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AN INVESTIGATION INTO ATTERBERG LIMITS AND THEIR SUITABILITY FOR ASSESSING THE SHRINKAGE AND SWELLING CHARACTERISTICS OF CLAY SOILS FOR FOUNDATION DESIGN

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ABSTRACT

Clay soils shrink and swell with changes in moisture content. This can be exacerbated in the presence of trees, and in the vicinity of buildings, the resultant effects can cause structural damage. For foundation design in such circumstances in the UK, reference is often made to guidelines published by the National House Building Council (NHBC), which were primarily written for low-rise residential structures. These guidelines are based on a clay shrink / swell potential assessed using Atterberg Limits and a 'water demand' classification for trees.

Atterberg limits are semi-empirical tests that assess a fraction of a soil sample which passes an arbitrary sieve size. The structural features of clay soils, mineralogy, chemistry, prior stress history and cyclic effects all influence the magnitude of volumetric change. Atterberg limits do not directly measure any of these features but have been related to some of them empirically.

This paper reviews the processes of clay shrinkage and swelling and the applicability of the Atterberg limits in the assessment of volume change potential. It concludes that modifications to the NHBC guidelines can make designs more site specific. However, because the guidelines are based on a cost - benefit analysis, they will over-design foundations for structures other than low rise residential houses and will not be relevant for others. It is concluded that a more appropriate analysis should be based on a wider overall assessment of all the available soil/site information, in conjunction with a simple assessment of plasticity.

Keywords: Atterberg Limits, Clay Shrinkage, Foundation Design, NHBC 4.2, Volumetric change, tree root damage.

1. Introduction

It has long been recognised that clay soils have the ability to undergo volumetric change as a function of change in moisture content, a property that is exacerbated by the presence of vegetation, particularly trees. Trees draw moisture from the soil at rates which vary according to the seasonal growth, age and species of the tree, resulting in shrinkage of clay soils. Conversely, swelling can occur if vegetation is removed or if water is added from a secondary source. The magnitude of the ground movements associated with this shrinkage/swelling phenomenon are sometimes sufficient to result in damage to nearby structures.

For foundation design in such soils, reference is often made to guidance published by the National House Building Council (NHBC) which uses Atterberg limits to determine the shrinkage/swelling potential of the soil (NHBC Chapter 4.2, 1992). Although these guidelines were primarily written for low-rise residential housing developments, because of a lack of other published guidance they are often used as a basis for foundation design for other types of structure where clay soils are present.

This paper presents an investigation into the mechanisms that cause clay soils to shrink and swell. The influence of trees and the interaction between clay soils, water, trees and buildings is then examined, including the derivation of the NHBC Chapter 4.2 guidelines (1992). A brief evaluation is presented of the existing test procedures for the measurement of volume change. The applicability of Atterberg Limit tests for the measurement of volume change potential is then reviewed.

2. Mechanism for Volume Change in Clay Soils

The ability of clay to expand and contract with changes in moisture content is largely attributed to the plate like layered structure of the material and its high porosity. Clays have a large surface area to volume ratio and are therefore able to absorb large quantities of water. The overall structure in all clays is dominated by large oxygen and hydroxyl ions which impart an overall slightly negative electrical charge. It is this property that is the basis of the double layer theory that is used to explain some aspects of clay behaviour.

The theory proposes that the overall negative charge is neutralised by the adsorption on to the mineral surfaces of cations and polar water molecules held within the pore fluid. This creates a strongly bonded adsorbed water layer near the surface of the clay particle which is separated from the free pore fluid by a layer of water with a high concentration of cations. This double layer of water is in the order of 20 to 40 nm width (Das, 1983). However, this theory does not adequately explain all aspects of shrinkage and swelling behaviour. Some authors believe that other mechanisms are also involved. Low (1981) for example concluded that the valence, size and hydration energy of the exchangeable cation affected the expansion of the layers and that once the layers had expanded far enough apart, the short range forces no longer operated and expansion was independent of the cation influence, swelling pressure was therefore related to the properties of the interlayer water.

