DAMAGE TO BUILDINGS ON CLAY SOILS

TECHNICAL BULLETIN 5.1

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COVER

An Edwardian Hall, founded on a heavy basaltic clay in Melbourne.

The sub-floor space was poorly ventilated and so soil moisture-contents were higher below the centre than at the perimeter of the building. In the past, underpinning with relatively shallow concrete pads had been conducted in an attempt to arrest movements arising from this difference in soil moisture-content. Distortions in the building continued to grow and the support of structural beams was eventually threatened. After consideration of the costs and possible effectiveness of repair options, a decision was made to replace the building.

DAMAGE TO BUILDINGS ON CLAY SOILS

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FOREWORD

This publication was produced by the Victorian National Trust in 1984 and is the fifth in a series of Technical Bulletins. It is published under the aegis of the Australian Council of National Trusts and is designed to complement the Conservation Bulletins series. Subjects published and planned to be covered are set out in Appendix E.

The Council records its thanks to Mr D. A. Cameron and Dr P. F. Walsh, Commonwealth Scientific and Industrial Organization and to the Steering Committee for the production of this Bulletin.

R. D. Davidson
Chairman
Australian Council of National Trusts

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INTRODUCTION

Foundation movements are a major cause of distress to established buildings. The main cause of such movements in Australia is the swelling and shrinking of expansive clays resulting from soil moisture changes. There are two aspects to this problem. Firstly, buildings must be managed in a manner that reduces the possibility of damage. Secondly, if foundation movements do occur, the damage should be repaired and measure taken to stabilize the footing system.

To achieve these aims, a sound knowledge of foundation behaviour is required. For example, unless the cause of the distress is clearly identified and appropriate remedial measures selected, there is a danger of further failure.

This report is concerned mostly with the damage that may be caused to existing buildings by movements of expansive clays resulting from soil moisture changes. However, in order to give this particular problem its proper perspective, some discussion of other forms of foundation behaviour is appropriate.

THE NATURE OF FOUNDATION MATERIALS

The foundation of a building is defined as the soil or rock upon which the footings are constructed. The term 'soil' is used in the engineering sense to mean the sand, silt or clay material below the organic top-soil layer. The various types of soil are distinguished by the size of the particles. Sands comprise material down to 0.06 mm. Silts include the range 0.06 to 0.002 mm, and clays consist of particles finer than 0.002 mm. When soils contain mixed types, it is usually the properties of the finer particles that predominate. For example, a sandy clay behaves more like a clay than a sand.

Obviously, if sound rock is present at or near the surface, it provides an ideal stable material upon which to found a building. Sydney sandstone is an excellent foundation. If the depth to sound rock is moderate, the piles or piers can be driven or drilled to the rock, giving a stable base. For small buildings, or where the depth to rock is excessive, the building is commonly founded within the soil layer. The expected performance of such material depends upon whether it is sand, silt or clay, as well as on loading and environmental factors.

Granular materials, including sands and gravels, are usually trouble free. Loose sands or heavily loaded sands can experience some settlement problems, but usually the settlement occurs immediately upon loading. Consequently, problems with older buildings are not likely unless a change is made in the loading. One less obvious way in which this could occur is by pumping water from the soil in an adjoining building site excavation. This may result in a significant lowering of the natural water level or water table and will effectively increase the load within the soil above the newly established water level. The additional 'load' may initiate settlement in loose sands or soft silts and clays. Other building activities such as blasting or piling can cause settlement due to compaction of vibration-sensitive sand.

It is important that those who are responsible for existing buildings that may be affected by new contruction on adjacent sites make a careful prior survey of the condition of the building in order to facilitate claims and repairs if damage eventuates.

Silts are fine-grained soils with particle size and properties intermediate between the two major groups of sands and clays. Such materials do not have the strength that comes from the plasticity of clays or from the particle to particle contact friction in sands. Moreover, silts can be subject to large settlements occurring over a long period. Loose silts are generally unsuitable as a foundation. Medium to dense silts may behave similarly to either clays or sands depending on the size and shape of the particles.

Clays are the finest grained soils. The upper limit on grain size is 0.002 mm, but most of the clay particles will be even smaller. With decreasing grain size, the surface area of the particles for a given volume increases and, consequently, surface effects dominate the physical and chemical behaviour of the clay. The individial particles of clays are plate-like crystals of clay minerals, and the properties of these minerals also influence clay behaviour. Therefore it is not surprising that there is no single laboratory test that fully describes a clay's characteristics.

When considering clay as a foundation material, the following three properties are of particular interest:

soil strength, more commonly expressed as load-bearing capacity,
settlement due to loading, and
potential expansive movement.

The bearing capacity of a clay, defined as the maximum load per unit area the soil can sustain without failing, should not be a problem in an existing building unless major changes in loading occur or the moisture content of the clay is dramatically increased. Protection of the foundation material from excessive moisture, due to either inadequate site drainage or plumbing leaks, is essential to proper maintenance of any building and should rarely be a cause of a bearing capacity failure.

Load settlement of clays is more likely to be a problem. Clays undergo settlement in two phases. Initial settlement is associated with water slowly squeezing out of a saturated clay as a direct result of the pressures applied by the building. This form of settlement decreases with time and can be readily predicted by standard engineering tests. In some cases this may be reduced by preloading the foundation material.

The second phase of load settlement results from slip of the clay grain-to-grain contact. Secondary settlement can proceed for centuries. As an example, it has been estimated that the London clays are settling at rates up to 300 mm per century. The rate of movement can be reduced by lowering bearing pressures (underpinning with wide pads) or transferring building loads to a more rigid foundation material (deep underpinning with piers).

Most people connected with the building industry are well aware of the problems of settlement of foundations under load. In Australia, clays are normally unsaturated (or dry) and load settlement problems are confined usually to relatively small deposits of marine clays and swamp sediment. Consequently, the major cause of footing failures is movements associated with changes in the moisture content of clays. Such changes cause either soil swelling or shrinkage, and the clays that exhibit this behaviour are termed expansive clays. Their distinctive behaviour is more commonly referred to as reactivity. The nature of these clays are described in detail in the next section.

CHARACTERISTICS OF EXPANSIVE CLAYS

All clays can swell or shrink and the amount of movement depends on the moisture change and the nature of the clay. Some of the most important factors that determine the potential reactivity of a clay are given below

(a) **Mineral composition.** The reactivity of a clay is influenced by the mineral composition of its plate-like particles. Montmorillonite mineral particles can swell substantially as water molecules penetrate the layers of their crystal structure. This effect does not occur with the more stable kaolinite mineral where only inter-particle movements are involved. Illite behaves in an intermediate fashion. Clay minerals can be identified and their relative proportions estimated by X-ray diffraction and spectrophotometric techniques, but rarely would such laborious methods be justified except for major projects.

(b) **Particle size.** Most expansive-clay behaviour is attributable to the influence of forces in the thin films of water surrounding and connecting grains of clay. With smaller grain sizes, the number and significance of these connections increases, which likewise increases the soil reactivity. The reactivity of the clay is moderated also by the amount of inert sand or silt particles present with the clay in the soil. The distribution of particle sizes may be determined in the laboratory, but it is a relatively time-consuming test.

(c) **Electrolyte composition.** The behaviour of a clay is influenced by the chemicals or electrolytes dissolved in the soil-water films at the grain interfaces. This dependence is most evident in the influence of lime stabilization on clays, where soil electrolytes are replaced by the calcium in the lime, thereby causing a reduction in the plasticity and expansive behaviour of some clays. However, in practice it is extremely difficult to ensure that the lime is dispersed uniformly throughout the foundation material.

(d) **Soil profile.** The soil profile is a record of the variation with depth below ground level of the different layers of foundation material, which are distinguishable by their colour, texture and composition. It can influence the reactivity of clay soil foundations in two ways. First, if the clay layer is very shallow, the total expansive movement will be lessened. Second, and more commonly, an upper soil layer of inert sandy or silty material can act as a moisture barrier and so reduce the amount of moisture change in the underlying clay layers.

So the behaviour of an expansive clay depends on a variety of parameters, some of which are difficult to quantify. It can be quite difficult to determine whether a particular clay profile is expansive and some guidance on this problem will be given in the next section.

IDENTIFICATION OF AN EXPANSIVE CLAY

In Melbourne, it has been possible to classify the expansive behaviour of the various soil profiles on the basis of geological maps. This has proved satisfactory because of the following special conditions.

(a) Most of Melbourne has residual soils which are formed by gradual weathering of the base rock *in situ*. Thus, their properties can be associated reliably with the underlying rock type. Also, the soils are generally consistent over large areas of the same rock type. In these circumstances, the classification of expansive behaviour can be based on a geological map. This is not possible for alluvial soils whose properties can vary significantly over a small area.

(b) The local climate consists generally of a dry, hot summer and a wet winter. Moreover, the clays are usually shallow (1 to 3 m depth). Thus, the extremes of seasonal moisture conditions can be used as a guide to the probable moisture changes under a building.

(c) In Melbourne, the clays have been studied extensively. This work has encompassed laboratory tests and field observations of actual houses, experimental footing systems and ground-movement stations. These data are not available for other regions.

On the other hand, in Sydney, much of the inner city area has been built on sandstone or on shallow sandy clay soils over sandstone, and consequently expansive clay movements are not significant. In the west of Sydney (e.g. Penrith, Blacktown and Campbelltown), the clays are sometimes deeper and potentially expansive. Sydney's climate provides substantial summer rainfall and consequently the changes in moisture conditions from summer to winter are not usually severe. However, in times of prolonged droughts, significant shrinkage movements, perhaps 10 to 40 mm, can occur.

Brisbane's more humid climate tends to diminish potential expansive clay movements although occasional drought does induce significant movement. Conditions are even more favourable in Perth, with the main city and suburban area being founded on sand. Hobart rarely encounters dry seasons severe enough to cause problems. Deep alluvial soils in the Tamar Valley south of Launceston have been known to present the occasional problem.

The situation is less favourable in Adelaide. The black earths (locally called Bay of Biscay soils) are highly expansive and also quite permeable. Adelaide has a very hot, dry summer and relatively heavy autumn/winter rainfall, so that changes in moisture contents due to seasonal surface effects can occur to considerable depths. Moreover, many of these areas are underlain by a highly plastic but almost impermeable clay ('Hindmarsh clay'). This clay is capable of substantial movements although the moisture changes that induce such movements may take decades to penetrate deeply into the clay.

In the rural areas of Australia, data on engineering properties of soils often do not exist. Invariably the reactivity of clay deposits has to be determined from first principles. Some of the more common methods of achieving this goal are as follows:

(a) **Experience and observation.** Perhaps one of the simplest methods is the observation of buildings, pavements, and fences in the area. These structures can be distorted by movements of highly expansive soils. Often such soils are well known by the local building department. Where there are no signs of distress to structures in an area where laboratory tests predict large movements, some circumspection is warranted before accepting the laboratory results.

(b) **Field experimentation.** A variety of field experiments is possible. A simple technique is to estimate the potential movement from the extremes of moisture content in the soil. The moisture content is measured at the end of a dry spell over various depths and again at a similar location in wet conditions. The movement is estimated by a simple formula relating movement to soil moisture change, which has been shown to be applicable for Melbourne Clays (refer Appendix A1).

Ground movement stations provide useful information. The movement at the surface and at depth is compared with a deep stable bench mark. Rods are installed in the ground at the required depths for monitoring. The sides of the rods are isolated from the soil. Observations are required over a range of moisture conditions and therefore one or more seasons are required to obtain any meaningful information. Accordingly, this technique may be practicable for major projects.

