substantial (e.g. concrete parapet wall)**	3
		Very substantial (e.g. concrete building wall)	1

(K) Determination of
combined height - proximity factor


Distance of tree from damage (m)
Tree height (m)
Rating: 1
Rating: 3
Rating: 6
Rating: 10
0
5
10
15
20
25
30
35
40
45
50
Cumulative percentage of individual tree with D or less:
50%
75%
90%
100%

Diagnosis of Interaction of Trees with Man-made Structures
Part 2 - Tree/Structure Risk Assessment Form (Sheet 2 of 2)

(L) Calculation of risk score

Risk score = Species factor × (Structural factor + Combined height-proximity factor)

Species factor	
Structural factor	
Combined height-proximity factor	
Risk score	

(M) Evaluation of risk score

Risk score	**Risk classification**		**Description**
< 5	Very unlikely		Adverse interaction of trees with man-made structures is very unlikely.
5 - < 10	Unlikely		Adverse interaction of trees with man-made structures is unlikely.
10 - < 15	Likely		Adverse interaction of trees with man-made structures is likely.
15 - 20	Very likely		Adverse interaction of trees with man-made structures is very likely.

(N) Remarks