A method for evaluating the influence of trees on expansive soil movement in light of case studies from SE Queensland

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ABSTRACT

The paper proposes a method for estimating the additional foundation movement caused by the drying influence of trees on expansive clay sites. The approach was derived from research undertaken in South Australia. Modifications to the method for less severe climates are proposed herein. This paper presents supporting evidence for the modified design approach from case studies of damaged buildings in South-East Queensland. In the cases considered, soil reactivity, its variation in the soil profile, and suction profiles were measured in most instances. Level surveys were conducted at the time of first inspection of the building damage, and generally later as remediation works took their effect. The difficulties of formulating prescriptive rules to account for trees in footing design are discussed.

1 INTRODUCTION

The Australian Residential Slabs and Footings Standard, AS2870, was first published in 1986. It provides guidance for the design of residential footings on reactive clay. The original standard, and the subsequent editions, including the current 1996 edition, do not provide a means of allowing for the exacerbation of expansive clay foundation movement caused by trees. Rather, the standard encourages the avoidance of tree influence on footing systems by setting limits on the separation of trees from the house. The site classification method in the Standard assumes reasonable site maintenance throughout the life of the building, which includes keeping trees sufficiently far away, so that there is no undue influence on the ground surface movement beneath the building.

An underlying philosophy of the Standard has been to provide footing designs for the predictable or normal changes in the soil-moisture regime and to encourage site maintenance over the life of the building, in order to avoid abnormal moisture changes. It is considered that in setting a minimum standard, the community cannot afford to waste resources in building houses for all possible extremes of soil moisture in the urban environment.

The separation rules in AS2870-1996 set limits on the ratio of D/H, where D is the minimum distance from the house wall to the trunk and H is the height of the tree. The separation ratios recommended by AS2870-1996 are often more stringent than Ward’s (1953) original rule, as the D/H ratio increases with level of site classification, and also if more than one tree is present.

The absence of tree design rules has always been a significant limitation of the standard, and with the recent trends towards smaller residential allotments, the limitation on the applicability of the standard is even greater. Design engineers try to minimise the risk of damage due to soil shrinkage settlements either by excluding trees or, as in South Australia, by designing footings to cater for the anticipated extra soil shrinkage. The current design criteria for “tree-designs” are based on simplistic methods, as very little information is available on the relative water usage of different tree species in the urban environment. Footings may be either over-designed or under designed.

There exist biological limits on the extent of extraction of soil water by vegetation. The wilting point suction, u_{wp}, can be defined as the soil suction beyond which the tree roots cannot continue to extract water from the soil. This concept is useful in setting absolute limits on the drying effect of trees and defining where in the soil profile water may be available to the roots. In arid areas, vegetation will often be unable to extract water from the top metre or so of a seasonally dry profile, because the soil there is already drier than the wilting point. In that situation, the vegetation must feed from deeper in the profile to survive. The wilting point concept is adopted in part in the current proposal. However a simplified approach has been adopted, which assumes that trees can affect design suction changes from the ground surface downwards, only to a maximum depth of five metres.

For design purposes, AS 2870 prescribes the shape of the soil mound under normal moisture changes. Drying of the soil by trees will affect the mound shape. Extra edge drying and therefore edge distance will be significant only to the side of the building where the tree is located. Accordingly it would be reasonable to design for an asymmetrical mound. However if edge distances are not increased, adoption of the simplifying assumption of a symmetrical tree affected mound may be sufficiently conservative and practical to compensate for the changed edge condition.

1.1 The South Australian Footings Group Approach to the Design of Trees

Since about 1990, the Special Provisions of the Footings Group (South Australia) have included a design method for trees for the generally semi-arid climate of this State. Most of the experience with this method has been in the City of Adelaide and its surrounds. Practitioners have readily adopted a modified suction change distribution for tree drying effects. Every footing system is designed for the expected design movement, using beam-on-mound computer programs.