The addition of water into the ground will also cause deformations due to a reduction in total stress. The initial movement will comprise an immediate but time dependant elastic rebound which encourages stress relief fractures and zones of secondary permeability which can localise further swelling. As the effective stress is changed, the associated volume change takes place at a rate which depends upon the compressibility, expansivity and hydraulic conductivity of the soil. These factors can also change seasonally and over longer periods due to the secondary permeability (Gostelow 1995).

Cyclic wetting and drying occurs in nature seasonally. It has been demonstrated (Basma *et al* 1996) that cyclic shrinking and swelling of clays can result in a decreased swelling ability and reduced water absorption when clays are fully wetted and partially shrunk. Conversely when the soils were fully shrunk, an increase in swelling potential was noted. This demonstrates that the swelling/shrinking processes are not entirely reversible. This may be explained by a hysteresis effect which leads to an increase in the soil density.

The mineralogy of the clay soil is also influential in shrinkage behaviour. The smectite group of clays (e.g. montmorillonite) are most often involved in expansive soil problems (bentonite for example, is sodium montmorillonite). The highly expansive clays of southeastern Britain, the London Clay, Oxford Clay and Gault Clay, also contain a high ratio of smectitic minerals (Driscoll, 1983). From the above it would therefore seem reasonable to suggest that both structural and double layer elements are

involved in the shrinkage and swelling process in clay soils and that the degree to which one or the other mechanism is involved is highly dependant on the properties of the individual clay and site circumstance.

Thus it can be concluded that the following parameters have a significant influence on the ability of clay to shrink and swell to varying degrees:

- Structure
- Particle size distribution
- Mineralogy
- Permeability
- Stress History
- Cyclic Processes
- Boundary conditions

Atterberg limit tests have been related to some of these properties and soils which exhibit high plasticity indices, i.e. those able to behave in a plastic manner over a large range of moisture contents, are often observed to have high shrinkage and swelling potential. However, Atterberg limit tests are undertaken on small remoulded samples of only the fraction of the sample passing a 425 μm sieve, and therefore do not quantify any of the above parameters. In particular, the important influence of the structural elements of the soil are lost in the remoulded samples. Atterberg limit tests can therefore provide a means for objectively broadly classifying a soil for a given site, rather than giving a quantitative value of shrinkage or swelling potential for that soil.

3. The Influence of Vegetation

The drying of soil by trees can be measured in terms of a "soil moisture deficit" (SMD), defined as the amount of water needed to be added to a soil to bring it to its normal moisture content at field capacity (Biddle, 1998). The extent of soil drying each year depends on the weather conditions during the summer, if rewetting does not fully replace all the moisture lost during the summer, a persistent moisture deficit (PMD) can develop (i.e. a 'bulb' of soil which remains dried) where the soil is continually affected by trees. (Figure 1). Progressive increase in this deficit occurs if drying is maintained. Additionally the associated shrinkage is reversible if soil drying ceases and the soil is allowed to rehydrate (Biddle, 1998).