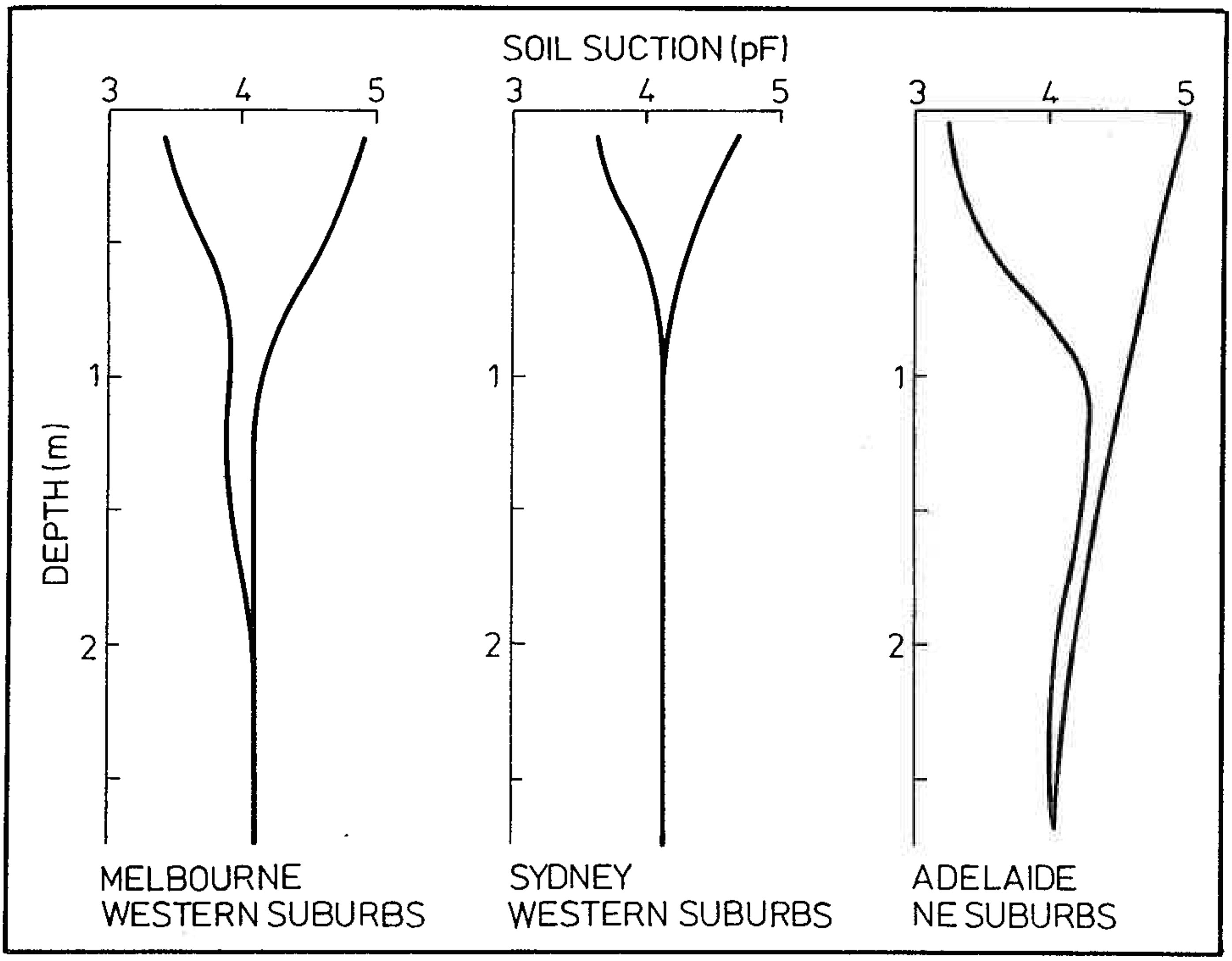
(c) **Simple laboratory testing.** The potential reactivity of clays is often related to index tests such as linear shrinkage, plastic limit, or proportion of clay-sized particles. An example of a simple classification system is given in Appendix A2. The reactivity of a clay certainly increases with these quantities but the relationship is not clear-cut and seems to depend on other clay properties that are not easily measured.

Simple correlations with index test values ignore the importance of the depth of the clay profile and the depth to which drying or wetting can occur. For Melbourne clay types and climate, experience has indicated that fairly stable sites could have clays with linear shrinkage values as high as 18%, although 12% would be more typical. Values above 20% were associated usually with highly expansive clay sites.

(d) **Precise laboratory testing.** In the laboratory, the expansion or shrinkage of clay samples can be induced by changing the moisture condition over a known range. The clay movement for a given moisture change is then conveniently termed the instability index of the soil. Once this instability index has been determined, ground movements at a particular site may be approximated by multiplying its value by the anticipated changes in soil moisture state with depth.

Measurements of this kind offer potential for a fairly accurate and rational theory for expansive clays. The more sophisticated tests are slow and expensive and therefore are often more suited to research than immediate practical design. However, other more simple test methods are available that are most likely adequate for engineering design problems.

Figure 1: Typical seasonal suction variations.



Terminology and Definitions

In order to discuss soil moisture changes, it is necessary to introduce the following basic technical concepts:

(a) **Soil moisture content.** The moisture content of soil is defined as the ratio of the weights of soil moisture and dry soil, expressed as a percentage. The significance of this moisture content value depends upon the type of clay. For example, at 25% moisture content, one clay may seem dry but another clay may be in a very moist state.

(b) **Soil suction.** A more useful concept is that of soil suction, which is a measure of the internal stress caused by the small amounts of water at the particle-to-particle interfaces. The common unit of suction is the pF unit defined in Appendix A3.

Generally, soil suctions can vary from pF 2.5 to pF5 under natural climatic conditions. High suction values are associated with dry soils and low suctions with wet soils. Over the normal range of suctions, moisture content is approximately linearly proportional to suction for a particular soil.

Soil suctions are commonly determined from measurements of the relative humidity of the air within the soil. Generally, good temperature control is necessary for reliable readings and measurements of suction are conducted in a laboratory rather than on site. (Further information on soil suction is presented in Appendix A3).

(c) **Instability index.** The instability index, as described earlier, is the percentage change in the height of a clay sample for a unit change in suction (%/pF). Typical values are commonly 3 to 6%, but for highly expansive clays the value may exceed 10%. (Refer Appendix A4 for methods of determination.)

Soil suction changes can occur around and under a building as a consequence of the following:

(a) Seasonal climatic effects.
(b) Interaction (the effect of the presence) of the building with natural seasonal moisture changes.
(c) Interaction of the urban infrastructure with natural seasonal moisture changes.
(d) Extraction of moisture by trees or recovery of soil moisture subsequent to tree felling.

Each factor is considered in some detail in the following discussion.

Seasonal Climatic Effects

Under natural conditions, the suction in the soil depends on the climate and vegetation. Over much of Australia, summer is a time of moisture loss with hot dry conditions. In winter, rainfall usually exceeds evapo-transpiration and wetter soil conditions prevail. These semi-arid conditions give rise to the typical seasonal suction profiles shown in Figure 1, where the variation in suction decreases with depth and finally reaches a stable value.

For more even climates, seasonal changes are not as significant and natural variations in suction are associated with exceptional droughts and wet seasons.

Interaction of the Building with Natural Seasonal Moisture Changes

When a building is first erected, the natural soil suction profile may lie anywhere within the range from the seasonally dry to seasonally wet profiles. The building then interferes with these conditions by sheltering the soil from rainfall and evapo-transpiration. If the building has a slab-on-ground or a suspended floor with poor sub-floor ventilation, the soil surface can be considered to be sealed. Consequently, soil suction near the centre of the building will come to equilibrium with the stable soil suction value at depth (refer Figure 2). The soil remote from the building will still undergo seasonal suction changes.

Below the centre of the building, there would be a long-term soil movement of either swelling or shrinking depending upon the initial soil suction. If the building was erected in the dry season (high suctions) there would be a long-term swelling, and the reverse would apply. This movement may continue for years or decades. Near the edge of the building, the soil suctions would be intermediate between the centre and seasonal values away from the influence of the building, and some seasonal variation would be expected. The resultant building deformation would tend to be as shown in Figure 3a.

Figure 2: Typical suction profiles beneath buildings.

Figure 2a: Sealed surfaces.

Figure 2b: Ventilated sub-floors.

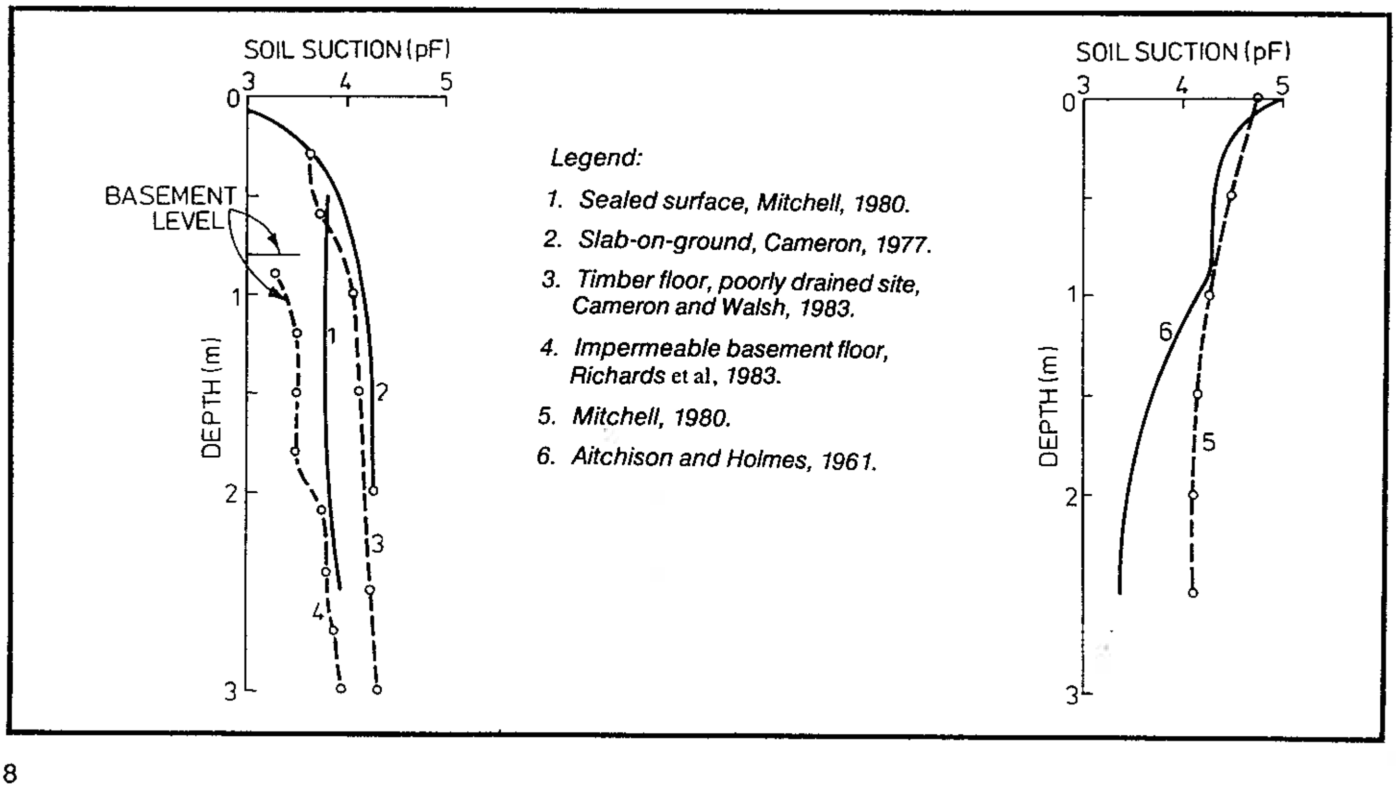


Figure 3: Typical deformation patterns.