AS2870 recommends a linear design suction change to reflect the influence of climate on a site. The maximum design suction change, Δu, is at the soil surface and decreases to zero at the depth of design suction change, H_s. This depth is four metres for Adelaide. The Footings Group method simply implements a design suction change, Δu_t, at depth H_s, which is determined by separation ratio (D/H), density of planting and the site Classification, exclusive of tree influence. The Footings Group debated about the engineer’s role and the unreasonable expectation to judge potential tree heights. The engineer needs to be advised of tree heights by the owner or building authority.

The Footings Group method impacts only on the height of the mound in the centre heave mode of deformation. However edge heave is possible following the death of trees and consequent recovery of soil moisture. Symmetrical centre heave mounds are adopted implicitly. Reinforced concrete footings are provided with up to 20% more steel to improve cross-section ductility in bending in centre heave, to allow for the greater uncertainty of design and the associated need to maintain structural integrity of the slab if design movement limits are exceeded.

The Footings Group (SA) method applies a caveat when designing according to the special provisions of the Group. This caveat carefully expresses the limitations of the design approach, which includes the uncertainties of the method and the need for greater tolerance of building distortion.

As with any simple design method for a complex problem, many criticisms can be levelled at this approach, and indeed it is hoped that with further research, the method can be improved. However, to the first author’s knowledge, very few problems have arisen in South Australia in relation to footings designed according to the Footings Group’s guidelines.

The Footings Group depth limitation of four metres is a crude approximation to the influence of tree groups. Interpretations of soil suctions in the vicinity of tree groups on urban sites, mostly within Adelaide (Cameron 2001), have indicated deep drying (H up to 6 m). Moreover, the total suction changes induced by trees are actually less severe than recommended by the footings Group; trees can only extract moisture from the soil up to the wilting point for the tree.

2 A DESIGN APPROACH APPLICABLE TO OTHER CLIMATES

A major unknown of the Footings Group approach is its applicability to less severe climatic regions, which have smaller values of the depth of design suction change, H_s. This paper proposes a design suction change due to extreme tree drying (trees within D/H of 0.5) as illustrated in Figure 1. Initially, the grey area was matched to the extra drying area observed in Adelaide. The design value of the difference between the wilting point suction and the equilibrium suction at depth (u_{wp}-u_{eq}) was taken to be the maximum value of 0.5 pF (Jaksa et al, 2001). The actual depths of tree drying, H_t, were assumed to be four metres for a lone tree and six metres for a group of trees.

Applying these values to regions with other climates led to extreme movement estimates which are unsupported by experience, so further variables were included in the method. The first takes the form of an assumed relationship between $(u_{wp}-u_{eq})$ and H_s, on the basis that H_s is a proxy measure of the severity of climate. The relationship is presented in Table 1. The proposed relationship is not intended to suggest that the wilting point suction is reduced in more temperate climates, rather it reflects the possibility that the wilting point is less likely to be reached. The second variable that was introduced was reduction of the assumed depth of tree drying, H_t, according to the following scheme:

Single tree:

$H_t = 3$ m for $H_s \leq 2$ m and $H_t = 4$ m for $H_s = 4$ m

Group of trees:

$H_t = 4.5$ m for $H_s \leq 2$ m and $H_t = 6$ m for $H_s = 4$ m

For other values of H_s, H_t can be determined by linear interpolation. The "observed" suction profile in Figure 1 was transformed on the basis of equal areas into the “proposed design approach" profile, as defined by the parameters u_{td} and H_{td}. Values of these parameters are provided in Table 1.

The design depth of suction change, H_{td} is generally greater than the normal prescribed depth of suction change, H_s. This may impact on the required depth of site investigation, but not as much as would be the case if the “observed” depth of suction change, H_t, was adopted.

