

# A GEOTECHNICAL ENGINEER'S APPROACH TOWARDS TREES.

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## Abstract

In the geotechnical engineer's mind, complex natural systems like trees and their interaction with the soil and the atmosphere need to be simplified into more manageable concepts. To a lesser degree, the same could be said of agronomists and foresters. Simple engineering rules and guidelines have been developed based on investigations of damaged houses and other buildings, and the experience gained from implementation of these guidelines. The intent of the geotechnical engineer and footing designer is to reduce the risk of damage to property to an acceptable level. However our understanding of trees in the urban environment is quite poor; for example, there is still little evidence to differentiate between species, and not much to go on regarding the influence of soil types and different regional weather patterns. Further development of engineering guidelines can only follow with increased research effort and improved models for prediction of soil moisture re-distribution near trees.

In this paper, the author presents his limited experience with trees and buildings and other infrastructure, which extends over more than 35 years. This 35 year period has included a number of significant research projects; lessons learned so far in these projects are discussed.

## Introduction to trees and buildings at CSIRO

The author's first job was as an experimental officer with CSIRO Division of Building Research in Melbourne in the 70's and 80's. Working under Dr Paul Walsh, he was charged largely with geotechnical investigations into the performance of house footing systems. CSIRO gave assistance to homeowners, mainly in the Eastern suburbs of Melbourne, to try to understand why cracks had appeared in their houses. It became apparent that trees were desiccating soil, causing shrinkage settlements; older houses with significantly sized trees, were often left too close to buildings. It was seen that a proximity rule could be simply applied relating safe distance,  $D$ , between tree and building to the height of the tree,  $H$ . A proximity ratio of  $D/H$  less than or equal to 0.5 seemed to be when troubles were likely (Cameron and Walsh 1981).

### Proximity ratios

Safe proximity ratios had been expounded much earlier by Ward (1953) in the UK ( $D/H > 1$  for trees with high water uptake), and Wesseldine in New Zealand (1982). The latter researcher published the findings of 28 cases of building damage in the Auckland area, associated with the silver dollar gum tree (*E. cinerea*). For single trees,  $D/H > 0.75$  appeared to work. For groups of trees  $D/H_{safe}$  increased by 50 to 100%, presumably due to competition between root systems increasing the lateral spread and depth of roots.

Cutler and Richardson (1981) conducted the Kew Gardens Survey into distance of separation of different tree species and the incidence of damage, following a drought in the UK (October 1975 to August 1976), which had sparked numerous insurance claims for building damage due to subsidence. More than 2,000 incidences of building damage were reviewed. However the extent or severity of damage was not included in the study. It may be assumed that given the style of construction common in the UK, that the buildings were more susceptible to damage than the majority of housing in Australia. Furthermore, the lack of tolerance of even minor cracks in buildings in the UK at the time may mean that the level of damage suffered by some buildings would have been ignored in Australia as simply aesthetic and easily repairable. Driscoll (1984) reviewed the data from the Kew Gardens Survey and concluded that approximately 75% of damage cases could have been avoided if a safe proximity ratio of 0.5 had been applied. Freeman et al. (1994) suggested safe proximity ratios of 0.5 for 'less thirsty trees' and 1.0 for thirsty trees. Based on the Kew gardens survey, thirsty trees included Oak, Poplar, Willow, Cherry/Plum and White Beam/Rowan.

Similar information to that provided by Kew Gardens on species implicated in damage was not available in Australia. However, a study by the Engineering and Water Supply (SA) on tree root intrusion into service pipes was used as an indirect indicator of species vigour in seeking out water. In this Engineering and Water Supply study (Baker 1978), tree roots in pipes were examined and identified leading to a hit list of species involved in

clogging pipes. A CSIRO pamphlet entitled "Trees and Foundations" was released (Cameron 1980 & 1985) which listed trees to avoid based on Baker's study.

