City of Salisbury

University of South Australia

THE INFLUENCE OF TREES ON SOIL MOISTURE, DWELLINGS AND PAVEMENTS IN AN URBAN ENVIRONMENT

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PROJECT SUMMARY

This project has studied the influence of urban street trees on soil moisture, ground movements and species' water demand on extremely reactive soil. The project has provided the basis for a more appropriate method for footing design on reactive sites with trees, and guidance on the apposite selection of species. Six sites have been established within a new subdivision to monitor deep soil moisture changes, surface movements of floors and roads, and tree suctions. Seasonal soil movements away from trees have been monitored using a Ground Movement Station (GMS). The project is unique as soil movements and street trees' water demands were studied as the street trees have grown. Some findings of the study were hampered by the heavy -handed irrigation of the subdivision during the initial monitoring period.

Keywords

Expansive Clays	Street Trees
Soil Suction	Ground Movement
Leaf Water Potential	Footings

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1. AIMS AND BACKGROUND

1.1 AIM

The aim of the project was to provide a rational method for design of footings on reactive soil sites with trees, and to provide guidance to Local Government on the appropriate selection of street tree species.

1.2 OBJECTIVES

The objectives were: -

- To compare the soil moisture patterns and movements of reactive clays in the presence and absence of trees
- To investigate potential link between tree physiology and development of soil moisture patterns
- To establish the performance of building footings and pavements built to both current Australian Standards and the "tree-design" guidelines of the Footings Group, IEAust.
- To develop information on the water demand of tree species to incorporate in footing design rules
- To provide information on tree species to improve assessments of causes of damage to buildings
- To produce guidelines to assist Local Governments, researchers, engineers and builders to better understand and design for the likely soil moisture changes and movements in urban environments

2. BACKGROUND AND LITERATURE REVIEW

2.1 BACKGROUND

Many populated parts of Australia are underlain by expansive soils, such as the western suburbs of Sydney and Brisbane, the western and northern suburbs of Melbourne, the foothills of Perth, almost the whole of suburban Adelaide and many regional centres of Australia. Although it is known that trees add to the drying of soil at depth, few houses are designed with footings that have been stiffened to counter the influence of trees. If the approach to designing footings for tree effects is improved to the point that it can be adopted in Standards Australia AS2870, then the hesitation to planting trees in the urban landscape can be overcome and the frequency of costly legal disputes over whether or not a tree has impaired the performance of a building may be reduced.

Local Government is the main beneficiary from this research, as it will provide a better understanding of the potential urban problems with reactive soils and street trees. At present, if there is any complaint about a street tree being a threat or a problem, local government is last option is to fell the tree. Designers of footings benefit from this research as it provides preliminary scientific information from the field on tree drying of various street tree species to enable more rational footing design methods to be implemented. The suitability of street trees in urban areas has benefit for the nursery industry, as a higher demand will be placed on those trees that are better suited to specific sites condition and soils. Nurseries will be able to provide better tree stock to councils and land developers, thus improving the viability of street trees. Increased planting of more suitable street tree species in urban areas will add to the national greening of Australian cities and urban areas, reducing greenhouse emissions, adding to biodiversity and ensuring the amenity and value of urban areas are retained.

Local Government provides amenities, which balance the soft elements (trees and shrubs) with other elements of the street and reserve environments. Provisions for trees are clearly enunciated in the Australian Model Code for Urban Development that the City of Salisbury has adopted in their Development Plans. Therefore, the planting of trees on reactive clay soils cannot be avoided. Trees are an essential part of an urban landscape, providing shade and habitat, and generally improving streetscapes. With the introduction of the Local Government Act 1999 in 2000, Local Government is potentially liable for tree root intrusion into properties, producing direct physical interference or which significantly affect the soil moisture regime, causing buildings to become distorted. On reactive clays soils, the selection and position of street trees must be considered when planting near houses. With the current trend towards small block sizes, street trees are often unavoidably close to houses. Therefore local government organizations need to know how far apart trees and buildings should be (using D:H ratios), the most suitable tree species and methods of assessing the large range of available street trees.

This research project is of great benefit to engineers and to Local Government, as it provides much needed information on trees and soil suction changes near trees on reactive clay sites, which can be used to predict movements and thereby improve the future design of footings for houses. As well, footing designers will be better equipped to design for the potential effects of trees.

Collaboration between the University of SA and the City of Salisbury in this research on street trees began in 1999 as part of a related project investigating soil moisture and suction changes near established trees. This initial project has led to further projects including the current project focussing on more reactive soils and younger trees that can be studied until maturity.

2.2 THE RESEARCH PROBLEM

The combination of Adelaide's reactive soils and the prevailing semi-arid climate means that houses and pavements must withstand significant soil movements. Trees in an urban environment can add to these movements and can cause unacceptable distortions and cracking. However trees are an environmentally desirable part of urban streetscapes. Street trees are provided by Local Government Authorities to improve the landscape, enhance the environment and usually to maintain or increase land values. Apart from their aesthetic value, trees provide a valuable habitat for fauna and extend the urban wildlife corridor, thereby protecting and enhancing biodiversity (Moore 1997). Trees however, may present a nuisance if they become too large for the streetscape, lose branches in storms or uplift pavements.

This research has been concerned with the indirect damage to pavements and buildings caused by street trees, through the extraction of moisture from clay soils, causing deep drying and shrinkage settlement. Past research has shown that tree root systems can generate shrinkage settlements in reactive clay soils at appreciable depths (Richards et al 1983 and McInnes 1986). Tree-related desiccation is likely to cause greater ground movements than normal in the dry season. This extra soil movement may result in unsightly and perhaps structural damage.

Generally houses over ten years old have not been designed to cater for tree-drying effects and are at a greater risk of damage than recently built houses. More recent house construction remains just as susceptible, if designed to the current Australian Standard AS2870-1996. The Standard encourages the avoidance of manageable extreme moisture changes and does not provide guidelines for designing for trees close to dwellings. The site classification assumes reasonable site maintenance practices are adhered to throughout the life of the dwelling and trees are kept sufficiently far away, so that they have no influence on the design site surface movement. AS2870 recommends proximity rules, which are designed to keep vegetation sufficiently far from houses so as to not have any influence. Proximity rules are expressed by the ratio D:H, where D is the minimum horizontal distance between the tree trunk and the walls of the building. The proximity ratios recommended by AS2870-1996 are often more stringent than Ward's (1953) rule, as the D:H ratio increases with level of site classification and also if more than one tree is present. AS2870's planting guidelines do not attempt to distinguish on the basis of species.

With the current trend in Australia towards smaller housing lots, the prescribed safe distances for rows of street trees may lead to a relatively treeless urban environment in areas of clay-rich soil profiles, a situation which would be aesthetically unacceptable (Flora 1978).

Footing design engineers try to minimise the risk of soil shrinkage settlements by excluding trees or, more recently, by designing footings to cater for anticipated soil movement (without trees). Current design criteria for "tree-designs" are based on simplistic empiricism, as very little information is available on the relative water usage of different tree species in the urban environment. Without this information, footings are either being over designed, adding substantially to building costs, or under designed, resulting in footing failures as the trees reach maturity.

2.3 EXPANSIVE OR REACTIVE SOILS

Reactive soils in a semi-arid climate swell during wet periods and shrink during the summer-autumn months. Settlement occurs when the soil moisture content decreases and trees assist this movement by further extraction of water in dry periods, which may lead to flexure of footings and associated cracking of masonry houses (Holland 1979).

In South Australia, design of footings for expansive or reactive soils has developed substantially since the pioneering work of Aitchison and Holmes 1953 and 1957, and has provided guidance to the rest of Australia.