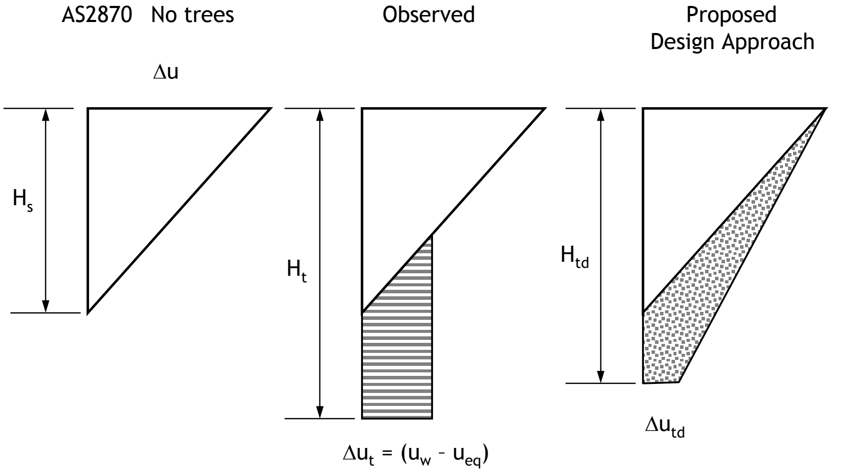

Figure 1: Design suction changes and observed patterns of suction change

Table 1: Proposed maximum design depth of tree drying and design suction change (assumes a design surface suction change of 1.2 pF)

H_s (m)	$(u_{wp}-u_{eq})$ (pF)	Single tree		Tree Group	
		Δu_{td} (pF)	H_{td} (m)	Δu_{td} (pF)	H_{td} (m)
1.2	0.25	0.25	2.05	0.40	2.50
1.5	0.3	0.25	2.40	0.40	2.95
1.8	0.35	0.25	2.70	0.40	3.35
2.3	0.4	0.30	3.00	0.45	3.75
3	0.45	0.30	3.35	0.45	4.20
4	0.5	0.42	4.00	0.61	5.00

Based on the maximum suction change due to the tree as defined by Figure 1 and Table 1, the maximum potential ground movement attributable to the tree, $y_{t\ max}$, can be calculated as usual by integration over the suction change profile, taking account of the variation in soil reactivity through the profile as well as the lateral confinement factor, α (refer clauses F1 and F2 of AS2870). For this calculation, suction changes from tree effects at any level in the soil profile equals the difference between the normal design suction change and the total suction change with trees. Then movement $y_{t\ max}$ is modified to take account of the actual separation of the building from the tree resulting in movement estimate, y_t. Interpretation of ground movement data in Canada (Bozozuk, 1962), suggested an almost linear decrease of movement with relative separation, RS, from a row of 17 m high elm trees. The generalized equation is:

$$y_t/y_{t\ max} = 1.05 - 1.125RS \qquad (1)$$

where $RS = (D/H)/S_{max}$

The authors debated the need for maximum separation S_{max} to be related to the site class as in AS2870 and have concluded that a single rule should be adopted for all classifications, namely maximum separations of 1.0 for a single tree and 1.5 for tree groups. This approach assumes that the radial development of the root system is inherently limited by physical or physiological factors and is not affected by the presence of the building and its effect on the soil moisture regime. This assumption is unproven at this stage. Examples have been seen where trees have extended roots considerable distances to invade building foundations, presumably to take advantage of the soil water available in a covered foundation. It has also been observed that tree root growth can be encouraged towards buildings by the disturbed ground in service trenches.

Once the design movement at the building perimeter due to any trees, y_t, has been determined, a modified mound height, $y_{m\ tree}$, can be calculated (equation 2) and a design conducted assuming a symmetrical mound with height, $y_{m\ tree}$. The y_t estimate is included in $y_{m\ tree}$ without reduction because the full amount of the y_t movement is expected to occur within the building footprint.

$$y_{m\ tree} = 0.7y_s + y_t \qquad (2)$$

The impact of these interim recommendations on footing design and performance need to be judged by practitioners with experience in each climatic region, before they can be generally accepted. In Adelaide, there has been 15 years of successful footing design using raft slabs and a similar design approach, admittedly in a climate which results in deeper drying by trees. The following section explores nine case studies of damaged houses in SE Queensland, in light of these design recommendations.