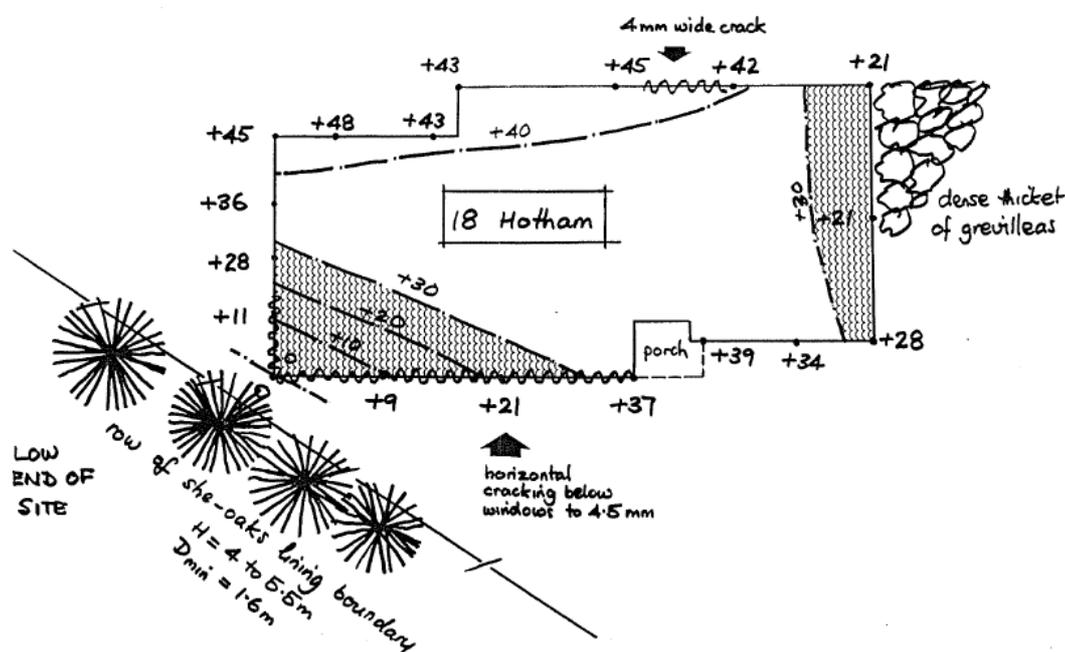
In 1982, the author teamed up with arborist Ivan Earl in Melbourne to provide advice to homeowners on managing sites with trees (Cameron and Earl, 1982). Ivan provided a list of trees that were found to be a problem in Melbourne. The document suggested that the level of management on treed sites should be commensurate with the level of risk and could include tree maintenance (pruning foliage/roots), cut-off walls, or alternative footing designs. In line with the title, "Trees and Houses: A Question of Function", it was implied that homeowners could choose to put up with the some cracking if they loved well-vegetated allotments and were not overly concerned about cracks in walls.

Proximity ratios were again expounded by Cameron and Earl (1982), being 0.5, 0.75 and 1.0 for low, moderate and high risk sites, respectively. Similar proximity ratios were adopted in AS 2870 1986 (and subsequent editions) in the Standard's guidelines to homeowners for minimising risk of damage from single trees. For groups or rows of trees, the ratios were increased by 50%.

An unfortunate outcome of the promulgation of proximity ratios was that it made it an easy option for forensic engineers and building inspectors to blame nearby trees, without a more thorough investigation. Given that many homeowners could not afford more than a few hundred dollars for investigation of building damage, this should not have been unexpected. Proximity ratios are at best rules of thumb which, as stated by Freeman et al. (1994), cannot account for "the shrinkage potential of the soil or the depth of the foundation. They went on to say that "it is the leaf area of the tree rather than its height that ultimately determines its moisture demand".

#### Investigating damaged buildings

A level survey of the floor of a damaged building, or at floor level on external walls, can be quite telling as seen in the example in Figure 1. An arbitrary datum point was chosen at the corner of the building, close to the row of she-oaks, which was the lowest point on the floor.



**Figure 1. Contours of relative differences in level across a concrete floor at the time of inspection. Difference in level of 48 mm. The floor appeared to have settled adjacent to vegetation.**

Level surveys can be quite useful also in monitoring recovery of building movement as indirect remedial actions take effect, such as tree removal, thinning of groups, deep root barriers, pruning and soaking the ground (Cameron and Walsh 1981). An example was given by Cameron (1983, Case 1) for a single storey, timber floored house in Melbourne; a row of trees were aligned with one wall, just within the boundary of the allotment. The trees were within proximity ratios of 0.2 to 0.9. Relative to the opposite side of the house, the

wall next to the trees was a maximum of 50 mm lower as determined by a level survey taken in February. Cracks in the masonry veneer wall were up to 5 mm wide and the serviceability of windows had been affected. The owner decided to remove all the trees and soak the ground with gravel filled boreholes. Shortly after tree removal, the settlement of the wall had recovered by about 45%.

Although level surveys of floors are quite cost effective and informative, further information is required for a more thorough forensic investigation on clay sites. It is important to establish the soil profile, soil reactivity of soil deposits and a study of soil suction variations with depth (suction profiles) and across the site. It is not always possible to do all that is needed, unless there is a need for resolution of a potentially costly dispute between the client and another party.

### An introduction to tree physiology

Before leaving CSIRO in Melbourne for Adelaide, the author became involved with a project with Melbourne City Council on trees in the urban environment, as did Greg Moore from Burnley Horticultural College. Roger Sands from Melbourne University was also involved and he and his research candidate undertook some fascinating, but time consuming experiments on trees in Melbourne's parklands (Misra and Sands, 1992). The instrumentation was the author's first introduction into how sap flow might be measured by heating a horizontal probe inserted into a tree trunk and examining how heat dissipated with time. Many years later, the equipment has become more robust and attractive to researchers, and sap flux equipment has been used by the author since 2006.