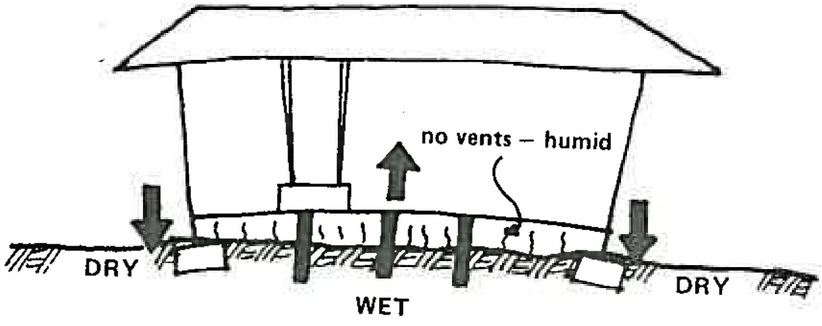


Figure 3a: Floor with no ventilation and poor site drainage.

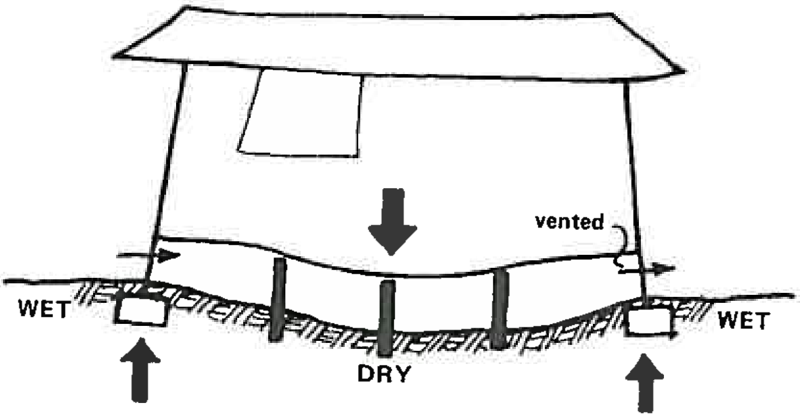


Figure 3b: Floor with ventilated crawl space and good site drainage.

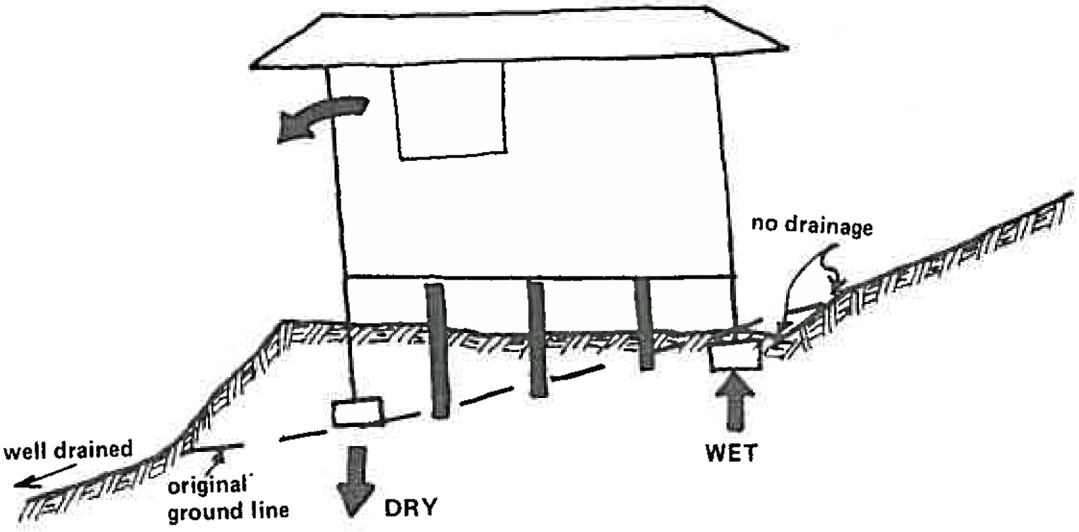


Figure 3c: Cut and fill site with poor drainage of the face of the cut.

This seasonal movement may not be completely reversible. A long-term shrinkage settlement can result from the moisture cycling under heavy loads.

Where the building is on a well-drained site and has a well-ventilated sub-floor space, the soil under the building will eventually become very dry as demonstrated by the suction profiles in Figure 2b. The resultant soil shrinkage may cause subsidence of the sub-floor supports as shown in Figure 3b. Such movements have been observed in some small multi-storey buildings as well as in houses.

Soil suctions under a building can be lowered also by plumbing leaks, bad drainage, site aspect, and garden watering. Plumbing leaks can produce disastrous movements, and should be remedied as soon as possible. Poor drainage is not uncommon. Particular care should be taken to ensure that surface water does not collect adjacent to footings and that roof drainage is maintained properly. The effects of inefficient drainage are often most noticeable on cut-and-fill sites where water accumulates in the cut area yet drains freely from the filled area on the opposite side of the building. Consequently, the soil heaves along one side but shrinks along the other, and the building almost leans downhill (refer Figure 3c).

Differential drying can arise from the site aspect, with an exposed north side of the building experiencing more severe drying cycles than the shaded southern area. Garden watering has produced failures, usually from the excessive use of fixed watering installations. Proper maintenance of moisture conditions in a garden is essential to prevent either excessive soil drying or wetting.

Trees can have an enormous effect on soil suctions and will be discussed separately.

Interaction of the Urban Infrastructure with Natural Seasonal Moisture Changes

For very deep clays, long-term changes in moisture conditions will occur as a region changes from a natural grassed, wooded area, or market garden with established drainage and seepage areas, to an urban environment with paving, buildings, gardens and efficient stormwater drainage. Changes from septic to sewerage systems will also change the overall soil suction profiles. These changes are superimposed on the seasonal and local effects mentioned in the previous section. They have their most significant influence on the deeper layers of clay, say from 3 to 15 m. To some extent, swelling movements are restricted by the soil overburden pressures (or self weight) at depth, but nonetheless large movements are possible. Moreover, these movements occur below the level of most footing systems. The movement may proceed very slowly; for example, movements in Adelaide have been recorded over a period of 30 years. Generally, if the deep-seated movement takes place over a wide area, buildings may not be adversely affected unless building sites are located across a boundary of the affected area, or soil reactivity varies sharply within the area allowing differential ground movements to occur.

Extraction of Moisture by Trees or Recovery of Soil Moisture Subsequent to Tree Felling

Trees require substantial amounts of water. During dry spells, tree roots draw moisture from the soil. If soil water storage is not fully replenished, the roots will extend in search of further soil moisture in subsequent dry periods. Clays will shrink with extraction of moisture (increasing suction) and subsequently, overlying structures may settle.

The removal of large trees poses the converse of this problem. As soil moisture is gradually restored, clays swell and heave. Shallow seated footings may be uplifted by the soil, depending to a large extent on the loads carried by the footings.

There are many factors that determine the extent of moisture removal by trees. Some of the more important factors are as follows:

(a) **Soil profile.** Obviously, the proportion of expansive clay in the profile is a determining factor in assessing the potential for damage to a building. However, the soil profile can also affect tree root growth patterns and hence the potential zone of drying. For example, the presence of a water table or rock layer may control the extent of root growth since roots will not penetrate either of them. Furthermore, if an expansive clay is covered by non-expansive soil layers, the depth of root penetration relative to the depth of the top layers will determine the overall movement.

(b) **Proximity of trees.** The lateral root systems of trees act as the primary soil moisture collector. Limited field data (Yeager 1935) indicates that soil moisture conditions and tree species are the main factors in determining lateral root spread. In persistently wet soil, roots tend to be more concentrated and penetrate deeper.

For convenience, the lateral root spread can be related to the height of the tree, H, and may vary from 0.4 to 2.1 H in natural field conditions (Yeager 1935). So the potential zone of soil drying in terms of the tree height can vary considerably.

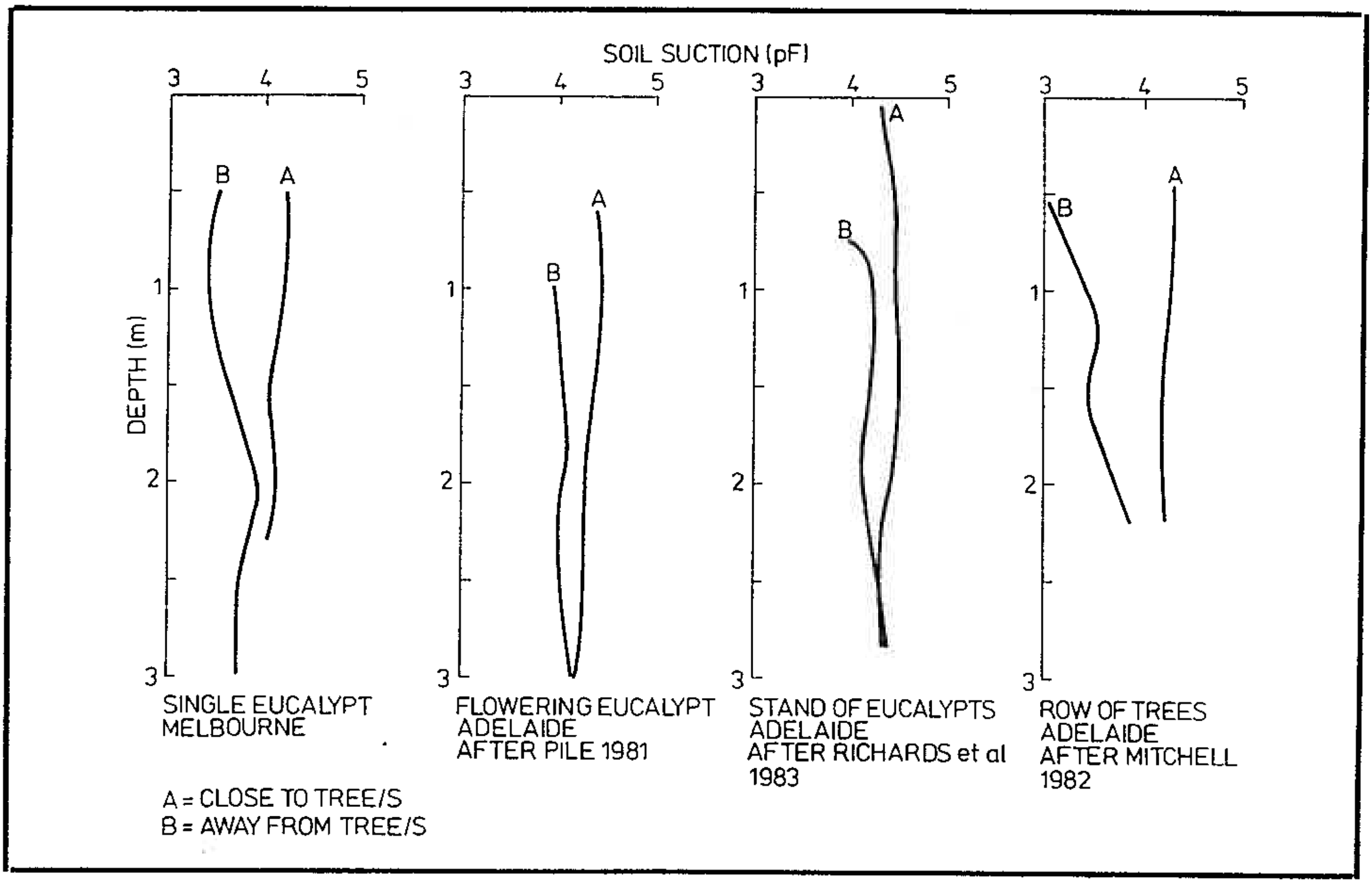
(c) **Number of trees.** The competition for soil moisture between the roots of neighbouring trees may extend the normal lateral root spread of individual trees.

(d) **Tree species.** The species of tree determines the tree's potential water uptake, the pattern of root development for a given site, and its ability to survive in dry soil conditions. In other words, the species can determine the zone of soil drying and the extent of drying within that zone.