3 CASE STUDIES FROM SOUTH EAST QUEENSLAND

Nine case studies were provided by the second author. Sites included Class S, M, H and E sites. Wall and footing construction varied. Some of the investigations were conducted within 4 years of construction, and the deformations that were observed were not always simply dominated by the vegetation; there were instances of poor drainage and occasionally leaking pipes (cases 1, 6 and 9). Floor deformations were measured and the maximum out-of-level across the floor ranged between 33 and 154 mm. Many of the trees on site existed prior to construction, for example, case 6 concerned a large eucalypt felled immediately prior to the house construction and located within the house plan.

The suction profiles nearest to the tree were generally not taken right at the tree, but rather near to the building at its closest approach to the tree. Unfortunately suction samples were not always taken past a depth of two metres or so. As expected on the basis of climate, the total suctions were generally less than commonly seen in South Australia. Rebound of the floor following tree removal occurred within a relatively short period after tree felling (1-2 years). The observed rebound differential displacements of the floor ranged between 20 and 65 mm.

The proposed total suction changes for design for two case studies concerning isolated trees are illustrated in Figure 2; the measured maximum suction change differences across the site at the time of the investigation are provided in each diagram. In these diagrams the design suction profiles provided for comparison have been scaled to allow for the fact that the suction measurements were not taken at the tree, but rather at the building.

Data from case studies involving more than one tree are similarly presented in Figure 3. Case study 1 (suctions not shown) was of particular interest as total suctions were determined on samples taken from almost identical borehole locations between 1996 and 1999, over which time, two of the trees grew rapidly and the relative separation to the building decreased from 1.25 to about 1.0. As expected, the soil suction data suggested that, at the initial tree height of 4.5 m and hence initial separation ratio exceeding unity, the trees did not have any influence on the soil suction profile. However as the trees grew further, the slab deformation patterns that developed confirmed the growing influence of the trees (no suction data available for this period). Subsequent to the tree removal the suction profile reverted to a moist state.