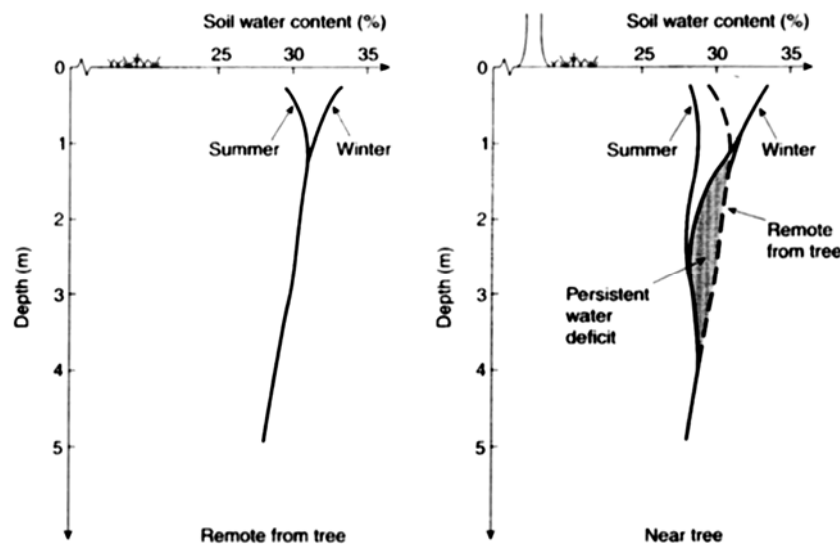


Figure 1: Variation of soil water content from summer to winter, showing persistent moisture deficit. (left, remote from tree, right, near to tree) (BRE 298, 1999)

A PMD can be present to substantial depth and can lead to heave if it is allowed to recover. In some cases the PMD can recover whilst the tree is still present. For example, if the species is very long lived the efficiency of the roots can diminish; the soil will then begin to recover whilst the tree is still present (Biddle, 1998). Alternatively if a tree has been removed or damaged, heave will usually occur

in the early autumn when soil rehydration begins. However, the magnitude of a PMD is controlled significantly by the species of the tree present, Poplar, oak elm and willow are the most likely to produce PMDs some distance from the tree trunk (Biddle, 1998).

4. The Interaction of Buildings, Trees and Clay Soils

The current NHBC Chapter 4.2 guidelines have been developed to help assess the affect of trees in clay soils near buildings. Much of the research behind the guidelines has been undertaken in the south east of England where the majority of the highly expansive clays are found and where the climate is drier (maximum SMD). Hence tree root problems in this area are further exacerbated and more clearly visible. A nation-wide survey commissioned by the BRE plotted the percentage of underpinning works in the UK undertaken in each of 12 arbitrary regions (BRE 352, 1993). The results showed that about 50% of underpinning was undertaken in London and the Home Counties. However, the influence of the shrinkable London Clay, tree roots and dry summers was first officially realised following investigations of bomb damage in north London after the second world war (Driscoll, 1983). The Building Research Station (BRS) published a digest in 1949 which stressed the importance of taking care when siting dwellings in the vicinity of trees and shrubs and advocated the separation of trees and buildings to distances equal to the height of the tree or 1.5 times the height for rows or groups of trees (Biddle, 1983).

In 1971, insurance companies extended household insurance cover to include subsidence. Figure 2 shows the number of claims submitted to UK insurance firms for cracking and distortion in homes.

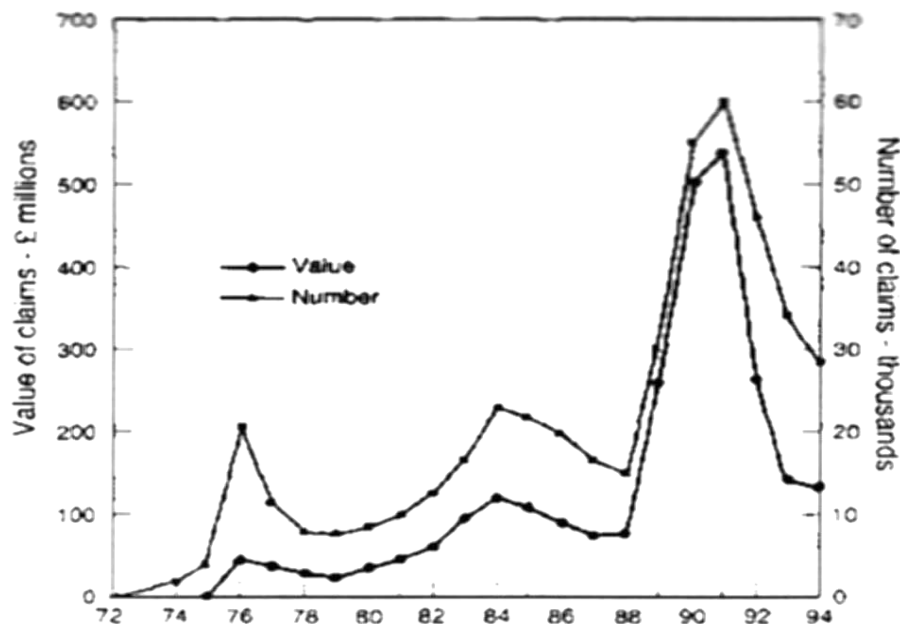


Figure 2 : Annual value of insurance claims for subsidence and heave damage to housing (BRE 251, 1995)