(e) **Age of tree.** The age of the tree relative to the building is important when considering whether it is safe to remove a tree. If the tree is much older than the building, a careful analysis of soil conditions will be required to prevent damage by heaving foundations. If however the tree is younger than the building, then the maximum possible heave after the tree is removed will be less than the soil shrinkage that has already occurred. Damage may still occur if old settlement cracks have been filled with rigid fillers. As the foundations heave back the filler is compressed, causing bulging of wall renders.

To demonstrate the potential extent of suction changes in clays occurring as a result of moisture extraction by trees, a few typical suction profiles have been reproduced from the literature in Figure 4. Generally, the suction data have been determined during investigations of building damage in which a suction profile in the ground between tree and building has been compared to the profile in an adjoining area relatively devoid of trees. Such studies give valuable information regarding the possible depth and extent of the tree drying effect.

Figure 4: Typical suction profiles near trees.



RESPONSE OF BUILDINGS TO FOUNDATION MOVEMENTS

The tolerance of a building to foundation movements brought about by moisture changes in clays is determined by the type of construction of its footings and walls and the building materials used.

Footings

The footings of old buildings are frequently inadequate. Concrete for footings became part of general building practice only towards the end of the 19th century, but steel reinforcement for concrete was not introduced until the 1920s. The addition of reinforcement led eventually to the concept of the footing as a beam with some capacity (or stiffness) to span local ground movements. Prior to this time, footings were used only to transmit building loads to the soil and therefore non-structural footings of rubble, stone, or brick were common.

Reinforced concrete strip-footings are capable of some beam action, which increases with both the level of reinforcement and the depth of the section. Increasing the footing depth is also advantageous in those expansive clay areas where the depth of moisture change is relatively shallow. As the depth of the footing approaches the depth of negligible moisture change, potential movements at the footing base decrease to zero. However, deep footings can interfere with normal soil moisture distribution, thereby creating differential moisture conditions and hence soil pressures either side of the footing sufficient to rotate it. The increased surface area of the footing can also give rise to high friction forces in a swelling soil.

Deep basements or cellars act as an extended footing system and thereby reduce building movements when compared with similar buildings seated on shallow footings.

Deep piers or piles that penetrate the zone of soil suction change can be most effective in resisting the effects of reactive soils. However, problems can still occur in older buildings. First, shrinking soils remove side friction support so that friction piles may become effectively overloaded as the soil dries, and some load settlement may occur. Second, swelling soils can cause uplift of piers (or piles), the magnitude of which is controlled by the depth of the pier and the load carried by it. If the pier is not reinforced, uplift forces can cause tensile failure of the pier section.

A further problem exists with the footing beams supported by the piers or piles. In the case of swelling clay soils, the underside of the beam must be isolated adequately from the surface soil movement, otherwise the beam may be pushed up off its pile supports.

Walls

Walls vary considerably in their tolerance to footing movements. Apart from the type of wall, tolerance to movement can depend upon the number and size of openings, the height to length ratio of the wall, the degree of articulation in the wall, and the pattern of the ground movement. Articulation is the segmentation of long walls into smaller panels with the use of vertical construction joints, full height windows, and/or independent infill panels over openings. Its effect is to accommodate movements by providing freely opening and closing joints in the wall.

The type of wall material and construction has a considerable effect. Modern brick-veneer construction is thought to be between 2 and 3 times as accommodating as cavity brick. Common wall types in order of increasing tolerance to footing movement are stone masonry, cavity brick, brick veneer and weatherboard.

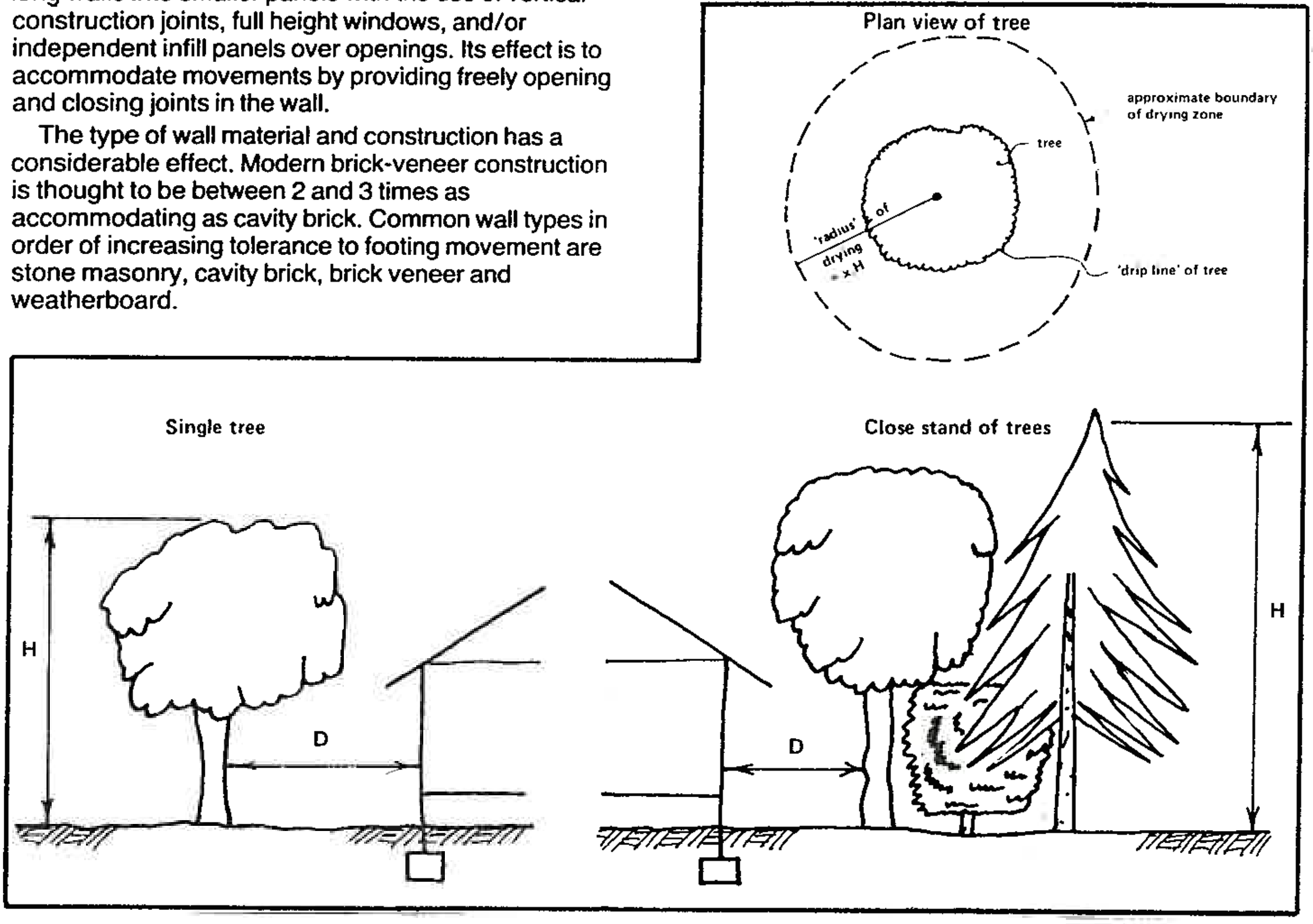
SUMMARY OF EMPIRICAL TREE PLANTING RULES TO AVOID BUILDING DAMAGE

Some of the many factors that influence the magnitude of soil suction changes caused by trees have been discussed already. The extent to which subsequent expansive clay movements are translated into building movement and damage is governed by the nature of the particular building.

To minimize the risk of damage, empirical tree planting rules state the minimum safe horizontal distance (D), in terms of a proportion of the tree's maximum height (H), at which a tree can be planted from a building's perimeter (Figure 5). A brief review of the available literature on tree damage to buildings is presented in Appendix B. Wherever possible, damage observations have been related to D:H ratios.

Building damage is unlikely if D:H exceeds 1 for single trees and 1.5 for dense stands, rows, or clusters of trees. These limits may be relaxed if the soil profile or clay reactivity is such as to limit potential shrinkage settlement, the building is relatively tolerant to distortion, or its footings are able to resist movement. For example, investigations have shown that the risk of damage to conventional brick-veneer dwellings in Melbourne is minimal for a D:H ratio greater than 0.5. Unfortunately, there is very little evidence at present to allow variations in the D:H limits for different species of trees, although it should be possible theoretically.

Figure 5: the D:H ratio for empirical tree planting rules.



INVESTIGATION AND REPAIR OF BUILDING DAMAGE

Effective repair of buildings cannot be achieved without a proper investigation of the problem to uncover the cause (or causes) of damage. Further analysis of the site may then be required to determine the feasibility of rectifying the damage. In all circumstances, the initial diagnosis should be approached with an open mind and must be carried out methodically.

Causes of Damage

Most of the causes of wall cracking can be classified according to the stage of planning or construction of the building during which they occur, as described below:

(a) **Site investigation.** Either a site investigation was not required or the investigation failed to reveal potential problems. In the case of older buildings, where the emphasis was placed on soil bearing capacity, the possibility of reactive clay movements may not have been explored.

At sites where load settlement could be a problem, important information may not be revealed if the investigation has not been carried out to suitable depths or has not been extended adequately to encompass the whole site. The properties of the soil within a depth below the footing equal to twice the footing breadth influence the load-settlement behaviour of the foundation. The number of exploratory boreholes required is dependent largely on the site conditions. For example, it is well-known in Melbourne that Quaternary basalt flows can vary considerably across a site. As a consequence, one corner of a building may be underlaid by rock and the opposite corner by a considerable depth of residual soil.

(b) **Footing design.** The designer may misinterpret the site investigation report or, in the absence of a report, wrongfully assume certain soil properties. Again, lack of knowledge of soil moisture movements has resulted in inadequate designs for older buildings. A further problem may exist where footings have been designed structurally, but the designer has failed to consider the susceptibility of the superstructure to cracking, and deflection tolerances have been exceeded.

(c) **Site drainage provisions.** Drainage is an essential consideration to prevent excessive moisture movements and consequent heave or consolidation of soft or loose soils. Therefore the specification of site drainage should be a design responsibility that must be coordinated with landscaping requirements.

(d) **Construction.** Faults in construction arise commonly from poor workmanship, mis-reading of plans, and ignorance of the properties of building materials. Concrete shrinks and subsequently cracks, and often the cracks are taken wrongly as an indication of settlement. Masonry expands and so can induce vertical cracking in long runs of walls at restraints such as building corners. Green hardwood timber in subfloors or wall frames can distort significantly as it dries, thereby cracking the building elements it supports.

(e) **Post-construction maintenance.** In terms of moisture movements in reactive clays, the more common problems include location of trees too close to the building, and neglect of either site drainage or the maintenance of plumbing lines. A further problem may exist with pier and beam construction where a gap was provided beneath the beam to isolate it from soil heave, but has later been filled during landscaping of the surrounding area.

Other causes of damage do exist which do not come into any of the above categories. For example, the dewatering of foundation excavations in neighbouring properties, vibrations arising from either blasting or traffic, and underground mining, all lie largely outside the direct control of the property owners.

A Routine Investigation Procedure

To ensure a thorough diagnosis of the cause of building movements, each investigation should follow a planned, standardized procedure. One suggested routine is as follow:

Record construction data.
Obtain the history of the damage.
Record crack locations and widths.
Conduct a level survey of the building.
Ascertain the typical soil profile of the site.
Obtain soil samples at depth across the site.
Carry out laboratory or field tests if required.
Analyse the above information.