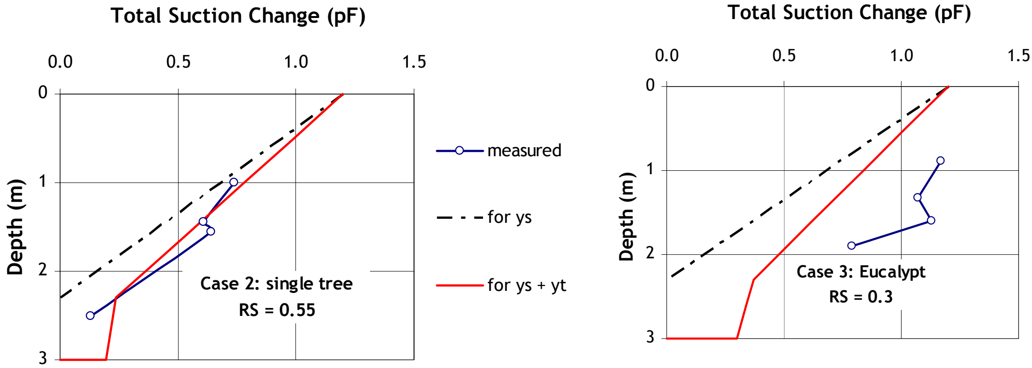

Figure 2: Suction changes, case studies involving single trees

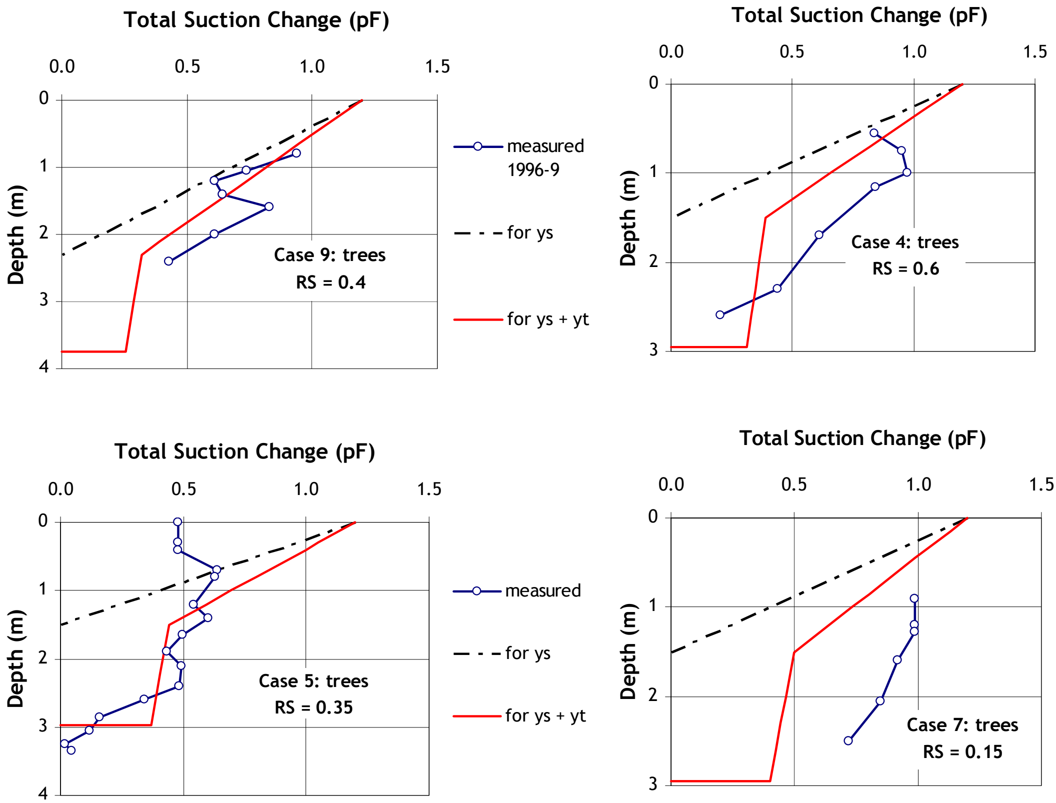

Figure 3: Suction changes, case studies involving tree groups or rows

3.1 Discussion

The measured suction differences, albeit limited by depth, often exceeded those proposed for design purposes (cases 3, 4 and 7), indicating other forces at play such as poor site drainage. The concern remains that the tree drying influence may be underestimated. Attempts were made to estimate ground movement due to tree drying using the proposed method, and then comparing this estimate with the observed rebound of the floor, Δ_R. The estimates for single trees (3 cases) were less than or equal to Δ_R, while for groups of trees, the estimates were approximately twice Δ_R, despite the previously noted underestimation of suction difference. However estimates of ground movement cannot be directly compared with footing movements unless the influence of both the stiffness of the footing and the loads it carries are considered. Furthermore, approximations were necessary to extend soil profile information to make these estimates.

An interesting question arose as to the appropriate depth, H_c, at which factor α becomes operative when calculating ground movement due to tree drying. In the movement estimates discussed, this depth was not changed despite knowing that trees causing deeper movement. An increase of H_c commensurate with the depth ratio H_{td}:H_s, would decrease significantly the estimates of ground movement. Further investigation on this issue may prove fruitful in finalising design principles.

4 SUMMARY

Trees can be accounted for in design, but with less certainty than we can classify sites. An adaptation of the Footings Group SA approach has been made for a range of climates, based in part on the wilting point concept. Subsequently, case studies from SE Queensland have been compared with the proposed design rules, with some success. Five major concerns remain with respect to the ability of the method to predict tree influence on building foundations. These are the influence of species, the validity of tree height as a measure of lateral influence for all species, the over-conservative estimates of the effect of tree groups on the drying profile, the assumed non-plasticity of tree root development near buildings and the evaluation of the interim method when applied to other temperate climates.

Although the proposed approach recognizes some important features of tree drying, the influence of species has not been included. Instead the design approach has adopted a conservative value of (u_{wp}-u_{eq}) for all tree species.

4.1 Further Research

Research into the influence of trees is costly as it involves site monitoring. Although equipment for monitoring of tree physiology has improved, a single experiment does not go far in advancing our knowledge. Unfortunately this can often mean funding for such research is difficult to find.

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