The highest numbers of claims coincide with the severe droughts of 1975/76 and 1989/90. Following the 1975/76 drought, the Department of the Environment published guidance in 1979 which recommended redevelopment of foundations rather than relying on separation between structures and trees.

The need to devise a scheme for assessing the likelihood of the occurrence of structural damage has long been established. A definition of where problems might occur is usually made by an assessment of the type of soil present, the type of tree and the proximity and type of foundations of the building. To facilitate this, many attempts have been made to classify both clay soils and tree types according to the likelihood of their causing damage.

The problem involved in attempting to classify the likelihood of damage according to tree type is in finding criteria which can be used to compare the soil drying patterns of different species of tree. Soil

drying patterns vary greatest in their lateral extent. Biddle (1998) suggests that criteria which could be used to compare different species might comprise radial spread of root influence, vertical extent of root influence and angular distortion due to root influence. The largest survey of tree root influence was undertaken by Cutler and Richardson (1989) who conducted a survey of roots that had been sent to the Jodrell Laboratory of the Royal Botanic Gardens, Kew for anatomical identification purposes between 1971 and 1979. People who had sent in root samples were sent a survey card asking them for details such as the distance from the tree to the damaged building and the radial root spread. Analysis of this data has also been used to estimate the likelihood of a particular species to cause structural damage based on the frequency of the species involvement in damage cases.

Water demand, meaning the "ability of vegetation to cause drying of a clay soil" (Biddle 1998) is used by the NHBC Chapter 4.2 (1992) to rank tree species. The water demand is related to the likely growth rate and growth pattern of the tree. This ranking takes into account the depth and radial extent of the roots and ranks each species as high, moderate or low. The different angular distortions created by broadleaf trees compared to evergreen trees are accounted for by a change in the slope of the line on the foundation depth calculation charts (Biddle, 1998). The effects of the SMD are also taken into account by reducing the foundation depth for every 50 miles north and west of the London area. These guidelines were essentially subjective and based on the research and past experience of the NHBC.

It has been demonstrated that many other factors, such as the vigour of the individual tree, the availability of nutrients in the soil and climatic / environmental conditions in the vicinity of the individual tree seem likely to have a strong influence on the growth and therefore ability of the tree to damage adjacent properties.

Classifications for clay soils using Atterberg plasticity indices are used by the NHBC Chapter 4.2 (1992) and BRE Digest 240 (1993), which uses a 'volume change potential' based on the plasticity index modified to account for the fines fraction of the soil by multiplying it by the percentage of the sample passing the 425 μm sieve. Sridharan and Prakash (2000) detail several soil classification schemes proposed by various authors based on liquid limit, plasticity index, colloid content, shrinkage limit, shrinkage index, free swell index and oedometer expansions. No scale of expansion is indicated by these classifications and the boundaries between the various degrees of expansion are often seemingly arbitrary.

Modifications to the model used by the NHBC 1992 guidelines have been suggested by Biddle (1993) in order to recognise the following points:

- Using only 3 classifications for soil shrinkage and "water demand" leads to sudden steps. Actual plasticity index data and more detailed classification for tree vigour would be more appropriate
- The guidelines assume a tree will grow to a theoretical mature size, which may not be appropriate for all trees.
- The model used assumes a large crown area for trees. This does not allow for trees with small crown areas, or trees of exceptional size.
- The guidelines do not allow for trees which are growing very rapidly.
- The model for climatic variation is not very sophisticated.
- The vulnerability of the structure is not accounted for, nor the amenity value of the tree.