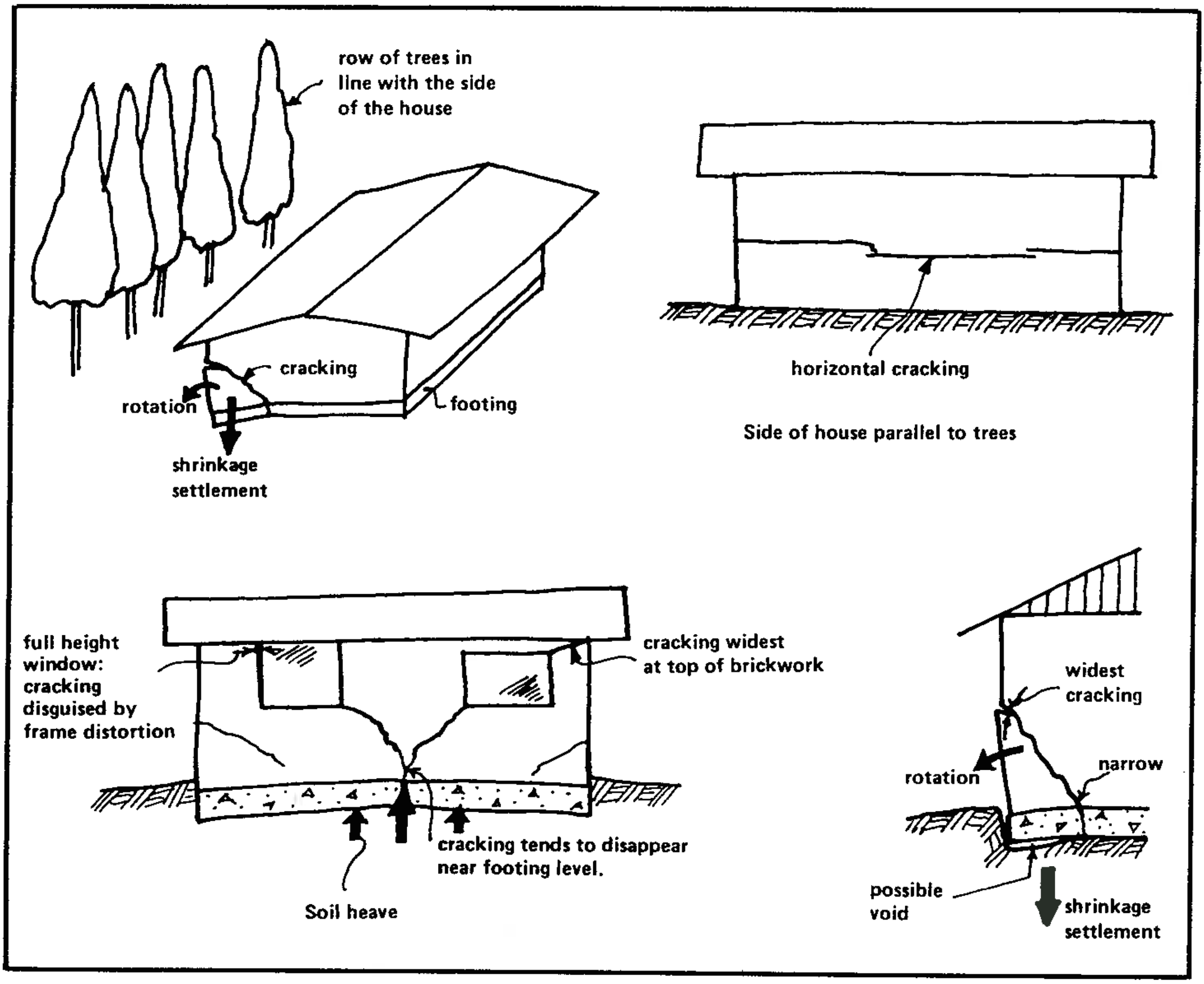
Construction data are essential in determining qualitatively the susceptibility to movement of the building as a whole. The type of footings, their dimensions and reinforcing, as well as the wall contruction, are all important factors. In some cases, construction plans may not be available and an excavation must be carried out to gather the necessary data.

The history of damage may provide clues to the cause of movement. Cracks that appear in summer or early autumn are unlikely to be caused by soil consolidation, but rather by soil shrinkage, Cracks that open in summer but close to some extent in winter are due probably to reactive clays, while cracks that progressively get larger as time proceeds can be due to either secondary consolidation of soft clays or extended drying of reactive clays by growing trees.

The date when damage was first noticed can verify whether any substantial changes in the environment of the building could have been responsible for the movement. For example, in the case of tree damage, damage could be expected to appear within 5 to 10 years of tree planting in a semi-arid climate. In more temperate climates, however, damage may not become apparent until the first major drought after planting.

The location, direction, and width of cracking provide clues as to the mode of deformation of the footings and the magnitude of the differential movement. Horizontal cracking indicates that a wall has bowed, possibly as a result of footing rotation. Cracks that are wider at the top of a wall than at the bottom occur when footings are

Figure 6: Common crack patterns and their causes.



in the centre-heave or hogging mode. Dishing movements have the reverse effect. Figure 6 illustrates some common crack patterns and their causes.

The widths and frequency of cracking are used to assess the extent of damage (Appendix C), which may help to provide a more rational basis for selection of an appropriate remedial treatment.

Level surveys of damaged buildings are often particularly valuable. With due regard to original building tolerances, they can still provide a reliable picture of differential movements across a floor. Generally, with older buildings, levels may be taken only on masonry walls preferably at or near the damp proof course. Timber floor levels will probably be unreliable due to either previous re-stumping operations or possible fungal decay problems at the time of inspection.

Once the mode of footing deformation has been established, the reasons for the foundation movement must be investigated. A quick check of the soil profile will soon confirm the probability of soil consolidation or reactive clay movement. If the latter is suspected, a comparison of soil moisture conditions beneath the high and low spots of the building will be essential to the investigation.

Remedial Treatments

Knowing the cause of the damage, a remedial treatment may be assigned that takes into consideration the present extent of damage and both the risk and cost of further damage.

In severe cases of load settlement, a form of underpinning is normally recommended to stabilize the movement of the building. Underpinning provides new support to the building and can either be designed to decrease foundation pressures using wide underpins (Figure 7a) or to transfer the foundation loads by means of piers to a deeper and stronger base (Figure 7b). The latter result may be achieved also by small diameter 'root' piles (Figure 7c) which are, in effect, concrete piers cast by a pressure injection technique (Koreck 1978).

Figure 7: Underpinning techniques for load settlement.

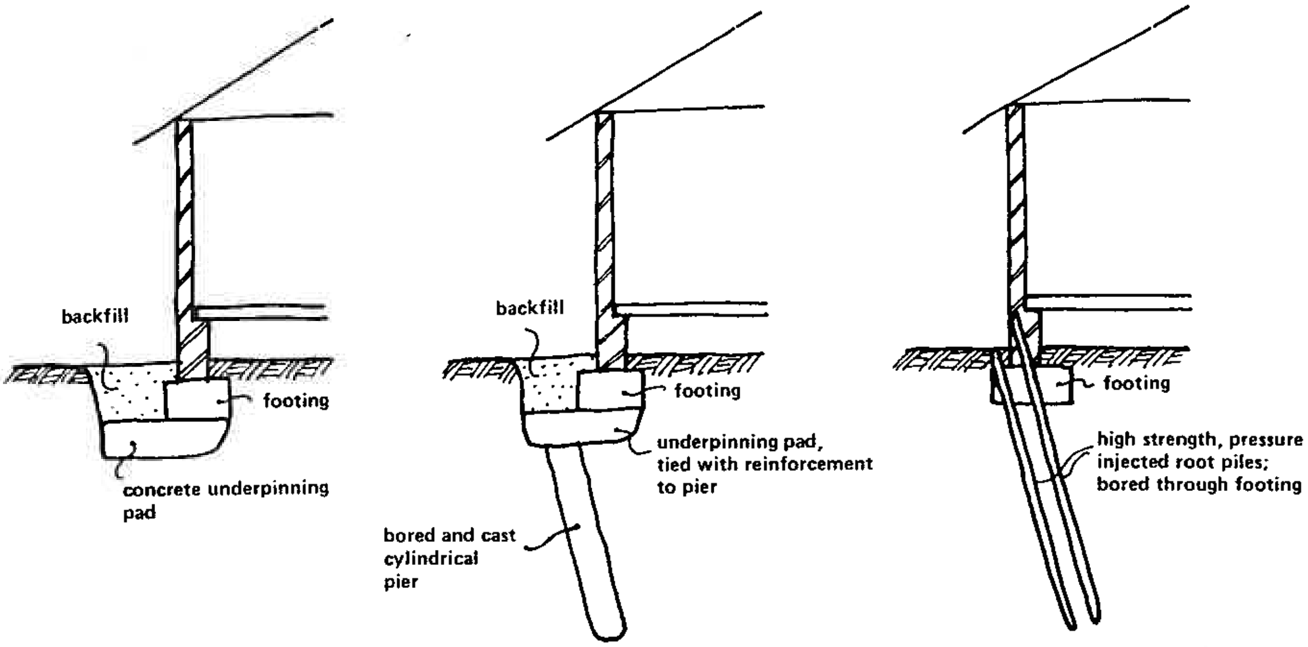


Figure 7a: Traditional underpinning. Figure 7b: Deep underpinning with piers. Figure 7c: Underpinning with root piles.

Figure 8: Cut-off wall construction.

Figure 8a: Typical details.

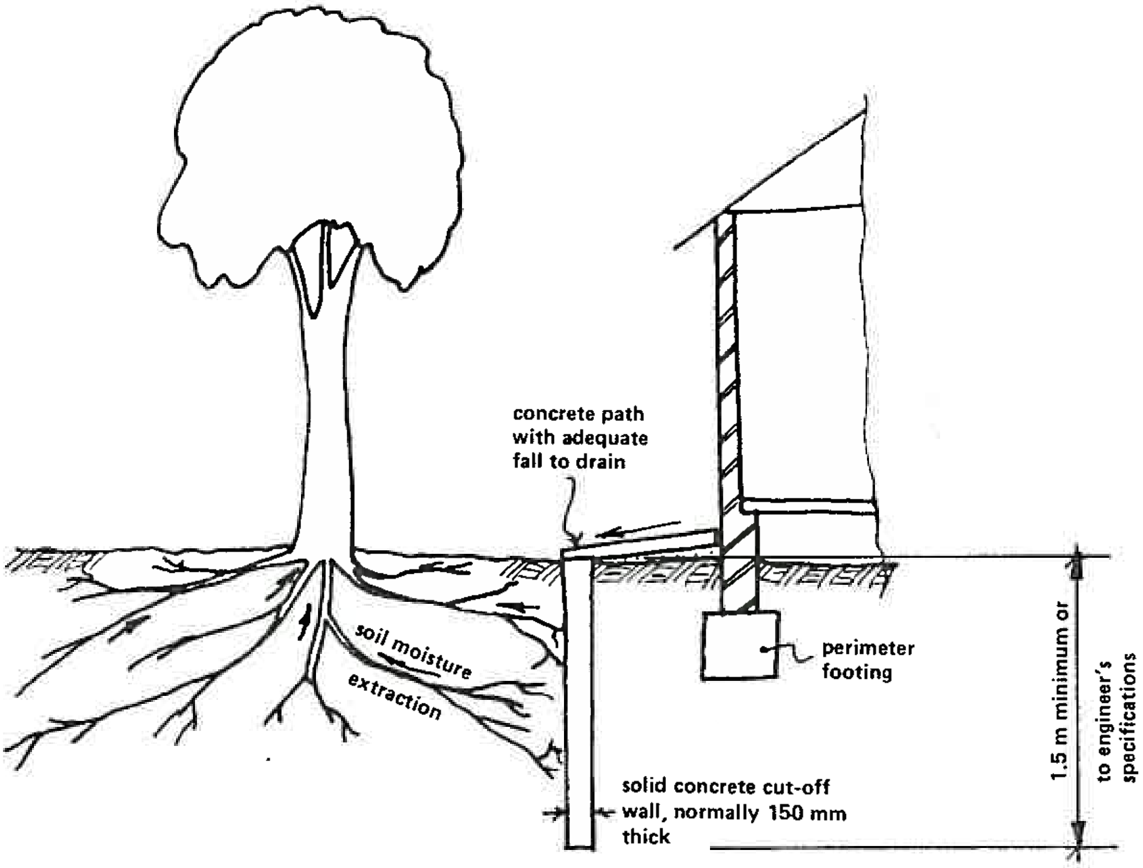


Figure 8b: Construction of a concrete cut-off wall.