Early trials were made with stiffened strip footings, grillage raft footings, raft slabs and a variety of deep footing systems. International research influenced the Australian research. Lytton from Texas AandM (e.g. Lytton 1972) was influential on development of design of raft slabs, while researchers from Israel influenced the experimental studies of Holland (e.g. Kassiff and Ben-Shalom 1971 and Kormonik 1969). Subsequent research in Australia, combined with the South Australian experiences, culminated in the first release of design guidelines for footings (Standards Australia, AS2870 - 1986). Examples of the research effort that resulted in the Standard can be found in papers by Aitchison et al 1973, Cameron 1989, Walsh 1985, Holland 1981 and Mitchell 1984.

Currently, expansive (or reactive) clay sites are classified in accordance with the Australian Standard 2870-1996 as "Slightly", "Moderately", "Highly" or "Extremely" reactive, depending on the amount of the design ground surface movement, y_s, expected over the 50 year design period in an urban environment. The site classification assumes reasonable site maintenance practices are adhered to throughout the life of the dwelling. In particular, designs to AS2870 assume that trees are kept well away from buildings. New homeowners are supplied with CSIRO Building Technology File pamphlet, BTF18, which advises homeowners on site maintenance and expected footing performance, and which discusses the threat of shrinkage settlement represented by close trees on reactive clay sites.

Environmental conditions of an area play an important role in the behaviour of soils. Climate dictates the design level of soil moisture changes at a site and therefore the site classification. Annual variations in intensity of rainfall and evaporation, depth of ground water table and site drainage patterns influence both the extent and the pattern of ground movements on a reactive site. Additionally, soil profiles at a site can vary markedly, leading to differences in movement across a site, even if the site experiences a uniform change in soil moisture condition.

Australian Standard AS2870 recognizes that urbanization causes environmental changes, which can lead to greater depths of movement and a moderation of seasonal climatic effects. On a well-drained and uniformly reactive site, these environmental changes lead to initial dishing of the ground under a house and, in following years, a doming distortion is likely to develop. As the soils beneath the edges of a house undergo almost seasonal variation in moisture condition, dishing is most noticeable over the winter-spring period, while doming is most distinct during summer-autumn. Civil engineers design footings to counter these movements in order to avoid large deflections of the structure, and hence distortion and cracking of walls.

2.4 GENERAL EFFECT OF TREES ON CLAYS

Much of what we know about trees is based on indirect evidence. For example, the aggressiveness of different root systems of trees near water pipes was revealed in studies of root chokes by the Engineering and Water Supply Department (South Australia) in Adelaide. CSIRO (Australia) and Cement and Concrete Association of Australia (Cameron and Earl, 1982) published information on potential damage to houses by trees, based on this information. Most people would find little argument with the species that were revealed as potential threats to house footings, although pine trees and date palms would be two exceptions in the opinion of the authors. The species list is provided in Appendix A. It was also assumed in the adoption of these species that climate differences around Australia would make little difference, although it is well known that the extent of a tree root system is greatly affected by water availability (Yeagher 1935).

Research on the influence of trees on reactive clays was initiated in the United Kingdom, where Ward (1953) recommended safe planting distance of trees of height, H, from buildings a distance, D, away. He prescribed “proximity rule” of D:H = 1 to ensure buildings were not damaged by the soil dessication. In Canada, Bozozuk (1962) demonstrated the decrease of drying settlements with distance from a row of 17 m high elm trees. In the UK in the mid 70’s, a severe drought caused much shrinkage settlement and it was realised that a large proportion of the ground movement under footings was related to the drying effects of trees. Further research effort was initiated in response (e.g. Cutler and Richardson 1981, Biddle 1983 and Driscoll 1983).

Biddle (1983) conducted studies of soil moisture deficits around specimens of certain tree species in open grassland. Five different clay soil profiles were investigated at three locations underlain by clay soils. Soil moisture was monitored with a down-hole neutron moisture meter to a maximum depth of 4 m. Generally it was seen that the lateral extent of drying was contained within a radius equal to the height of the tree. However the depth and radius of drying, both horizontally and vertically, appeared to be species dependent. Poplars caused drying to a radius of over 1.5 times the tree height and caused the deepest drying close to the trees, probably to a depth in excess of 4 m.

Cutler and Richardson (1981) reported on the investigations of 2,600 cases of building damage in the UK. Trees implicated as a cause of the damage were recorded and their proximity to the building noted. A database of species was established and was reviewed to find the maximum distance for a tree to “cause” damage in 75% of the cases recorded for that species. The greater the distance relative to the height of the tree ($D{:}H_{75\%}$), the more dangerous the tree. Unfortunately the information has had little impact on Australian practices owing to differences in climate, differences in tree species and different sensitivities to damage between homeowners in the UK and Australia (Radevsky 2000). In fact, the degree of damage was not considered and may have often been insignificant in the Australian context. Furthermore, the usual construction in England is cavity brick walls on strip footings, which is far less tolerant to movement than masonry veneer walls on a stiffened raft, the dominant construction style in Australia.

In the USA in Texas, Tucker and Poor (1978) studied a housing estate, which was in the process of being demolished because of the extent of damage to the houses (masonry veneer walls on slabs). Tree species were mulberry, elm, cottonwood and willows. Differential movements were measured and compared with D:H ratios. The results of the study revealed an average background movement of approximately 50 mm due to site reactivity, which was apparent at D:H ratios above two. The data strongly indicated that tree effects were significant at D:H values greater than one. Differential movements in excess of 120 mm were observed, where trees were close to the building.

In New Zealand, Wesseldine (1982) demonstrated the influence of the silver dollar gum (*E. cinerea*) on houses. The research indicated a threshold value of D:H of 0.75 for single trees to cause damage and 1.0 to 1.5 for groups of these trees. The extent of damage was not included in the correlation.

Early research in Australia on the effects of trees was not reported widely until the mid 80’s (e.g. Pile 1984, Richards et al 1983 and Cameron and Walsh 1984). This research was related largely to appraisals of damaged buildings. In Melbourne, studies of damaged masonry veneer houses on strip footings (Holland 1979 and Cameron and Walsh 1984) concluded that significant damage was only likely if the proximity of a single tree was less than or equal to 0.5 times the tree height, H. Pile (1984) reported building distortions and suction profiles to a maximum depth of 4 m in Adelaide, which were affected partly by trees.

In 1986, Standards Australia, AS2870, adopted a philosophy of designing for footings, assuming that trees were sufficiently distant from the structure not to cause any untoward effects. The proximity rules were modified to include potential effects of site reactivity and the density of tree planting, but not tree species. This philosophy has remained intact. Despite there not being a prescriptive Standard for designing for the tree drying, engineers have been pressed by the community to accommodate the extra soil settlement that may arise. Knowledge of the in situ soil suction changes around trees is essential to reliably estimate the ground movement in expansive clay soils. Once the magnitude and pattern of the ground movement is known, footings can be structurally designed to mitigate adverse effects and to facilitate an acceptable performance of the structures they support.

Currently, additional design soil suction changes are provided in the guidelines of the Footings Group (IEAust SA), where trees are present on a site. These suction changes do not recognize either any influence from tree species or the concept of “wilting point”. Vegetation is unable to draw moisture from the soil at high levels of soil desiccation, or soil suction. The limit at which this occurs is termed the wilting point and its value differs with species. Values of total suction of 1.55 to 3.1 MPa corresponding to the wilting point have been reported (McKeen 1992). If roots encounter soil at the wilting point, then the roots may extend into new areas of soil, where there is greater water availability, or the vegetation may die, or the plant may become dormant until water becomes available, all these possibilities being dependent on species. Design suctions generated by trees using the Footings Group approach tend to be higher than observed suctions at the wilting point.

2.4.1 Soil Suction

Soil suction is the negative pressure of the pore water in the soil, expressed on a logarithmic scale in “pF” units, where pF is the logarithm to the base 10 of the suction head in centimetres. Soil suction is an internal soil pressure and has the same units as pressure. The logarithmic unit is often preferred as these pressures can be very high. The "pF" unit can be defined as: -

$$\text{suction in pF} = \log(\text{suction in kPa}) + 1.01 \qquad \text{Equation 1}$$

High suction infers a low moisture content or dry soil. The usual range of soil suctions in the field in a semi-arid climate is 3 to 5 pF (approximately 100 kPa to 10 MPa); with 3 pF being a wet soil and 5 pF a dry soil.