5. The Measurement of Volume Change

Measuring the potential for volume change in clay soils is an important factor in foundation design. Besides Atterberg limit tests, other tests are available to determine clay shrinkage and swelling capacity. The problems of using remoulded samples and the complicated and laborious British Standard shrinkage limit tests have been overcome with a new shrinkage limit test using a larger, undisturbed clay specimen, a laser range finder, a digital height gauge and an electronic balance as proposed by Hobbs *et al* (2000). This new test does not take any longer to perform than the existing BS tests. As no sample handling or immersion is required, a bigger, more representative sample can be used. Structural features of the soil sample are preserved and the shear strains of different layers can also be distinguished.

Related research by Sridharan and Prakash (1998) found that the shrinkage limit of a natural soil was not related to its plasticity as defined by the Atterberg test, but primarily governed by the soil packing, which was in turn governed by the grain size distribution.

Laboratory tests to measure shrinkage and swelling directly are not without their problems. The new shrinkage limit test proposed by Hobbs *et al.* seems promising, but because this test is new little information regarding its practical use is available and it requires the use of specialist test equipment, which is at present only available at the British Geological Survey. The effects of overburden pressures are difficult to simulate with most of the tests, and some tests still use only the <425 μm fraction of soil and are hence no better than Atterberg limits. Oedometer swell tests have been shown to greatly overestimate swelling and 3D swelling strain tests include problems such as cutting a perfect cube of sample and sample disintegration in the water.

Instead of a direct measurement of the shrinkage and swelling of the clay, suction can be used to determine if a clay soil is desiccated. A quantitative estimate of the depth and degree of suction is useful to determine if subsidence has been caused due to clay shrinkage and estimate the potential for heave if the source of the desiccation (e.g. a tree) is removed (BRE 412, 1996). Soil suction can be measured in the laboratory using the filter paper technique (BRE, IP/4 1993), however there are many problems with this method. The test requires great care and a very precise analytical balance to 0.0001g accuracy. Soil adhered to the filter papers will give inaccurate weight measurements and papers must be in full contact with the soil, but without causing compression of the papers. It is difficult to judge when the equilibrium water content has been attained. Very high suctions (in excess of 8 MPa) do not give a very good fit with the calibration curves (BRE, 1993). Ridley and Burland (1994) commented that the filter paper test was subject to some possible errors and depended on the exposed surface area of the soil, the temperature at which the measurement is made and the time period for which the filter paper is exposed to the soil. Additionally, sampling will cause damage which affects the suction value (Croney 1977).

Desiccation can be identified by a number of different methods. The comparison of pore water pressures, moisture contents and shear strengths close to trees and at some distance from trees can show the effects of soil drying. Some relationships between suction and Atterberg limits have been established. A relationship between suction and plasticity index for remoulded soils was identified by Black (1962). The plasticity characteristics for many British clays plotted onto a Casagrande A line plasticity chart correspond closely to a line described by

$$(I_p) = 0.838 (\omega_L) - 14.2$$

Black surmised that at any given plasticity index, British soils with an equal consistency index will have the same suction. To estimate the suction, the liquid limit corresponding to the sample's given plasticity index is derived from the equation above. The consistency index is calculated, then using the new liquid limit of the soil, its given plasticity index and its given consistency index, a new moisture content is calculated using

$$\text{Given } C_i = \frac{\text{new } \omega_L - \text{'effective' } \omega}{\text{Given } I_p}$$

(derived from Black, 1962). This 'effective' moisture content can then be used in the graph in Figure 3 to derive the soil suction.

Biddle (1998) proposes that it is possible to make a qualitative analysis of the amount of heave using a highly simplified approach with a score chart based on the NHBC Chapter 4.2 (1992) water demand classification. The scores for each of the three factors shown in Figure 4 are determined, added together and divided by the plasticity index of the soil divided by 10. The duration of the heave shown is qualitative with 'short' likely to be less than 5 years and 'long' in excess of 10 years, using the chart in Figure 5.