## Trees, buildings and other infrastructure, UniSA

Having joined the South Australian Institute of Technology in 1988 (which later became UniSA), the author soon learned that time for research projects was much more limited than at CSIRO. Nonetheless, with time, some major projects did eventuate. In the early years, some case studies of trees and damaged buildings were undertaken in Adelaide. The basic tools for forensic investigation of buildings were level surveys of floors, establishing the soil profile and development of soil suction variations with depth (suction profiles) and across the site.

### Where are tree roots able to extract water from?

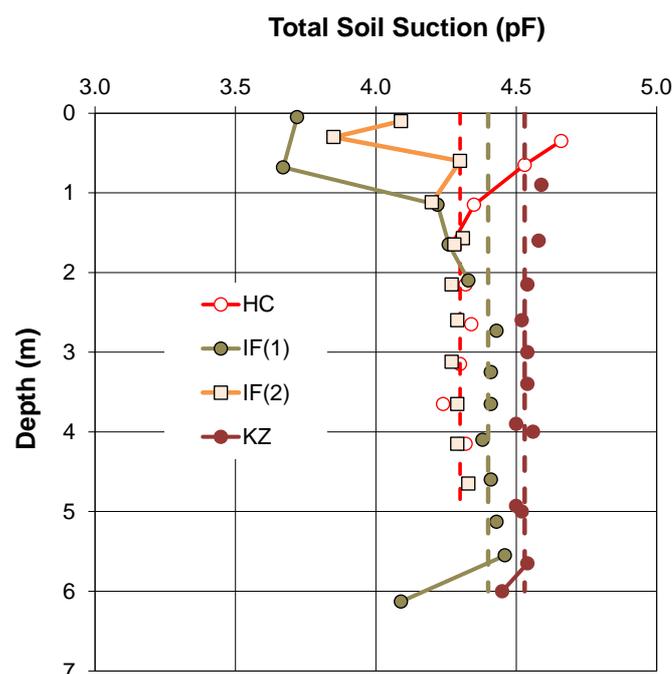
Differences in soil suction profiles near trees and away from trees provided valuable information into possible drying zones and the active root zone, or where water was being taken from. It came to light (Cameron 2001, Jaksa et al., 2002) that trees were unable to compete with the soil during dry seasons in Adelaide, at least in the top metre or two of the soil profile. If trees were to survive, they would need to extract water deeper from within the soil or find other sources of water. The concept of wilting point suction needs to be recalled; roots can only impose a certain minimum negative water potential (or maximum suction) to draw moisture from the soil. This suction may be termed the wilting point suction for the plant, which may have a value around 2 to 3 MPa. Near surface soils will be at higher levels of suction during summer and autumn, and so the soil will not release water to the plant. The value of wilting point suction is dependent on species.

Wilting point suction,  $u_{wp}$ , was inferred by Cameron (2001) from soil suction profiles taken near trees. Examples are given in Figure 2 from four sites in Adelaide near groups of trees, largely near eucalypts. Although the suction profiles were determined at various times of the year, each suction profile became relatively uniform (almost constant suction) below a depth of 2 m or so. The value of wilting point suction was taken as the constant suction value, and it varied as indicated between 1.9 and 3.3 MPa for these four examples. Another feature of Figure 2 is the depth to which the suction was maintained. Just two of the suction profiles, IF(1) and KZ, were deep enough to show that soil suction appeared to be decreasing towards the expected value at depth, which is termed the deep equilibrium suction. The deep equilibrium suction is usually around 4 pF, or 1 MPa for sites in Adelaide. The depth at which the wilting point suction decreased was close to 6 m. For lone (single) trees, the depth of drying appeared to be closer to 4 m. These depths may surprise some people; however depths of drying in wetter climates have been reported in the UK to at least 4 m (Crilly et al 1992), and to 3 m in France (Mathon and Godefroy, 2015). Both these examples were for dense tree plantings and the depths were limited to the depths of each investigation. Parry (1992) observed significant desiccation to a depth of 6 m depth near poplars in London clay.

More locally, Fatahi (2007) studied root distributions in two trenches excavated to a depth of 3.5 m, radiating out from a 13 m high blackbox (*Eucalyptus largiflorens*).

The tree was close to the Melbourne -Adelaide railway line near the town of Miram in the Mallee. Suction determinations by Fatahi suggested a depth of influence of at least 3 m and a lateral extent of 17 m, although active root density (roots 0.4 to 1.0 mm in diameter) was highest in the top 1.5 m and at a distance from the trunk of 7 to 9 m. Photographs of the excavation are provided in Figure 3.