Consequently, soil suctions, which usually range between 3 and 5 pF on site, correspond to negative pore pressures of 0.1 to 10 MPa, respectively.

Soil suction is related to the moisture content of a soil, but the relationship changes with each and every soil type. A linear relationship is usually assumed between suction and moisture content.

2.5 WATER POTENTIAL OF PLANTS

Information on the physiology of typical street tree species in an urban environment is very limited. A measure of the components of water potential is necessary to fully understand and explain the nature of plant water stress and soil water deficits (Campbell 1985). The components of water potential, namely osmotic, turgor and matric potential, represent the principal forces affecting the energy status of water in plant tissues (Brown 1982).

Leaf water potential (LWP) is one measure of the potential of the tree to extract water from the soil and is measured in MPa. A negative potential or suction is needed to drive the water through the plant and the atmosphere through humidity provides the pulling power to move water from the soil through the plant's xylem to the foliage (Knox et al 1995). Leaf water potential does not however measure the water use of trees. It only indicates the potential of the species to extract water from the soil under differing conditions. Leaf water potential (LWP) is similar in concept to soil suction. As water is lost from the leaves of a tree through transpiration, an essential part of photosynthesis, a negative potential or suction is set up within the leaf (Kozlowski 1982). The suction caused by leaf water loss, provides the pulling power to drive water from the soil through the plant's continuous system to the foliage (Biddle 2001). The "continuous system" is composed of the interactions between the soil, root, xylem and foliage (O'Malley 2001).

Xylem pressure or stem suction is another measure of the potential of trees to extract water from the soil. A freshly cut stem is placed in a chamber with one end outside the chamber. The chamber is pressurized until sap is seen to exude from the stem. The pressure at which this occurs is equivalent to the stem suction.

Only a few attempts at a direct correlation between the in situ hygrometer (leaf water potential) and pressure chamber (xylem pressure) have been performed on a limited number of species. Early research in the 1960's and 1970's showed good to poor agreements between the relatively new instruments. Turner, Shackel, and Le Coultre (2000) suggested that most of these discrepancies have been caused largely by the use of transpiring leaves, and incorrect cutting and handling procedures.

Information and research on soil water extraction, evapotranspiration, tree water use and stomatal behaviour is mainly based on agricultural and forestry plants and crops (Steward and Sands 1998, Ravina 1983, Balling and Zimmermann 1990, Bernardi 2000, Hatton, Landsberg, Reece and Knight 1999 and Raper 1998), but similar information for ornamental plant species used in urban areas is very limited. The research of Misra and Sands (1989) was unique in that it investigated the physiology (measuring sap flux) of two ornamental species, as well as ground movements, in a Melbourne park.

Research data on the role of trees in extracting water from the soil and tree desiccation (i.e. suction profiles) is also very limited, particularly for trees in an urban environment. Consequently there are no rational planting guidelines for tree species or footing designs for reactive sites planted with trees. So Local Governments must come up with their own individual tree selections and planting guides. Mostly based on past experiences but sometimes (and becoming more adopted) based on new ideas or trial plantings. Foundation engineers on the other hand must continue to adopt simplifications when designing for the effects of trees until further, more relevant data becomes available and further adopted by AS.

2.6 RECENT RESEARCH INTO TREES ON REACTIVE CLAY SITES

Biddle (2001) reported on his long-term studies of soil moisture changes around selected species of trees in a variety of clay soils in open areas in England, using a neutron moisture meter (NMM) to a depth of 4 m. Silvestri, Soulie′, Lafleur, Sarkis, and Bekkouche (1992) studied movements over three years of two damaged buildings in Montreal, Canada, and the associated patterns of soil movements, particularly around rows of maple trees adjacent to the buildings. Two catalpa trees also influenced the more severely damaged building. This work was unique in that investigations of building distress were allowed to continue over a significant period of time, allowing the installation of 3 or 4 neutron moisture meter access holes at each site to a depth of about 3 m, and the monitoring of soil moisture.

Richards *et al*. (1983) studied total soil suction regimes near groups of three different species of trees in parkland in Adelaide, South Australia. The tree groups were described as eucalypts, casuarinas and pines. Soil samples were taken from boreholes made progressively away from the tree groups. The eucalypts had the greatest drying effect while the pines had little effect on the surrounding clay soil. For the eucalypt site, the total soil suction reached 3.5 MPa at depth below the group of trees, and was not lower than 2 MPa throughout the exploration depth of 8 m. The radial extent of near-surface drying appeared to be 1.3 times the average height of the trees, H_{av}. The depth of drying decreased with distance away from the group.

The differences in total suction across a site are more important than the absolute values of suction. As pointed out by Richards et al 1983, soil salinity affects the suction values from one site to another. Where water tables are quite deep and significant vegetation is absent, it is generally accepted that soil suctions become relatively constant at depth. This equilibrium suction value, u_{eq}, relates to the suction expected under the centre of a large paved area in the same environment (Richards and Chan 1971). Cameron 2001 inferred the wilting points of trees from total soil suction data gathered around damaged house sites. He subsequently proposed that the difference between the deep equilibrium suction value and the wilting point suction was the true measure of soil desiccation of a given species. Jaksa, Woodburn, Kaggwa and Sinclair (2002) adopted the same strategy as Cameron for analysis of a further two treed sites in Adelaide.

RESEARCH PROJECT

3. METHODOLOGY

3.1 INTRODUCTION

Since March 2001, extensive research installations have been established on extremely reactive sites within a modern subdivision at Walkley Heights, north of Adelaide (See Figure 1). Street trees at the sites were immature and heavily watered by the developer's agents throughout the first years of the project (only turned off late 2003). The installations were regularly monitored to understand the development of background patterns of ground movement on a new housing estate and to investigate the water demands of the trees. Although the potential influence of the trees with time was not expected to be revealed directly, it was expected that projections could be made on future patterns of ground movement from the preliminary data gathered during the life of the project.

Seven research sites and 23 soil monitoring holes were established within an extremely reactive part of the Walkley Height's subdivision (Appendix D and Figure 2). Each site was planted with a single species of street trees. Four vertical access holes to 6 m below the surface were installed at each site, near the trees, between trees, under the pavement and away from the trees (See Figure 3). Surface levelling pads were located in the verge and Ramset nails were driven into the pavement near each site. These devices allowed the monitoring of both soil moisture (to 6 m depth) and surface soil movements. Tree water demands were evaluated using two methods (Leaf water potential and xylem sap pressure) on a monthly basis (Section 3.3).

A Campbell Pacific 503 Neutron Moisture Meter (NMM) was employed to measure volumetric soil moisture changes near and away from trees using deep access holes. Seasonal sampling for laboratory determination of soil suction was carried out when the NMM counts revealed a noticeable change in the soil moisture profile. Soil suction sampling was conducted during late summer to early autumn and again in late spring of each year. A Ground Movement Station (GMS) was established in the subdivision to monitor soil movements to 2 m depth, in an area well away from trees (Figure 5). The ground movement station was chosen to verify the general reactivity of the site. Leaf and sap suctions (water demand) were monitored with the use of an in-situ hygrometer for tree leaves and a purpose-built pressure chamber for plant stems.

Level surveys of a number of house slabs were performed prior to mainframe construction and other slabs within a year or so of house construction. The development of movement of many of these slabs has been investigated by re-survey's of the floor levels every 6 months (See Figure 13). The number of house and slab surveys was expanded to obtain a better coverage throughout the research sites. Information on footing designs has been gathered for each house surveyed.