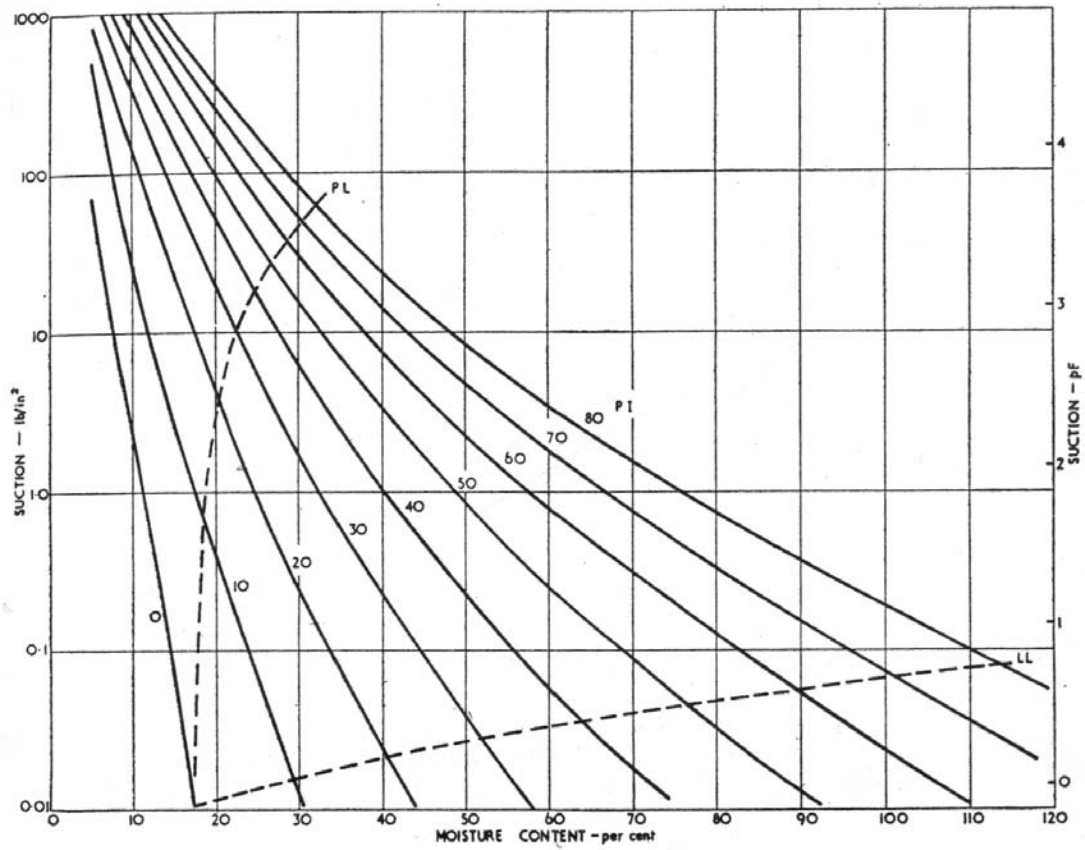


Figure 3 : Relationship between suction and effective moisture content at various plasticity indices (Black, 1962)

	Score			
	1	2	3	4
NHBC Water Demand	Low	Moderate	High	Poplar/ Oak
Tree Height (m)	5 - 10	10 - 15	15 - 20	>20
Proximity (Distance from tree, expressed as fraction of tree height)	1.5 - 1	1 - 2/3	2/3 - 1/4	<1/4

Figure 4 : Scores for assessment of risk of heave (Biddle, 1998)

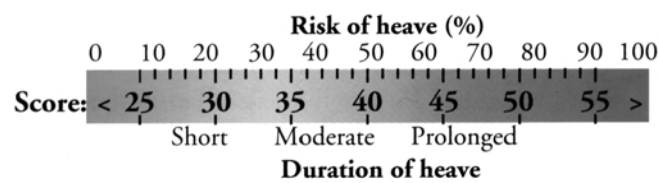


Figure 5 : Chart for assessment of risk and duration of heave (Biddle, 1998)