However, the use of underpinning in cases of damage due to expansive clay movements is limited and needs to be carefully designed to suit the particular situation. In such cases, the strength of the soil is rarely in question and the underpinning is required to stiffen the footing system or carry the footings to a stable depth. If shrinkage settlement has been responsible for the building damage, the latter option by itself may be adequate to stabilize the building. Where soil heave is a problem, the existing footing system should be structurally tied to the deep underpins. Root piles may then be the most satisfactory solution.

Alternative solutions consist of balancing differences in soil moisture distribution about the building. Lime stabilization will not be discussed as an option because of lack of experience with this technique and the recently reported failures of field trials (Poor 1975, 1976, 1978). Where damage is slight and the expected risk of further damage is low, moisture differences may be corrected by simple watering programmes and rectification of obvious causes of soil drying. Water is often required to penetrate deeply into a clay. Therefore, watering of narrow trenches cut into the clay or of regularly spaced, shallow boreholes is preferred to hosing of the soil surface.

Where the damage is more severe, a vertical cut-off wall may be installed beside the building to help redistribute and equilibrate soil moisture conditions. The cut-off wall consists normally of a thin (150 mm) but continuous concrete wall to a depth of at least 1.5 m (see Figure 8). The actual design depth is governed by particular site conditions. The services of a geotechnical engineer may be required to estimate this depth.

Figure 9: Soil swell v. *vertical restraining load.*

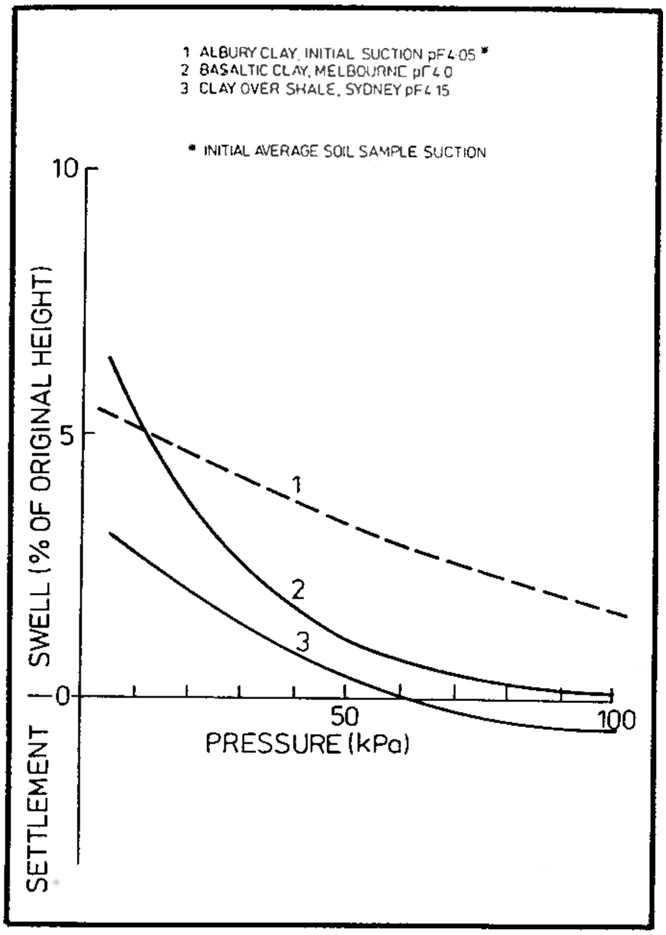


TABLE 1

REMEDIAL TREATMENTS FOR TREE-DAMAGED BUILDINGS OF SINGLE STOREY BRICK VENEER CONSTRUCTION

Level of damage	Treatment
Slight	Regular watering below the drip line of the tree (line below the outer extremity of the foliage).
Low	1. Trees which are within a distance from the building equal to one-third of their height to be regularly pruned (foliage only) and soil water reservoirs to be employed, or 2. Remove trees within one-third their height to the building.
Moderate	1. Regular deep root-pruning of trees within one half their height to the building, 2. Removal of trees within one half their height to the building, 3. Employ deep cut-off walls as root barriers and soil moisture redistributors, or 4. Employ deep underpinning.
Severe	1. Remove trees within three quarters of their height to the building, 2. Use cut-off walls, or 3. Employ deep underpinning.

Remedial Treatments for Tree Damaged Buildings

Taking the particular case of footings damaged by tree root absorption of soil moisture, remedial actions can be recommended that match the degree of damage as outlined in Table 1.

Cut-off walls, underpinning, and tree felling are the passive options in that they require little attention after the initial action, unlike the alternatives of soaking and pruning. In this respect, they are attractive options to property owners. However, both cut-off walls and underpinning need to be engineered carefully with due consideration to the extent and depth of soil drying or subsequent tree root development. Furthermore, cut-off walls are impractical where there is evidence of substantial drying below a depth of 2 m.

In certain circumstances, underpinning may turn out to be the only option. Table 1 gives remedial treatments for modern housing but not for larger buildings where foundation pressures may be much higher. As demonstrated in Figure 9, soil heave is dependent on load or pressure. Therefore, if the foundation pressures are relatively high, the possibility of soil recovery upon moisture restoration and hence closure of cracking may be correspondingly low. Laboratory soil-swell testing may be required to justify recommended remedial treatments in such cases.

Where soil shrinkage has been severe, regardless of loading conditions, it is most likely that full recovery of the building movement will not be possible, as many reactive clays suffer small but irrecoverable losses of volume as they dry out.

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APPENDIX A — IDENTIFICATION OF EXPANSIVE CLAYS

A1. **Soil Movement for Change in Soil Moisture Content**

Richards (1967) proposed the following relationship:

$h/H = (SG/3)\,(W_2 - W_1)/(100 + W_1 SG)$

h = vertical soil movement (m) in a layer of clay soil, H(m) thick, which experiences an average moisture content change from W_1 to W_2%.

SG = soil specific gravity (g/cm^3).

The above expression has been demonstrated to provide good estimates of seasonal soil movement (Holland and Lawrence 1980, Holland & Cameron 1981). The soil profile is divided into small layers and the vertical soil movements are calculated for each layer and added to give the total movement value. Soil moisture data are commonly in the form of suctions rather than moisture contents. Suction values are converted to moisture contents using an approximate linear correlation established for the particular soil in the laboratory.

The expression assumes that the soil voids are filled with water and therefore should theoretically only apply to either saturated or quasi-saturated soil. Thus, errors may become more significant as soil moisture contents fall below the plastic limit. Also, it assumes that swelling strains are equal in both the horizontal and vertical directions, i.e. the vertical strain is equal to 1/3 of the volumetric strain. This may be so for dry, heavily fissured soil, but the proportion of vertical movement will increase as swelling continues, closing fissures and producing large lateral soil pressures. In one field trial, McKeen and Hamberg (1981) demonstrated that between 0.7 and 0.8 times the volume change took place vertically. However their method of predicting the soil volume change was different to that described herein.

A serious limitation of the expression is that it does not take into account the effects of loads on the soil and so may be used only to estimate relatively shallow seasonal ground-movements and not movements beneath loaded footings. Therefore, estimates will tend to be conservative.

A2. A Simplified Classification of Soil Reactivity (Williams & Donaldson 1980)

The classification is based solely on the plastic index (PI) of the whole soil sample. Normally, laboratory determinations of PI are carried out on the fines of the sample, so that a correction must be made to this value as follows:

PI of whole soil = (PI of fines) (mass of fines fraction)/(mass of whole sample)

The classification is then:

PI (%) of whole sample	**Expansiveness**
<12	low
12<PI<24	medium
24<PI<32	high
>32	very high

Figure A1: Typical suction-moisture content relationships for different soil types.

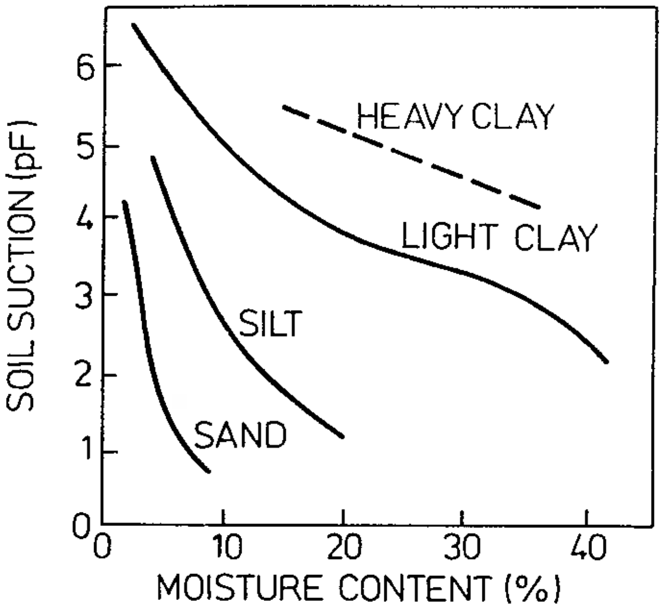
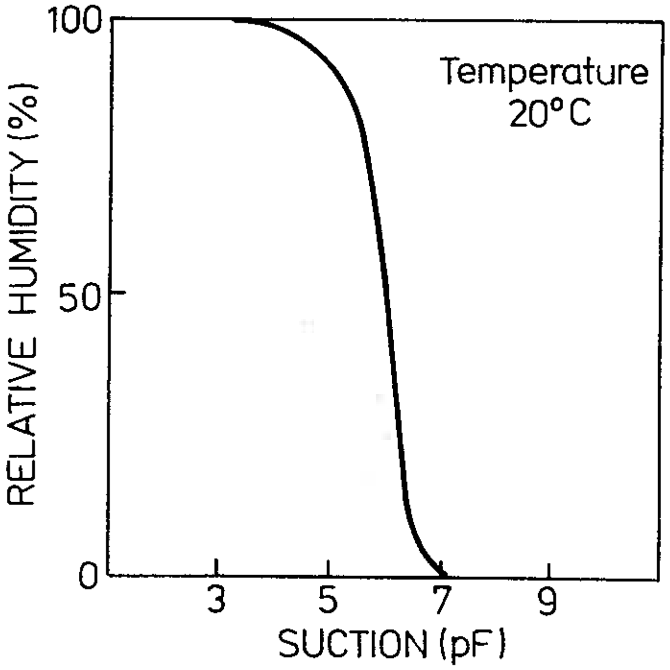


Figure A2: Relative humidity v. *suction, 20°C.*



A3. **Soil Suction and Its Measurement**

As demonstrated in Figure A1, soil suction is not only a function of moisture content but depends upon the type of soil. As distinct from soil moisture content, soil suction is a measure of internal soil pressures.