Soil moisture and suction data have been used to backup and account for the movements observed in the level surveys. To accomplish this comparison, the reactivity of the various sites has been evaluated by shrink-swell testing (Figure 7) down the full depth of the potential active zone (assumed to be 6 m with trees on site). The various measures of appraising water demand have been compared over time, firstly between measures, and then with the development of soil suction, both total and solute suction. An ultimate goal of research continuing on from this current project is to develop a preliminary numerical model for the desiccation caused by trees in an urban environment. Establishing a link between tree physiology and soil suction development would be a major step towards this goal.

In summary, the research project is a continuing extensive field trial, which has been demanding in terms of managing the project and the short time frame of the project.

3.1.1 The Subdivision

The subdivision that was investigated is approximately 17 km north east of the capital city Adelaide in South Australia. It is located within the City of Salisbury council boundary. A map defining the boundaries of the subdivision is provided in Figure 1. The first homes in the subdivision were built in 1999; display homes and major connector roads were built first. Houses are generally free standing, single or double storey, sited on relatively small land allotments (350 to 800 m^2).

According to the soil map of Taylor, Thomson and Shepherd 1974 (after Sheard and Bowman 1996), the near surface soils within the subdivision range from red brown earths, RB4 and RB8 to Terra Rossa (TR). These soils are generally regarded to be of limited depth. Contrary to this expectation, sites within the research area were frequently classified by footing designers as E-D (extremely reactive, deeply activated soil profile), according to Standards Australia 1996, AS2870.

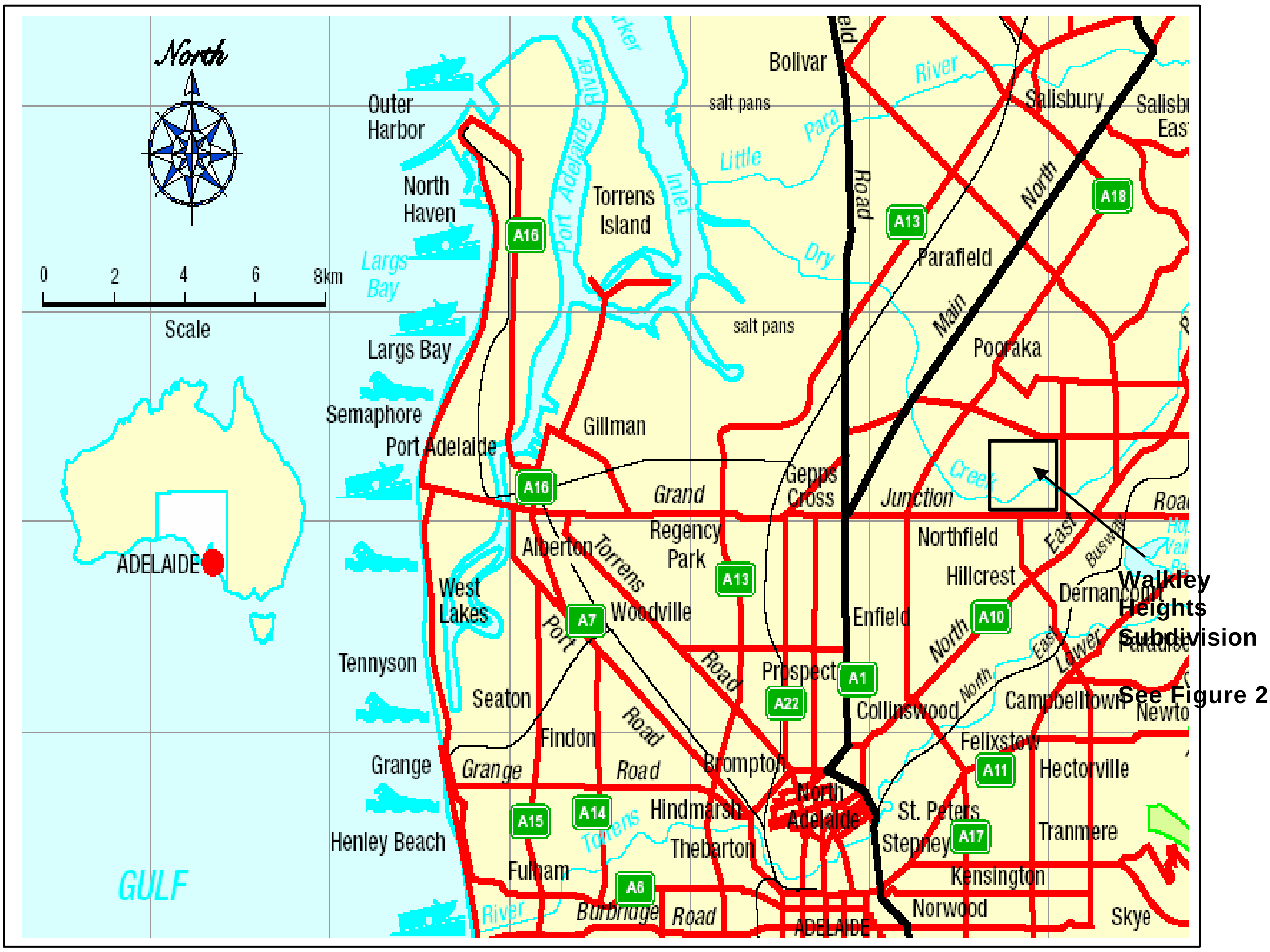


Figure 1: Location of the Walkley Height Subdivision, Relative to Adelaide and Surrounding Suburbs

3.1.2 Research Sites

Preliminary Investigations

The research area within the subdivision is concentrated in the earliest developed section, in the north eastern corner of the subdivision (development stages 1 to 3) Figure 2. This area was chosen as it was the most developed area (in 2001) and there were still a number of houses to be built, which could be monitored. In June 2001, a preliminary inspection was conducted of the sub-soils surrounding the planned study area. Three sites were selected, Homestead Drive by the Elms retirement village, Jackaroo Crescent and Polo Court. Polo Court was initially favoured as there were existing mature dwarf sugar gums, which were intended to be part of the monitoring program. Deep boreholes were made at each of these locations and samples were taken to assess soil moisture levels and soil profiles. The preliminary subsoil exploration revealed two important facts; firstly the heavy clay soils in the nature strip adjoining the retirement village underlying Homestead Drive had been saturated by the irrigation system. The soils at Jackeroo Crescent were significantly drier. Secondly, the sub-soil at Polo Court is pre-dominantly weathered rock and as such was not suitable for sub-soil monitoring.

Research sites were chosen based partly on the criteria of a suitable mix of built and incomplete housing, and a deep clay soil profile. All of the six chosen sites have design surface movements in excess of 100 mm (with no allowances for trees in the estimation of the design surface movement).

There are seven research sites in total, the seventh site comprises a station for measuring ground movement with depth, away from the influence of vegetation. Within these monitoring stations, 23 access boreholes have been installed, which allow regular monitoring of soil moisture levels. Figure 2 provides the general locations of the monitoring facilities.