These observations from investigations of damaged buildings (Cameron 2001) gave rise to an idealized tree influence zone for trees within a soil profile, which is illustrated in Figure 3. The red and blue triangular zones represent possible design suction changes in the absence of any trees. The depth of the tree influence zone is dependent on whether it is a single tree or a group of trees. The suction changes indicated in Figure 2 can be used by a geotechnical engineer to calculate potential ground movement for very close trees and then prepare footing designs, which will safeguard the building against serious damage.



**Figure 2. Observed suction profiles near groups or rows of trees for four sites in Adelaide. The dashed lines indicate inferred values of wilting point suction, ranging between 1.9 and 3.3 MPa (4.3 and 4.53 pF). Generally the data points are shown without connecting lines except in the top 1.5 to 2 m.**

### Development of guidelines regarding trees and buildings

The stance taken by the Standard AS2870 for residential buildings (Standards Association of Australia 1986) in the late eighties limited planting of trees on allotments for those who chose to have footings designed according to the Standard. In the mid-1990s, the house building industry in South Australia felt pressure from the community to provide footing designs, which could accommodate the extra movement due to trees. The Footings Group of South Australia responded by developing empirical guidelines to estimate additional design suction changes for a tree or trees on clay sites of different levels of reactivity in order to evaluate extra ground settlement (Footings Group 1996). Application of the guidelines required warnings to the client about the limited knowledge of trees held by geotechnical engineers. The rules were simple and tended to exaggerate how trees took moisture from the soil, especially for groups of trees. Nevertheless these rules proved to be effective over the 15 years since they had been introduced and so the Australian Standard (Standards Australia 2011) adopted a modified version of the Footings Group rules for South Australia, which considered the idealized tree influence zone and practical limitations of its implementation.



Figure 3. Photographs of trench excavation near Miram, Victoria, for Fatahi's study (2007) of root distribution

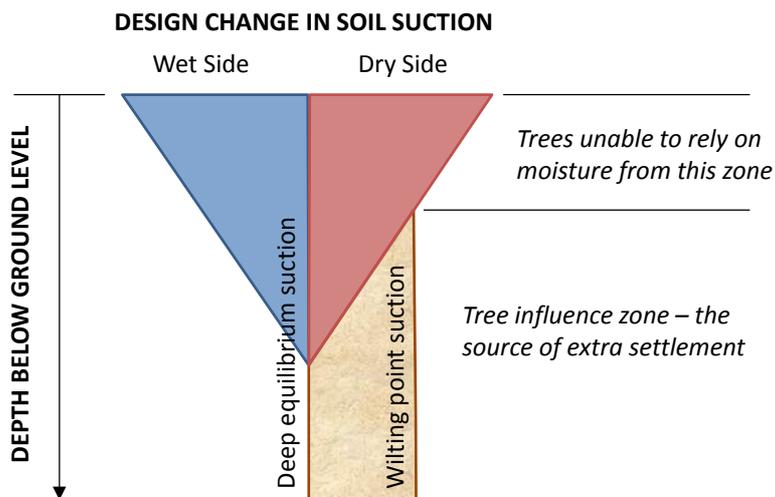


Figure 4. Idealized design suction change profiles for estimation of ground movement, with and without trees. Movement with trees is for trees close to the building ( $D/H \leq 0.5$ ).

Nigel Beal of Hughes, Beal and Wright presented case studies of building damage from South-East Queensland and with the author argued for a reduction of the extent of the tree influence zone for less severe climates (Cameron and Beal 2011). The influence of prevailing climate was adopted by AS2870 in guidelines published in the last edition of AS2870 (Standards Australia 2011). For instance, while the depth of suction change in Adelaide may be 4 m for a single tree, it may range between 2.5 and 2.7 m in the eastern suburbs of Melbourne and increase to 3 m to the west of Melbourne.