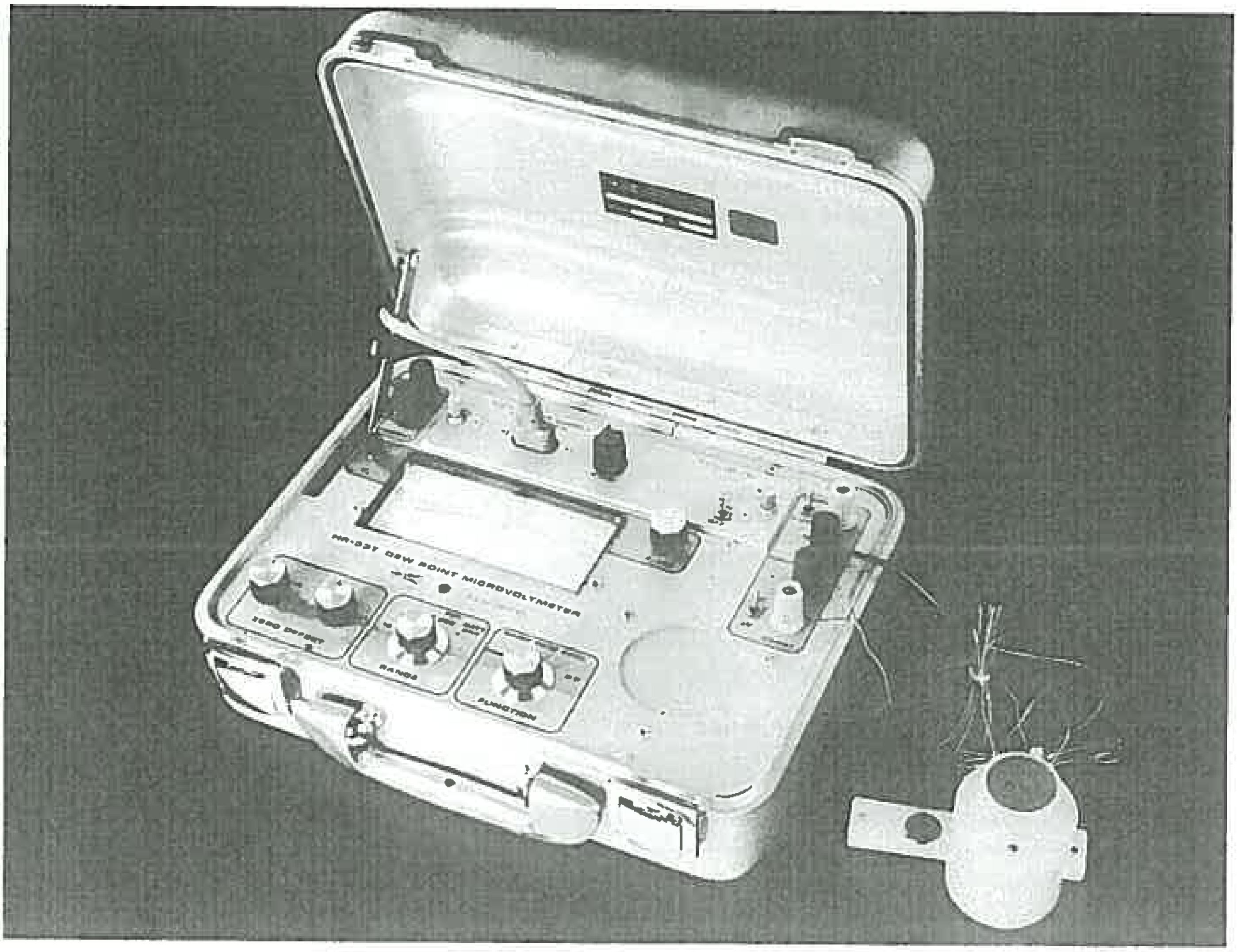
Therefore the units of measurement of suction are those of pressure. However, rather than use kPa, it has been found convenient to use a logarithmic unit, pF, which is defined as

$$\text{suction, pF units} = \log_{10}(\text{suction, kPa units}) + 1$$

Soil suction has two basic components; solute and matrix suction. The former is associated with the osmotic potential that occurs between solutions of different salt concentrations which are separated by a semi-permeable membrane. The latter consists of soil water surface-tension and electromagnetic forces, which act on the clay particles. A more detailed explanation of soil suction is given by Peter (1979). The soil suction measured in engineering laboratories is commonly total soil suction, which is a function of the relative humidity and the temperature, as demonstrated in Figure A2. The wet and dry-bulb hygrometer principle is regarded as the most reliable method of measuring relative humidity within the range of humidities shown in Figure A2. Therefore psychrometers employing this principle are commonly used. At least one commercial soil psychrometer is available under the American trade name, Wescor. The laboratory model is shown in Figure A3.

Alternatively, soil suction can be measured by using calibrated filter papers as indirect soil water sensors. Essentially the method consists of equilibrating the internal moisture stresses of the filter paper and soil which are kept in contact in a sealed container over a period of a week, determining the moisture content of the paper and then, from calibration data for the filter paper, deriving the corresponding value of soil suction (McQueen and Miller 1968, or Department of Main Roads, NSW 1977, 1980), the latter method requires the soil to be kneaded to ensure good contact with the soil. It is not known as yet how significantly this affects the soil suction value.

Figure A3: Wescor soil suction equipment.



A4. **The Instability Index**

The instability index is determined by measuring the percentage change in height of a soil sample caused by a known change in soil suction. Ideally, either solute or matrix suction may be varied. Membrane oedometers have been designed to provide such control (Peter 1979).

Investigation of solute suction effects may be important in certain saline areas, however it is accepted generally that matrix suction changes more often control clay behaviour.

Owing to the tedious nature of membrane oedometer testing, more simple methods of estimating the instability index for total suction change have been evolved. Shrink-swell tests on undisturbed specimens are being used more widely. In this method, two sub-samples of similar suction are prepared from a clay sample. One sub-sample is loaded to the required pressure, it is then innundated, and the sample swell is recorded over a period of 1 to 2 days. The final suction of the sub-sample can be measured.

The other sub-sample is either allowed to air-dry to an equilibrium mass or is dried at constant temperature in a vacuum dessicator over a supersaturated salt solution. Volume or length changes of the soil cores are measured during drying. The latter drying technique is preferable, since the relative humidity or suction of the sample is known once the soil mass reaches equilibrium. (e.g. for an ammonium chloride solution at 20°C, the equivalent suction is pF 5.5), whereas in the former case the end suction is often assumed. The various tests are depicted in Figure A4.

To calculate the instability index, the total percentage change of sample height in the swelling and shrinking tests is divided by the change in suction from the wet to the dry soil states. The method assumes that the instability index is a constant over the range of total suctions considered.

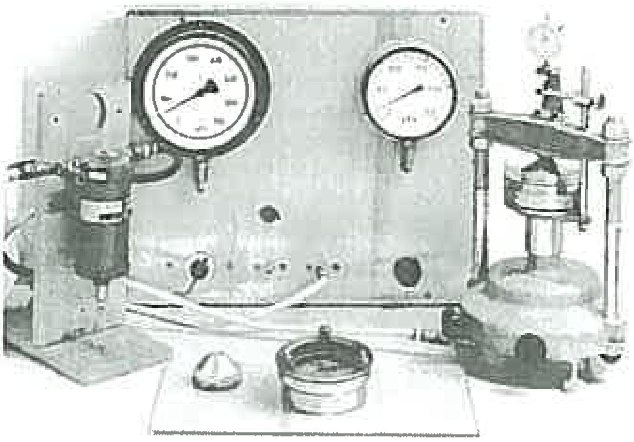
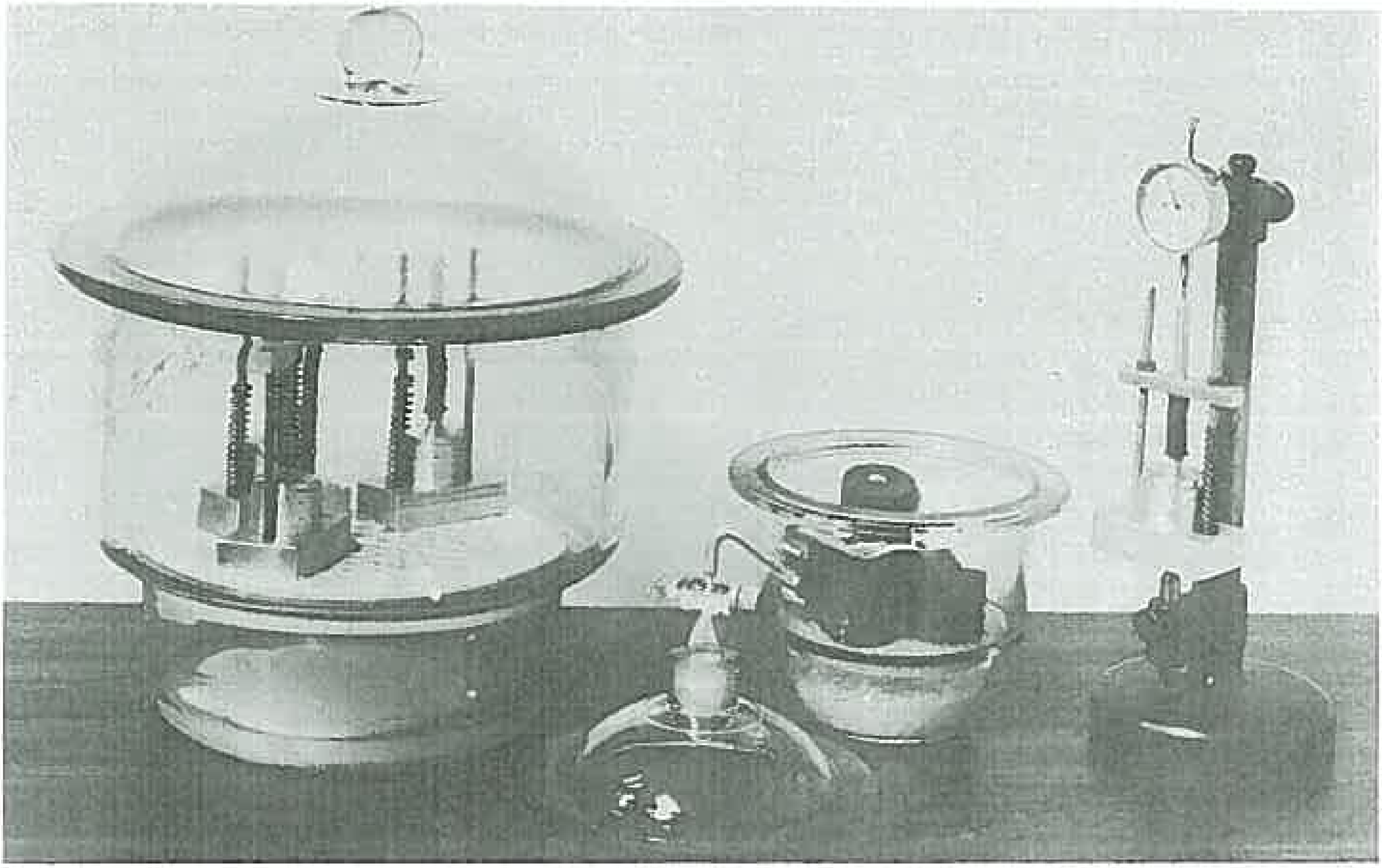


Figure A4: Laboratory methods of estimating the instability index.

Figure A4: (above) Swell testing cells.

Figure A4b: (below) Shrinkage testing. Spring-loaded shrinkage specimens in a vacuum dessicator over a saturated salt solution and soil cores with drawing pins embedded at their ends for length measurements.



APPENDIX B — REVIEW OF EMPIRICAL PLANTING RULES FOR TREES NEAR BUILDINGS

Owing to the complex nature of the problem of tree damage, simple empirical relationships have been sought between the ratio D:H (the closest distance of the tree to the building divided by the height of the tree) and the extent of drying and the frequency or severity of building damage.

Bozozuk (1962) demonstrated the effect of a row of elm trees 17 m high in a Canadian clay by monitoring the shrinkage settlement with depth (Figure B1). Surface movement decreased as D:H increased. Close to the row of trees, soil drying extended beyond 4 m but diminished rapidly at D:H values greater than 0.5. It may be concluded from the figure that a 1 m deep footing at a D:H of 0.75 would have experienced less than 10 mm of movement, depending on the stiffness of that footing.