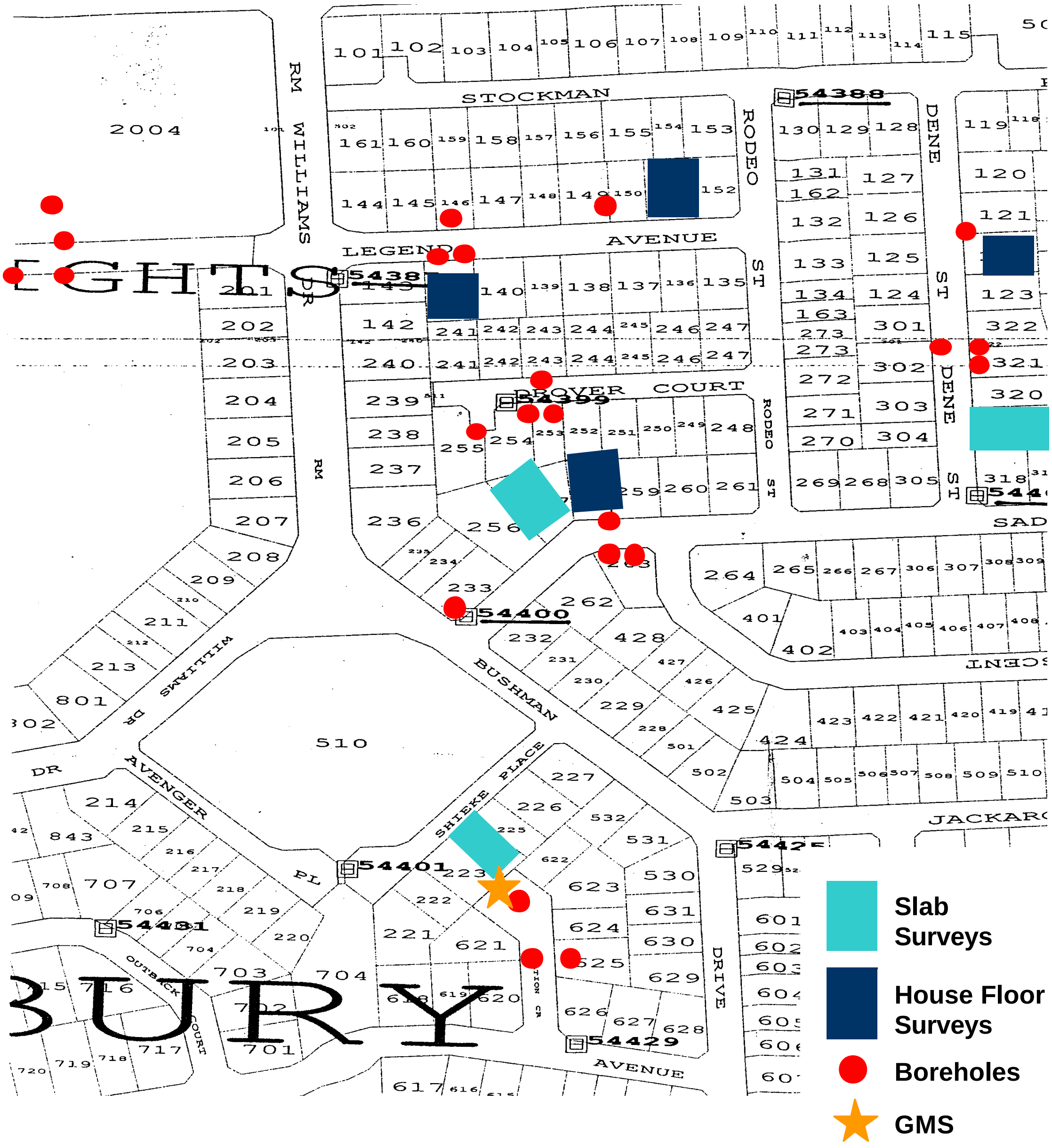


Figure 2: North-eastern Corner of the Walkley Heights Subdivision, including House Lot No's Research Boreholes, Surveyed Houses and GMS

The boreholes were cased so that on returning to the site for monitoring of sub-soil moisture, an NMM depth probe could be lowered into the soil and readings taken. The depths of the boreholes are given in Table I. Boreholes were located near the tree being monitored, between the trees (usually on the same side of the road), below the centre of the adjacent road and well away from the trees. A typical site layout is shown in Figure 3 for the Legend Avenue site. Table II provides distances between trees and boreholes. This information has been translated into D:H ratios in Table III. Tree heights at August 2003 are also provided.

It can be seen that the proximity ratios were generally high, due to the immaturity of the trees. Only at the Drover Court site did the D:H ratios fall below 1 for two of the four borehole locations.

3.2 TREE SPECIES

Four tree species are represented at the six monitoring sites across the subdivision. The tree species that were investigated were the Chinese Elm (*Ulmus parvifolia),* Golden Raintree *(Koelreuteria paniculata),* Ornamental Pear *(Pyrus ussuriensis x calleryana)* and Coral gum *(Eucalyptus torquata).* Three of the species were exotics (chinese elm, pear tree and golden rain tree) with the remaining planting being an Australian native eucalypt (coral gum). Trees of the one species were planted on both sides of the street. There was some duplication with sites having the same species as a consequence of residents' reluctance to accept certain species of ornamental trees, mainly Australian natives. As most of the trees are not native and are relatively newly introduced species, little knowledge has been obtained on growth habits and suitability in Adelaide's urban areas. The City of Salisbury has initiated studies in the past on selection of street tree species, for example, Grimwade (1981) studied the regional characteristics and the most suitable urban trees that should be planted in the Salisbury council area.

The oldest trees at the beginning of the current research project were the elm trees (stock planted in 1999), followed by the pyrus, koelreuteria (stock planted in 2001), and coral gum (stock planted, mid 2002). A number of trees have been replaced over this period due to vandalism, death and poor growth. Where possible, the trees were replaced with a tree similar in height and age to the original stock, although this was not always the case. Recent photographs of the trees are given in Figure 4.

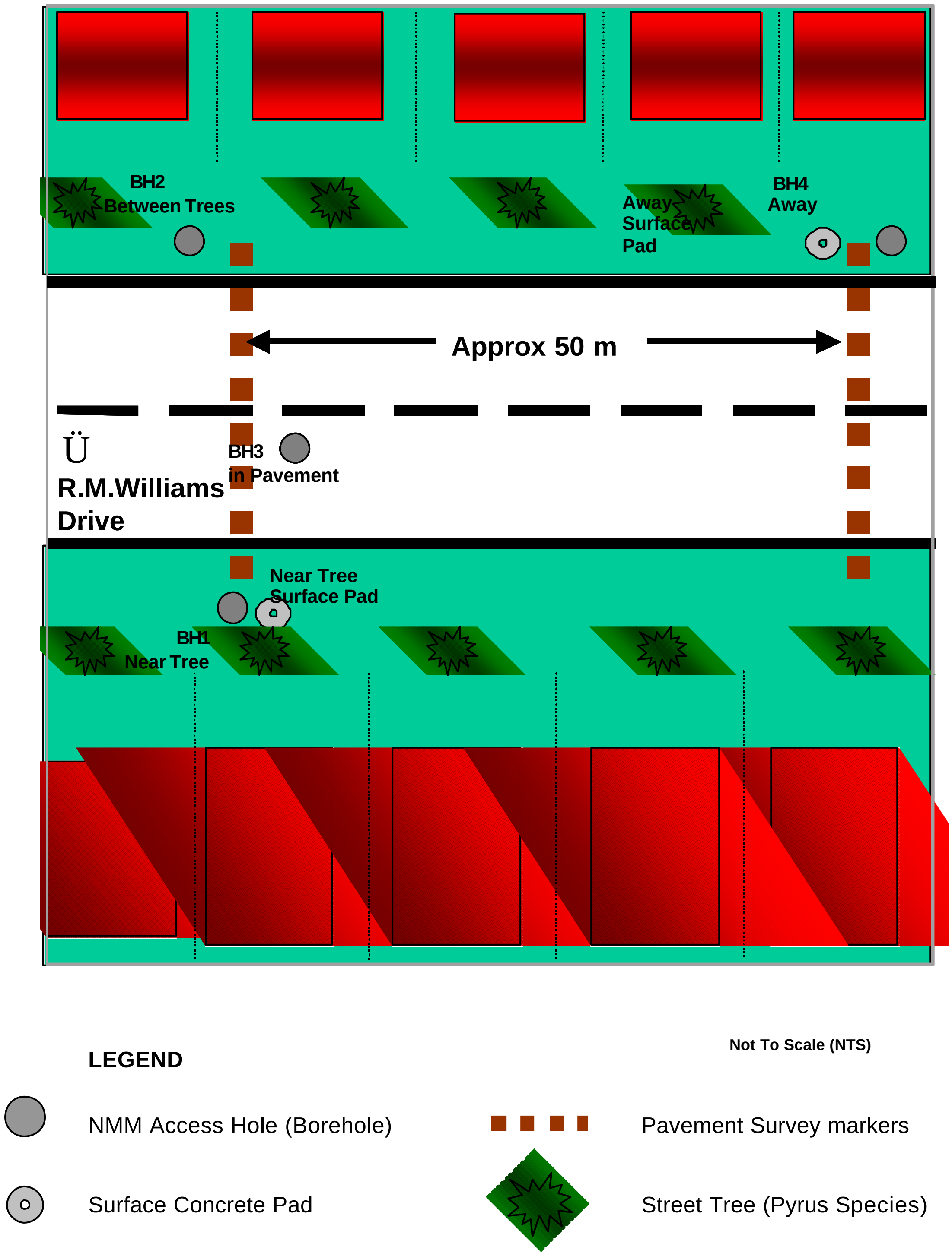


Figure 3: Legend Avenue - Site Overview

[See Appendix F for other Site Overviews]