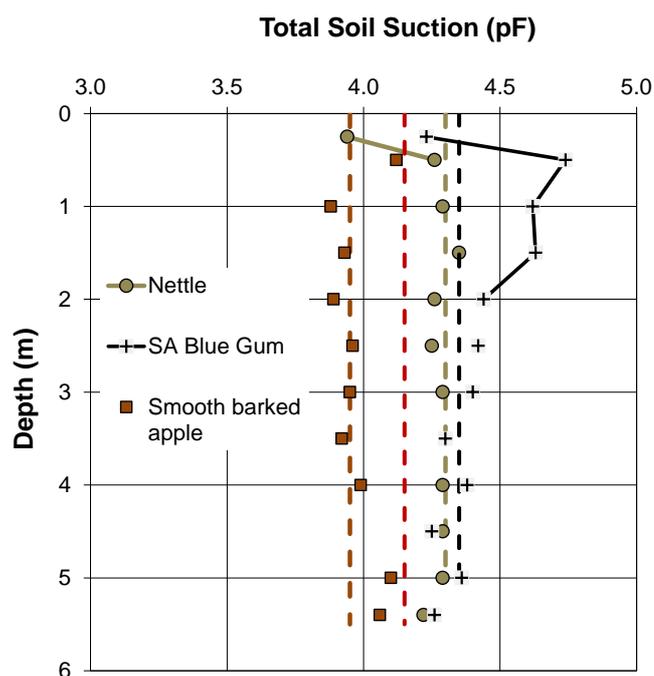
The design suction change profiles in AS2870 are for estimation of the maximum drying settlement when the tree or trees are close ( $D/H \leq 0.5$ ). Reductions of movement can be made on the basis of relative separation distance, if the designer is satisfied that the eventual height of the tree/s can be predicted reasonably well. Who should take the responsibility of assigning tree heights is a vexed question.

Again with these guidelines for accommodating trees in suburban Australia, the influence of tree species has been ignored owing to the paucity of published data. Neither leaf area nor canopy volume plays any part in the current scheme. So there is much scope for research, which could improve the guidelines.

### Research concerning trees

At UniSA, research funded by the City of Salisbury commenced into established street trees in 2000-2001 (Cameron and O'Malley 2002). Leaf water potentials were measured regularly and soil moisture levels were checked using a neutron moisture depth probe lowered down deep access boreholes between street trees, under the pavement and away from the trees. Five species of trees were monitored. Soil suction profiles were determined usually when access tubes were constructed for neutron moisture meter access. Examples of soil suction profiles between rows of street trees are shown in Figure 5. Again it can be seen that the suction profiles below approximately 2.5 m were fairly uniform and contrasted with suction profiles taken either away from the trees or below the road. Inferred wilting point suctions for the three examples were 0.9 MPa for the smooth barked apple trees, 1.9 MPa for the nettle trees and 2.2 MPa for the South Australian blue gums. Wilting point suctions for red ironbark trees and jacarandas were 1.7 and 1.4 MPa, respectively. The range for the five species in the study was 3.95 to 4.35 pF units.

Leaf water potentials were taken in the early afternoon each month on four of the species and were not seen to vary much between species. In hindsight, daily variations of leaf water potential would have been preferable to assess the maximum daily value. The values of leaf suction taken from the four target trees varied little over the course of the year, ranging between 4.2 pF and 4.35 pF (1.5 and 2.2 MPa), which was similar generally to the variation of inferred wilting point suctions, except for the smooth barked apple tree.



**Figure 5. Suction profiles between rows of established street trees in the City of Salisbury (2000/2001)**

The research into established street trees led to a wider research project concentrating on more highly expansive clay sites within the recently developing new suburb of Walkley Heights. This time however the street trees were just being established and were mainly exotic species which were favoured by the residents and the developer. The age of the trees was considered to not be as important as it was conjectured from the previous project that leaf suctions might be useful in predicting future developments of soil suctions. Moreover, early ground movements could be monitored before the trees had much impact and so movements attributable to the trees could be discerned more readily during future monitoring.

This research effort continued between 2001 and 2006 through funding from the City of Salisbury and the Local Government Association (Cameron and O'Malley 2002, O'Malley and Cameron 2005). Aaron O'Malley undertook the research project under the supervision of the author. The strategy from the previous research project continued, with leaf water potentials complemented by xylem pressure measurements (Scholander pressure bomb) on the young street trees. Xylem pressure measurements were seen to have advantages over leaf water potentials as xylem pressures can be determined on leafless trees, and the two instruments produced similar readings, as seen in Figure 6. In this Figure, data are presented for an ornamental pear and for a coral gum. The xylem pressures varied greatly between 0.5 and 2.35 MPa for the ornamental pear, and the leaf suction tracked the xylem pressures quite well when the tree was in leaf. The xylem pressures recorded for the evergreen coral gum showed less seasonal variation and values were consistently higher than the leaf suction.

The Walkley Heights research project did not come to any significant conclusion since in the early years the verges were overwatered and the trees struggled to take hold in the clay soils. There was little if any evidence of any drying settlement due to the trees. One thing that became apparent was that often the soil suction that was measured was predominantly solute suction, as confirmed by electrical conductivity testing in the laboratory.