Figure B1: Shrinkage settlement v. *depth and distance from row of elm trees, Canada.*

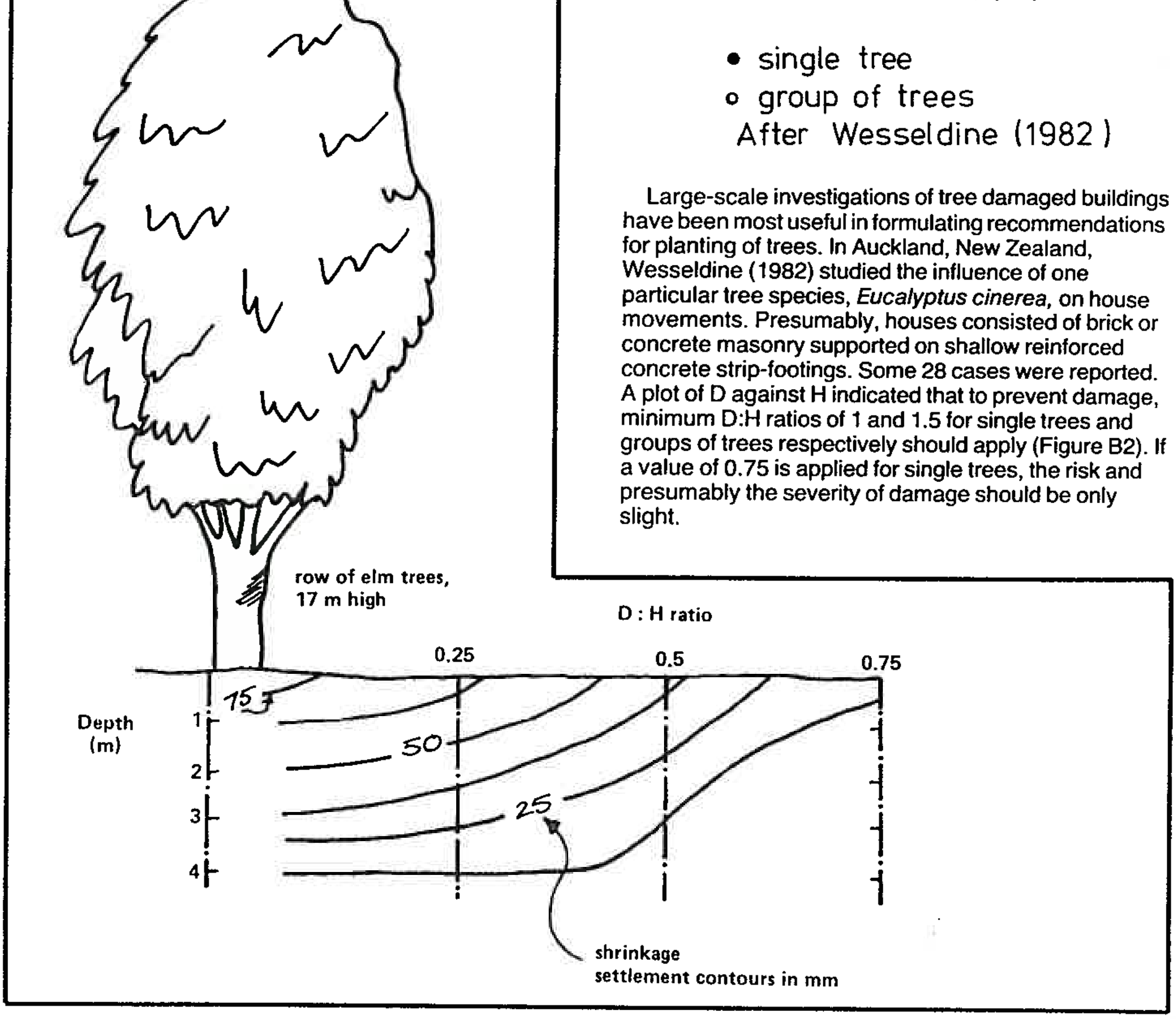
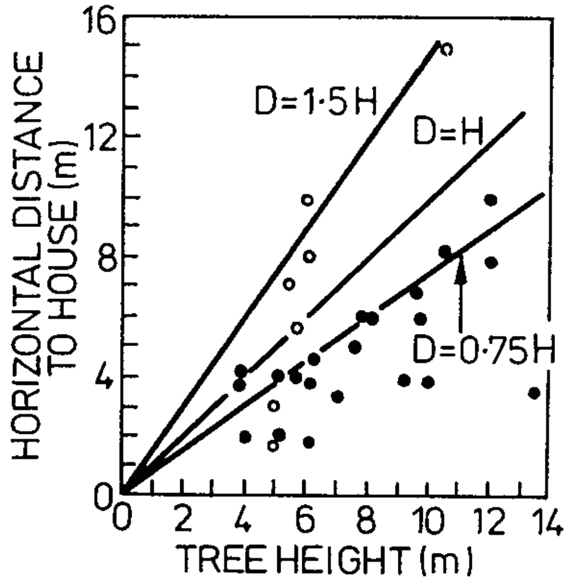


Figure B2: D:H ratios for Eucalyptus cinerea, *Auckland, NZ.*



Large-scale investigations of tree damaged buildings have been most useful in formulating recommendations for planting of trees. In Auckland, New Zealand, Wesseldine (1982) studied the influence of one particular tree species, *Eucalyptus cinerea*, on house movements. Presumably, houses consisted of brick or concrete masonry supported on shallow reinforced concrete strip-footings. Some 28 cases were reported. A plot of D against H indicated that to prevent damage, minimum D:H ratios of 1 and 1.5 for single trees and groups of trees respectively should apply (Figure B2). If a value of 0.75 is applied for single trees, the risk and presumably the severity of damage should be only slight.

CSIRO investigations indicate that for Melbourne conditions, a D:H ratio of 0.75 for either groups or single trees should restrict adequately the incidence of damage to modern brick veneer houses founded on conventional shallow strip footings (Cameron and Walsh 1981). An attempt was made to demonstrate the relationship between the degree of damage and D:H (Figure B3). However, lack of data and variations in reactivity of clays, soil profile and tree species impaired the demonstration. The degree of damage was drawn from the classification system of Tomlinson *et al.* (1978) which is reproduced in full in Appendix C. Holland (1979) also found that damage became markedly less severe for D:H greater than 0.5.

A similar approach was adopted by Tucker and Poor (1978) in a study of a suburban subdivision in Texas. Houses were typically brick veneer on concrete raft slabs. Trees included fruitless mulberry, elm, cottonwood and willows. Rather than relate D:H to a qualitative degree of damage, the researchers chose the measured differential vertical slab movement (Figure B4). Their plot does not distinguish between the movements brought about by the trees and that occurring normally as a consequence of moisture movements beneath slabs. However, at D:H greater than 2, it can be reasonably assumed that the trees have negligible effect and so the corresponding plotted points at or above this value represent the possible range of slab centre-heave in this subdivision. Therefore, the plot indicates that the effect of trees is not significant until approximately a D:H of 1.

Figure B3: Degree of damage v. *D:H Melbourne.*

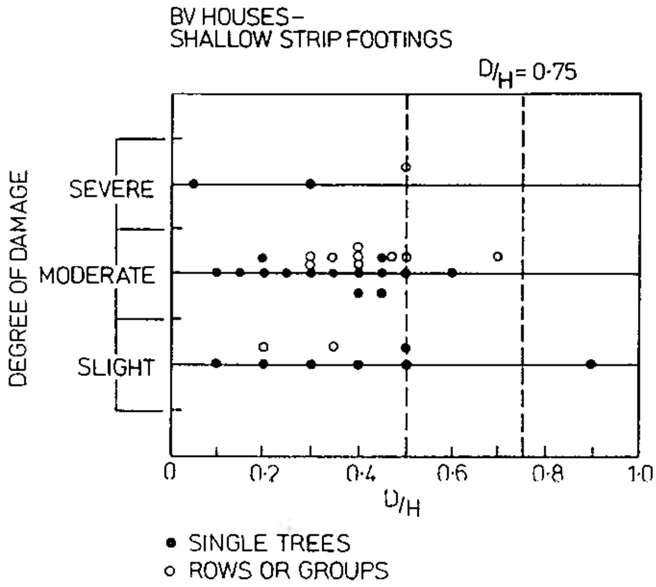
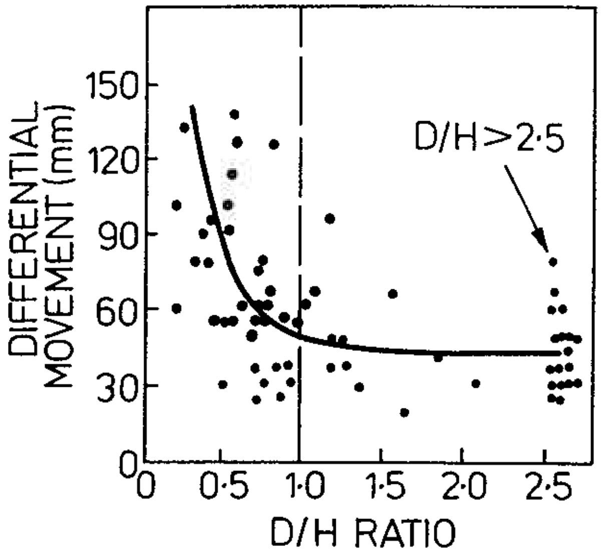


Figure B4: Differential slab movement v. *D:H, Texas.*



After Tucker & Poor (1978)

In England, Cutler and Richardson (1981) ignored consideration of the extent of damage but concentrated on the relationship between D and the frequency of any reported building damage for different tree species. Presumably the buildings involved were predominantly cavity brick construction supported by plain concrete strip footings. Since the authors gave estimates of ranges of common tree heights, their data can be summarized in terms of D:H ratios. Conservatively assuming that only the minimum tree height was achieved, the frequency of damage was equal to or greater than 10% for D:H equal to 1 for the following species — oak, elm, Sorbus species, horse chestnut, cherry, plum, apple and pear. However, if the *average* tree height is assumed, only the horse chestnut poses a 10% risk at a D:H of 1.

Trees that represented a moderate risk in the study included ash, willow, poplar, birch, plane and conifers. The last two were found to be involved in building damage at a frequency of less than 10% at a D:H ratio of only 0.5.

In summary, damage to buildings on clay sites will be most unlikely if minimum D:H ratios of 1 and 1.5 are adhered to for single trees and rows, respectively. Damage should, at worst, be slight. Obviously, some relaxation of this planting rule can be permitted after consideration of the factors determining the risk of damage, particularly the degree of expansiveness of the clay, the soil profile, and the susceptibility of the particular construction to movement. Unfortunately, lack of data on the effect of tree species prevents comprehensive allowances for this factor, but some concessions may be made for plane trees and some conifers.

APPENDIX C — CLASSIFICATION OF DAMAGE ACCORDING TO CRACK WIDTH AND FREQUENCY

After Tomlinson, Driscoll and Burland (1978)

Category of damage	Degree of damage	Description of typical damage*	Approximate crack width (mm)
		Hairline cracks of less than about 0.1 mm width are classed as negligible	0.1#
1	Very slight	Fine cracks which can easily be treated during normal decoration. Perhaps isolated slight fracturing in building. Cracks rarely visible in external brickwork.	1.0#
2	Slight	Cracks easily filled. Re-decoration probably required. Re-current cracks can be masked by suitable linings. Cracks not necessarily visible externally; some external repointing may be required to ensure weathertightness. Doors and windows may stick slightly.	5.0#
3	Moderate	The cracks require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking. Service pipes may fracture. Weathertightness often impaired.	5 to 15# (or a number of cracks 3.0)
4	Severe	Extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows. Window and door frames distorted, floor sloping noticeably##. Walls leaning## or bulging noticeably, some loss of bearing in beams. Service pipes disrupted.	15 to 25# but also depends on number of cracks
5	Very severe	This requires a major repair job involving partial or complete rebuilding. Beams lose bearings, walls lean badly and require shoring. Windows broken with distortion. Danger of instability.	usually 25# but depends on number of cracks

*Account must be taken of the location in the building or structure where cracking occurs and also the function of that building.

#Crack width is one factor in assessing degree of damage and should not be used on its own as direct measure of it.

##Local deviations of slope, from the horizontal or vertical, of more than 1/100 will normally be clearly visible. Overall deviations in excess of 1/150 are undesirable.