Figure 4a. Homestead Avenue,
Chinese Elm (*Ulmus parvifolia*)

Figure 4b. Drover Court,
Golden raintree (*koelreuteria paniculata*)

Figure 4c: Saddle Crescent,
Golden raintree (*koelreuteria paniculata*)

Figure 4d. Legend Avenue,
Ornamental pear (*Pyrus ussuriensis x calleryana*)

Figure 4e. Dene street,
Ornamental pear, (*Pyrus ussuriensis x calleryana*)

Figure 4f. Station Court
Eucalyptus torquata

Figure 4: Photographs of monitored trees

Table I: Depths of cased boreholes

Site	Borehole 1	Borehole 2	Borehole 3	Borehole 4
Homestead Av.	5.50 m	4.55 m	5.60 m	5.65 m
Legend Av.	6.50 m	6.50 m	6.50 m	6.50 m
Dene St.	5.90 m	5.90 m	5.90 m	6.10 m
Drover Ct.	5.65 m	5.55 m	5.50 m	5.65 m
Saddle Cr.	5.20 m	5.60 m	5.15 m	5.50 m
Station Ct.	5.35 m	-	5.40 m	6.15 m

Table II: Distances from tree to boreholes and surface concrete pads

Site	Distance from Tree to Access Tubes and Concrete Pads (metres)					
	BH 1	BH 2	BH 3	BH 4	Pad tree	Pad away
Homestead Av. *Chinese elm*	1.2	6.6	6.4	9.6	1.0	10.0
Legend Av. *Ornamental pear*	1.6	8.0	4.5	50.0	0.7	50.4
Dene St. *Ornamental pear*	1.0	4.6	4.4	63.5	1.0	64.0
Drover Ct. *Golden raintree*	1.7	2.7	5.3	27.5	0.7	29.0
Saddle Cr. *Golden raintree*	1.0	4.5	4.5	49.0	1.1	49.0
Station Ct. *Coral gum*	1.2	-	11.0	44.0	0.8	44.5

Pad Tree = Surface movement pad near tree species (within 1.1 m)
Pad Away = Surface movement away from tree species (greater than 10m)

Table III: Tree heights and minimum D:H ratios between boreholes and trees, August 2003

Site Name	Tree Species, Common Name	Tree Height (m)	Minimum D:H ratios			
			Near tree	Between trees	Below Pavement	Away from trees
Homestead Av.	Chinese Elm	4.5	0.25	1.35	1.40	2.15
Legend Av.	Pear tree	1.7	0.95	4.85	2.75	30.5
Dene St.	Pear tree	2.4	0.40	1.90	1.85	26.5
Drover Ct.	Golden Raintree	3.4	0.50	0.80	1.55	8.0
Saddle Cr.	Golden Raintree	3.1	0.35	1.45	1.45	15.8
Station Ct.	Coral Gum	1.7	0.70	-	6.5	26.5

3.3. MONITORING EQUIPMENT

3.3.1 Neutron Moisture Meter (NMM)

A commercial NMM was used to measure the soils volumetric moisture contents. The neutron probe used in this study was a Campbell Pacific Nuclear Model 503DR Hydroprobe. Fast neutrons are generated by the probe using a 50mCi (1.85 GBq) Americium-241-Beryllium source with a strength of 111000 neutrons per second. A Helium-3 proportional counter detector of 13.2 cm in length and 2.54 cm in diameter is used to measure thermalized neutrons. The source is situated 3 cm below the detector. Neutron counts of 32-second durations were taken used for soil moisture monitoring.

The neutron moisture gauge consists of a probe containing a source of fast, high-energy neutrons that move radially outward from the source and a thermal neutron detector, together with the associated electronic equipment necessary to supply power and to count neutrons. When the neutron probe is lowered into the borehole, the fast neutrons emitted by the source collide with the atomic nuclei of the surrounding medium. Each collision between a neutron and a nucleus results in a transfer of energy from the neutron to the nucleus. Since neutrons and hydrogen atoms have the same mass, fast neutrons are mainly slowed down by collisions with hydrogen atoms, much like a billiard ball hitting a stationary ball of the same size and each moving away with equal speeds (one slowing down and the other speeding up). As hydrogen is associated with water molecules, the more collisions the higher the count and therefore the greater the water content in the soil.

3.3.2 Tree Water Relation Instruments

The aim of water relations sampling is to determine any discernible species differences in water usage which may be useful when recommending what species are best for certain urban areas and streets and improve design of footings to accommodate these trees.

The tree species water relations (water potential and sap pressure) were measured using a Wescor in-situ hygrometer and a custom built xylem pressure chamber (bomb). Two instruments have been used in this project, to firstly provide a comparison between in-situ water relations of street trees and secondly, to provide continuous monitoring of the trees' water potentials. The hygrometer measures only leaf potential, while the pressure chamber can be used for leaves, petiole, or stem potential measurements. Unfortunately, the hygrometer cannot be used when the deciduous trees have not leaves, so only sap pressures can be monitored during these times using the pressure chamber. Since three of the four trees are deciduous species, this feature has been a great benefit to the project.

3.3.2.1 Wescor in-situ hygrometer

The Wescor in-situ hygrometer measures the plants water potential (total suction), by measuring the in-situ leaf water potential of the plant leaves. The total suction of the sample using the hygrometer in dewpoint mode is deduced from the relative humidity of the pore spaces in the specimen. As the equipment is influenced by temperature gradients the equipment was insulated while measurements were made.

The insulation materials for the L-51 leaf sensors used in this study consisted of 3mm of styro-foam bubble wrap with a 5mm covering of highly reflective industrial aluminium insulation tape. The leads from the thermocouple were also insulated with the above materials. Aluminium tape was used as it reflects all wavelengths of radiation reducing the temperature gradients between the sensor and the Wescor instrument box.

3.3.2.2 Pressure Chamber (Bomb)

The pressure chamber measures the plants xylem pressure (matric potential), or stem pressure as it is sometimes referred to in the literature. The equipment measures the xylem sap pressure potential of excised leaves or stems. It is a simple but effective system whereby an excised sample is placed into an enclosed chamber and placed under tension with nitrogen gas. The tension at which the cut end of the stem starts to bubble with sap is the opposite but equal tension of the sample's sap pressure

3.3.3 Temporary benchmarks

As the nearest Lands Department Benchmark (LDBM) was located 750 to 1000 m from the research sites and was not easily accessed from the sites, a temporary benchmark (TBM) was established in November 2001 on Polo Court. A further two benchmarks were installed at the northern (Homestead Av) and southern ends (Station Ct) of the research area in 2002. The new benchmarks were required, as the original study area within the Walkley Heights subdivision had expanded with the establishment of a new site and the GMS in June 2002.