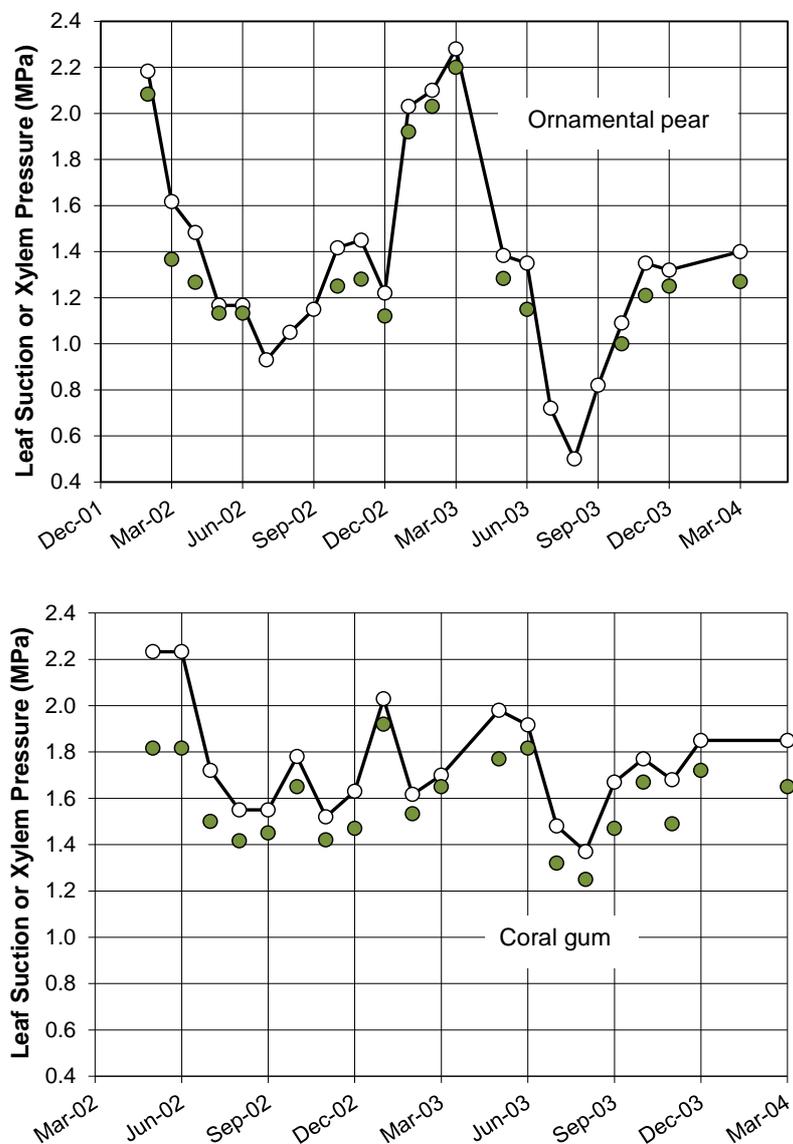


Figure 6. Leaf water potentials and xylem pressure variations with time (O'Malley, unpublished data). Leaf suction points are shown as unconnected data points, xylem pressures as connected points.

The experimental sites were not well maintained as further research funds were needed to re-vitalize the study; some trees and sites were lost. Final year civil engineering projects in 2010 and 2011 helped revive the sites, add two new sites and construct some soil suction profiles. Then in July 2012, an ARC Linkage grant was awarded to the University of Wollongong and UniSA for research into trees. The research project which is led by Professor Buddhima Indraratna of the University of Wollongong, is entitled, "The role of vegetation and associated root suction and reinforcement on the stabilisation of transport corridors and sloping ground". Essentially, the ARC project provided a full-time PhD candidate, Stacey Vorwerk, who commenced in August 2013, upgrading of the sites and some instrumentation. Since late 2014, new sap flow equipment has enabled almost continuous monitoring of four street trees of different species (golden raintree, ornamental pear, prickly paperbark and Queensland box). The industry partner for the UniSA effort is the City of Salisbury whose officers have helped set up and protect installations within the suburb.

The chief objective of the current research effort is to establish the water demand of the trees and the potential impact on the underlying soil. A primary aim is to verify simple soil-plant-atmosphere models, which may then be implemented in other situations for different tree species with some confidence. Accordingly, tree physiology plays an important role in the monitoring of sites. Leaf conductance, xylem pressure and leaf area index are being recorded.

Some early results from this current project are provided in Cameron et al. (2015). Monitoring over the coming growing season should produce some insightful observations and further publications.