There are many theories for estimating potential clay shrinkage and heave, and none of these are omnipotent. Many of the problems with trees, clays and foundation design have stemmed from the fact that movement which will occur within clay soils under the influence of trees often cannot be predicted quantitatively. We have demonstrated that there are many, more accurate, ways of assessing soil desiccation, swelling and shrinkage potential than solely by using Atterberg limits. However, none of the tests described are as widely used as Atterberg limits, many of the tests can be lengthy to perform, expensive and require specialised equipment. Simple and inexpensive Atterberg limit tests, although imperfect for such an assessment, allow a large number of samples to be tested, rather than a smaller number of more expensive tests, hence providing a wider overview of the site in question, provided the limitations of the tests are understood.

Other factors that cannot be assessed in the laboratory can sometimes have a great effect on the soil. The development of cracking is one example. Research by Ravinia (1983) showed that below the uppermost soil layers, moisture content may remain unchanged for a long period if no shrinkage cracks develop. Accelerated drying rates in hot dry weather cause shrinkage cracks in expansive soils. The influence of other plants besides trees can also have an effect. Deep rooting plants (2 to 3 m) can dry the soil to greater than or equal to its wilting moisture content (around 15 bars), and generally above the shrinkage limit.

Where buildings are already present and damage has been recorded, a level distortion survey can be more informative than any laboratory testing. The site history, presence of former vegetation (e.g. from aerial photographs), and the history of the damage, such as observations on the time of year when cracks were seen to appear, can all determine the cause of foundation movements. Analysis of cracking patterns can be useful, although cracks can occur in buildings for many reasons other than foundation movement (such as thermal effects, sulphate attack, rusting of steel fixings, vibration, overloading and drying out of new bricks) (BRE 361, 1991).

It seems reasonable to suppose, as in BRE 412 (1996), that the best option would be that reliance should not be placed on a single method but an overall assessment of all the available information.

6. Conclusions

The NHBC Chapter 4.2 guidelines (1992) use plasticity index as a measure of the soil swelling potential. It has been demonstrated that soil suction probably offers the best analysis of volume change potential, but there is no 'quick fix' test for this. Atterberg limits, because they are so widely used and have many empirical relationships, do form a useful soils classification, however for volume change potential, they are potentially misleading. An index of swelling and shrinkage is being developed by the British Geological Survey which will hopefully relate many laboratory tests to actual shrinkage and swelling potentials for commonly encountered clay types in Britain.

The classification of trees using water demand tends to group all trees of the same species with the same damage potential, which is not necessarily correct. There are also very many cases of trees close to buildings where no damage has been found. In addition, non-residential buildings are generally more flexible or more able to tolerate damage. A risk-based approach is needed to assess the cost implications of heave precautions versus likelihood of damage. It has been demonstrated that the propensity to cause damage is highly reliant on the individual tree.

The NHBC 4.2 (1992) guidelines represent the best existing guidance for foundation design in the presence of trees in the UK. The guidelines merely seek to provide a compromise between the costs incurred from deepening foundations and the benefits in reducing the risk of damage. The guidelines attempt to take all of the factors involved into account, but because of the inherent variability of the soil, tree and environment in which it is situated, the guidelines often take a worst case approach. Hence, the blanket application of NHBC standards to all types of building will over design some foundations and will not be relevant for others. The guidelines themselves state that the Chapter 4.2 "Gives the technical requirements and recommendations for building near trees, particularly in shrinkable soils". The limitations of this brief are often ignored and the guidelines are sometimes used to derive models for the extent of the root system, the influence of roots on the soil, of where damage might occur, and for guidance on tree planting and pruning. This may be inappropriate and misleading.

It has been recognised that the NHBC guidelines do not account for many site and tree -specific features, and circumstances where a cost-benefit analysis is inappropriate. To remedy this, a Subsidence Risk Factor has been proposed, although it has not, as yet, been incorporated into any guidelines for foundation design.

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