The network of benchmarks permitted the completion of level surveys more quickly and efficiently. They have also provided convenient data points for house and slab surveys. The benchmarks have been used to compare seasonal soil movements and to infer by difference the influence of urban development and in particular the street trees on soil movements. The new benchmarks have been surveyed back to the Lands Department marker to verify reliability of the TBM's on a number of occasions.

3.3.4 Ground Movement Station or GMS

A Ground Movement Station was installed so that movements in the absence of trees could be determined to depths of 0.5 m, 1.0 m, 1.5 m and 2.0 m within the soil profile at Station Court. The layout of the GMS is illustrated in 5.

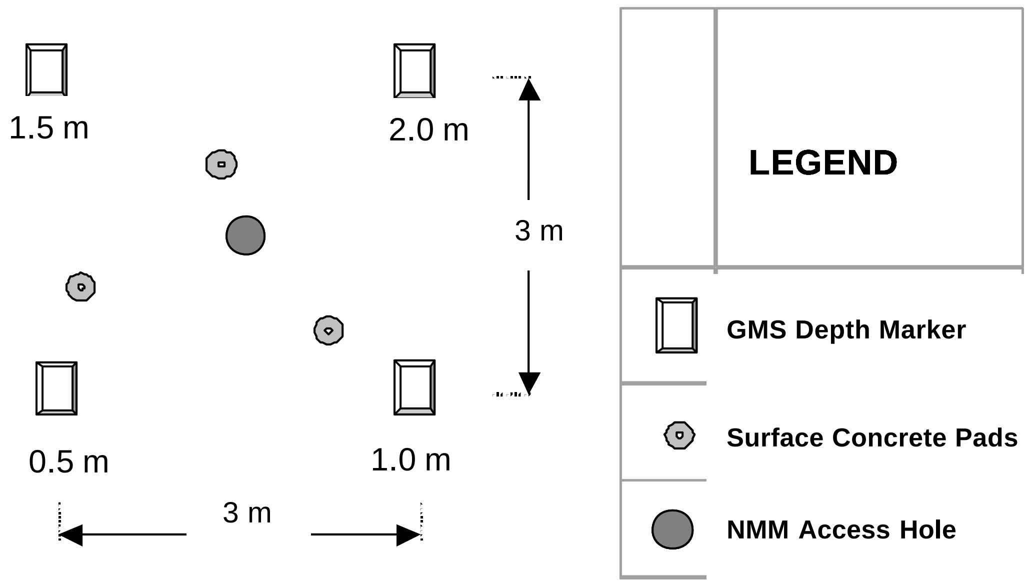


Figure 5: Walkley Heights Ground Movement Station - Overview

3.4 MONITORING STRATEGY

3.4.1 Sampling of LWP and Xylem Sap Pressures

Monitoring of the species water relations has been conducted on a routinely monthly basis, at similar times to the NMM and level surveys since February 2002. On each tree the middle canopy level/section was sampled with the two instruments. The middle canopy section was chosen as past research by O'Malley (2001) showed that this section provided the best overall water relations for the tree species at the time of sampling.

Usually just one tree from a site was sampled which was in close proximity to borehole one at each site. Three sub samples per tree leaf area or stem were measured per day, per species per month. All measurements of LWP and stem pressures were collected in the afternoon (12 to 5 pm) when the plants' suctions were high. This time is most favourable for LWP sampling as past experiments have shown that afternoon LWP provides the greatest magnitude of stress in tree species (O'Malley 2001). The highest suction is measured during the afternoon period as the trees wilt (or stress) and the lowest suction is measured at pre-dawn, where LWP is in equilibrium with the soil. Leaves lose greater amounts of water in the later part of the day due to adverse positions of the sun and environmental conditions (O'Malley 2001).

3.4.2 Neutron Moisture Meter

The NMM has been used monthly since June 2001 to provide an indication of soil moisture changes. The NMM probe was lowered down into the access tubes, which have been permanently installed to depths of up to 6 m at each site to monitor the moisture patterns of the surrounding soil. The major advantage of this method is that repeated measurements of soil moisture can be made in these access tubes at any interval, providing measurements of the seasonal and/or long-term changes in soil moisture content. After May 2003, NMM sampling was changed to bi-monthly, as the NMM plots were not showing great variations during the shorter monitoring periods.

A count ratio is made for each measurement by dividing the raw count (i.e. direct field count) by the standard count. The Standard Count (STD) is an air count that is taken with the NMM probe inside its protective casing and standing on top of it carrier box. The air count is taken before and after each day's measurements to ensure the NMM is working correctly and is also used to calculate the NMM count ratio.

In this project, NMM readings were first taken at the greatest depth of the tube, and then at 0.5 m intervals until the surface was reached. Cable stops secured to the NMM cable were used to position the NMM at specific depths in the access tube. Neutron counts of 32-second durations were taken for soil moisture monitoring. The counting time interval of 32 seconds was chosen because it gave sufficiently precise readings after comparison with 16, 64 and 256 second counts. It was more precise than 16 sec without wasting time, while 64 and 256 counts were deemed to long. Even using 32-second counts, it took approximately 15 minutes to take readings from each borehole (@ 12 readings per borehole).

4. SITE CHARACTERIZATION

4.1 SOIL TESTING

In order to assess the soil reactivity and hence site classification, four samples from selected depths from each site were tested as shrink-swell specimens. All 24 samples were classified by the Unified Soil Classification System (USCS) and visual–tactile methods. Atterberg Limits (liquid and plastic limits), were determined for each soil sample. In addition, some 150 free swell tests have been conducted on these samples from the six soil profiles. The free swell test is a simple means of evaluating expansiveness of the finer, disturbed soil fraction (dried, pulverized and sieved).

4.1.2 Soil profiles and Free Swells

The overall general descriptions of the natural soils of the area are high plasticity clays (CH) underlain at considerable depth by lower plasticity silty-clays (CI) or sandstone. Shallow bedrock was encountered at two sites below the higher plasticity surface clay profile these being both Legend Avenue (3.5 m) and Dene Street (3.0 m) soil profiles. Low plasticity clays (CI) were encountered to 1.0 m in Homestead and Station Court soil profiles overlying the higher plasticity clay which continued to depth. It was noted that there were minor variations between sampled borehole soil depths within each sites.

CH is the highest plasticity accorded to soil in the Australian adoption of the Unified Soil Classification System (USCS). Appendix B contains information on site borelogs (soil profiles) and free swell plots.

4.1.3 Atterberg Limits, USCS

All Atterberg Limit data as seen in the plasticity chart of Figure 6 plotted above the 'A-Line'. Soils generally plotted as CH, except for a few shallow samples and one deep sample.

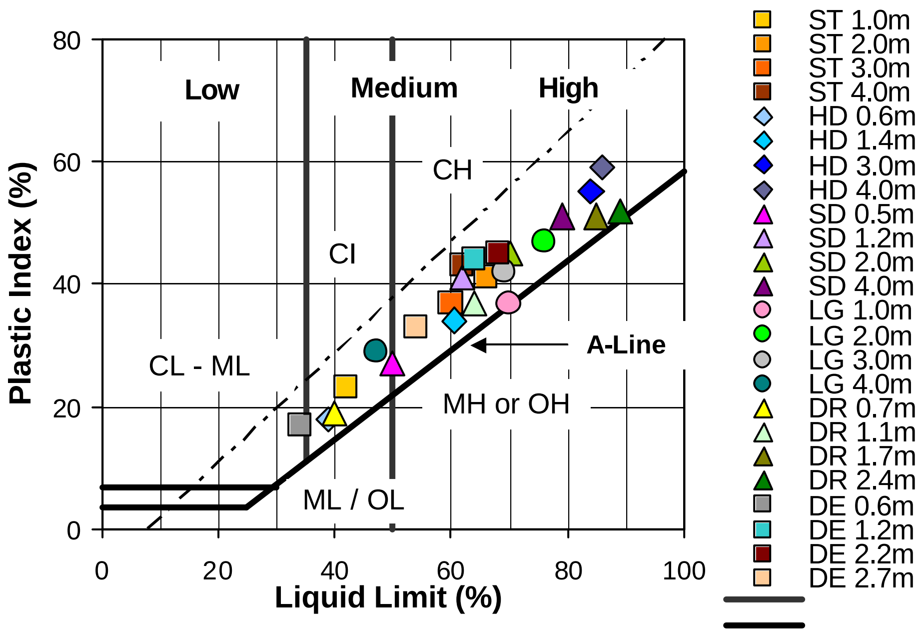


Figure 6: Atterberg Limits and Unified Classification of Site Soils

Sub-Legend

ST = Station Ct HD = Homestead Av SD = Saddle Ct LG = Legend Av DR = Drover Ct DE = Dene St