Another interesting research project arose from contact with the rail industry, which needed a solution for soft, wet subgrades and fouled ballast on sections of the Adelaide to Melbourne line. Maintenance crews observed that rail kept its shape on the plains along vegetated sections, but sections of line without significant vegetation had excess water and continually required maintenance. So from 2003 to 2008, the author was Project Leader of Rail CRC Project 86 in Theme 2, entitled, "The feasibility of improving rail infrastructure by using native vegetation on clay soils". Other partners in this project were the University of Wollongong, Australian Rail and Track Corporation (ARTC) and Queensland Rail. Wayne Potter of ARTC completed a Masters of Engineering by Research for his contribution to the project (Potter 2005), which consisted mainly of field trials to verify the observations of maintenance crews at Miram, Horsham and Wal Wal in Victoria and in Emerald in Queensland. Soil suction profiles were established across and under the track in vegetated and non-vegetated sites, and it was soon established that deep drying from trees in the rail corridor had improved the stiffness and strength of underlying soils greatly (Cameron and Potter 2008). It was also seen that soil salinity affected soil suctions, especially at the Emerald site (Cameron and Potter 2014).

Examples of suction profiles from the Miram site are provided in Figure 7. At Miram, a row of blackbox trees, approximately 7 m high, were aligned in the rail corridor, just 3 m from the edge of the ballast (refer photograph in Figure 8, right hand side). The Figure confirms earlier observations about deep drying near trees; the deep equilibrium suction had not been reached at the treed site at the depth of the investigation (4.5 m). In contrast at the non-treed site, suction profiles were close to the deep equilibrium suction at depths of 3 m and greater. More importantly for the long-term performance of the rail, the top metre or so of soil had been kept dry (saturated at the corresponding non-treed site). Accordingly, the stiffness of the drier shallow soil was 3.5 to 15 times greater than the soil at the non-vegetated site.

At the Miram site, sap flux equipment developed by Steve Green of Transflo NZ was used to measure transpiration of the blackbox trees (Cameron and Mills 2006). Photographs of the site and instrumentation are presented in Figure 9. A comparison was made between the reference evapotranspiration for grass,  $ET_0$ , determined using data from an on-site weather station, and transpiration of two trunks of a tree as measured by the sap flux equipment; the plots are provided in Figure 10. The data are cumulative and indicate that in the fairly non-interrupted period between mid-winter and the start of summer, transpiration kept pace with  $ET_0$  until it accelerated in mid-summer. In addition, almost 4kL of water had been transpired, during which time, cumulative  $ET_0$  exceeded 600 mm. The ratio of transpiration to  $ET_0$  produces an apparent area of transpiring canopy of six and a half square metres.

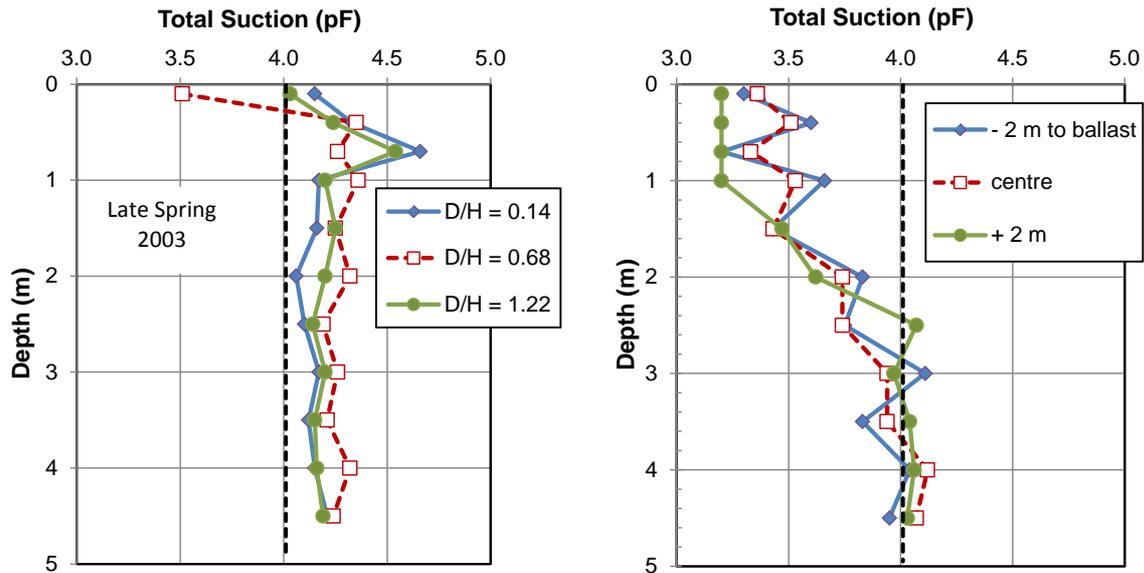


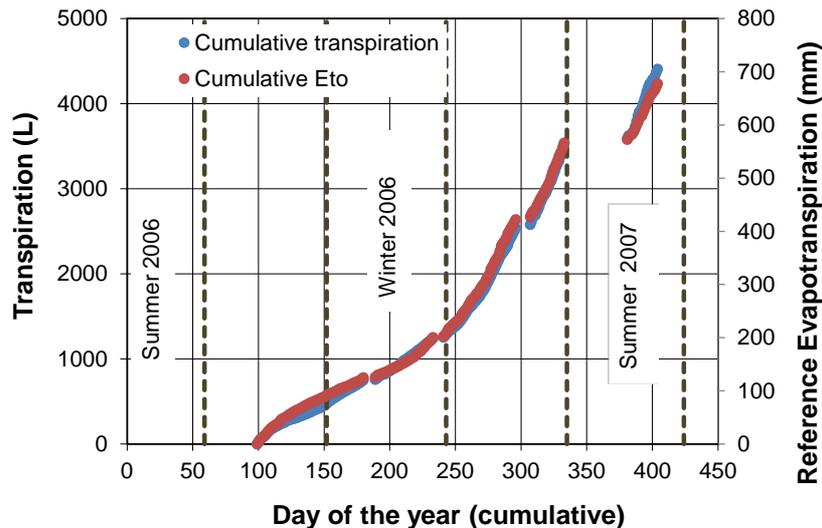
Figure 8. Soil suction profiles from the Miram site, 2 m either side of the track (ballast toe) and under the centre of the track (broken red line). The plot on the left side shows suction profiles near a row of blackbox trees, 7 m high. The plot on the right shows suction profiles at the same time at a nearby site without trees. The deep equilibrium suction was determined to be 4.0 pF, the average of 20 suction determinations at 4 and 4.5 m depths at the non-vegetated site over two sampling times. This value is depicted as a black broken line.



Figure 9. The Miram site and blackbox trees with sap flux instrumentation

As indicated by Cameron and Mills (2010), the sap flux equipment is not fool proof. The sensors and heater have to be accurately placed in the correct size drill holes. Cables need to be protected against heat spikes, and the properties of the tree need careful appraisal. Wood density and sap flux area are needed, as well as the width of the wound developed about the heater over time. Sapwood is not necessarily circular; it can be elliptical or quite irregular and so coring may not be adequate for assessing sapwood area. So although transpiration plots may look convincing, there will always be some concern over accuracy.

Within this Rail CRC project, a significant PhD was produced (Fatahi 2007), based partly on work at the Miram site, which provided a model to predict the drying impact of a tree and benefits of soil suction (Fatahi et al. 2008). A number of simplifying assumptions and parameters were required to make the prediction. For example, the root zone was simplified to a cone. The model is being further developed by researchers at the University of Wollongong to include the impact of solute suction in soils.



**Figure 10. Accumulation of reference evapotranspiration and transpiration of a blackbox tree with time. The broken sections indicate lost data from one of the probes or the weather station, due to a solar panel malfunction or to heat spikes in hot weather.**

The last research project in this discussion concerning trees involves Tim Johnson, who is well known to members of Treenet. The perplexing problem of tree root intrusion into pavements is not of direct interest to a geotechnical engineer, although it is a widespread problem that needs botanical and engineering experience to understand and provide solutions to. Tim's PhD supervisors are the author and Greg Moore from Melbourne University. The project commenced in 2008 and has been supported by the City of Mitcham and Adelaide and Mount Lofty Ranges Natural Resources Management. In the context of the current paper, measurements have been taken of tree physiology and soil moisture using all the equipment available for the Walkley Heights project, except the sap flow sensors (Johnson et al. 2011). However, Tim has investigated oxygen levels within the soil profile and mapped exposed roots below the footpath, which is the subject of his paper in these proceedings. Ground penetrating radar has also been trialled, on the silty clays and clayey silts of his experimental site.

## SUMMARY

The author's involvement with trees has arisen from the geotechnical engineering perspective of trying to resolve the problem of shrinkage settlements and damage to buildings. A multi-disciplinary approach has been required to progress research in this area and considerably more time and effort is required. In time, the water uptake of trees may be able to be predicted with reasonable certainty.

There have been many lessons learned over the years and many more still to uncover. Some of the lessons are as follows:

- Most trees are capable of causing drying settlement
- The literature suggests root systems can be quite extensive given the right circumstances
- Trees with a good water supply (replenished water storage in the soil) should not cause problems
- Trees need oxygen in the soil for their root systems – reactive soils can have cracks and fissures which can provide oxygen
- The depth of drying is deeper than the root zone ascribed by arborists usually
- Trees in competition can extend roots deeper and wider
- Trees can die if their root systems are not sufficiently vigorous
- The wilting point suction concept is useful in explaining suction changes within a soil profile
- Proximity ratios are primitive; as suggested by others, canopy form may be more important
- Raft slabs for houses can be stiffened at some cost to the community to accommodate the potential for tree drying – in some cases, deep piling may be more suitable
- We don't know very much about trees in urban environments – much more research is needed
- Trees and nature don't abide by rules in Australian Standards

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