4.1.4 Soil Reactivity

Reactivity tests (shrink-swells) were performed in accordance with AS1289. Typically the shrink-swell indices from the research sites were low near the surface (1.0 % per log MPa) and quite high at depth (a maximum of 9.5 % per log MPa). This difference is reflected in the soil profile changes, ranging from silt-clays at the surface to high plasticity clays at depths greater than 6.5 m, and beneath this clay, siltstone bedrock or weathered siltstone were encountered in a number of holes. It should be noted that 4% per log MPa would be regarded as a highly expansive soil, 6% per log MPa very highly expansive and 8% per log MPa, an extremely expansive soil.

Shrink-swell indices have been summarized in Table IV and have been plotted in Figure 7 for each of the sites. The plots indicate layer boundaries. A noticeable drop in reactivity is evident at two of the sites (Dene and Legend) as these two sites are underlain by shallow, low plasticity, clayey silt at approx 3.5m depth (drilling auger refusal on siltstone at between 3.0 and 3.8m at these sites)

Table IV - Summary of soil reactivities for all sites

Depth (m)	Reactivity (%)					
	Station	**Homestead**	**Legend**	**Dene**	**Drover**	**Saddle**
1.0	0.9	2.8	6.5	2.0	1.4	4.0
2.0	8.7	2.8	7.8	8.6	9.0	4.0
3.0	7.0	7.9	6.6	3.3	9.5	6.1
4.0	5.1	8.8	2.3	1.5	-*[1]	6.0
Sampling Date	June 2002	March 2002	March 2003	September 2003	September 2003	November 2002

4.2 SITE CLASSIFICATIONS

Site classifications according to AS2870-1996 were undertaken for all of the sites, based on the soil reactivity data and the idealized soil profiles in Figure 7. The soil profile was sub-divided into layers of known reactivity index and movement estimates were made by multiplying the shrinkage index (or shrink-swell index), by the average suction change in the layer, by the layer depth.

As the depth of seasonal soil shrinkage cracking is taken as three metres in Adelaide, corrections for lateral restraint are generally not made. Due to the deep active zone adopted in Adelaide, the test sites were generally classified as extremely reactive or Class E-D (AS2870-1996). In many cases the estimated site surface movements in the absence of trees in the subdivision were above 100 mm. The design site characteristic movement for the sites, y_s, ranged from 45mm (Station Ct) to 125 mm (Drover Ct) (with no influence of trees) as shown in Appendix D and in Figure 7.

[1] an undisturbed sample could not be recovered from this depth at the time of sampling

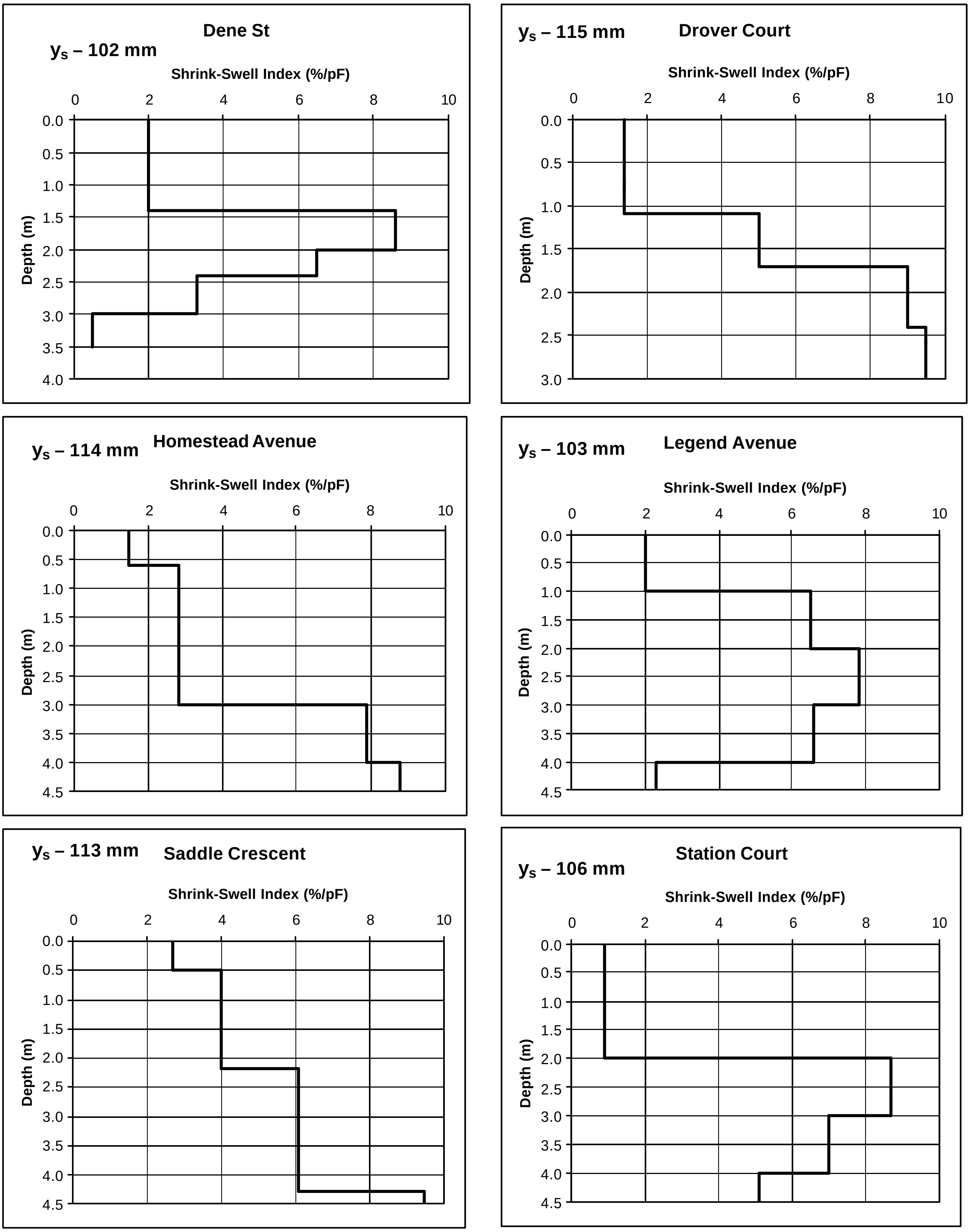


Figure 7: Site Reactivities (%/pF) vs Depth of Soil Profile

Note: y_s value – maximum surface movements for each site (house closest to sampled site)

5. RESULTS OF MONITORING

5.1 INTRODUCTION

Monitoring has included the following tasks since inception of the project:

- Two hundred and fifty initial borehole soil suction sampling have been drilled and sampled (2001)
- Twenty-five months of soil moisture patterns through measurements with a down-hole probe have been undertaken to depths of up to 6.0 m.
- Twenty two months of level surveys (of pavements and road verges) have been collected
- Twenty two months of species physiology (LWP/sap pressure) have been collected
- Floor level surveys of four house floor (and three slabs) have been undertaken and re-checked approximately 6 months, 12 months and 18 months later

The following sections summarize the observations from the various monitoring tasks.

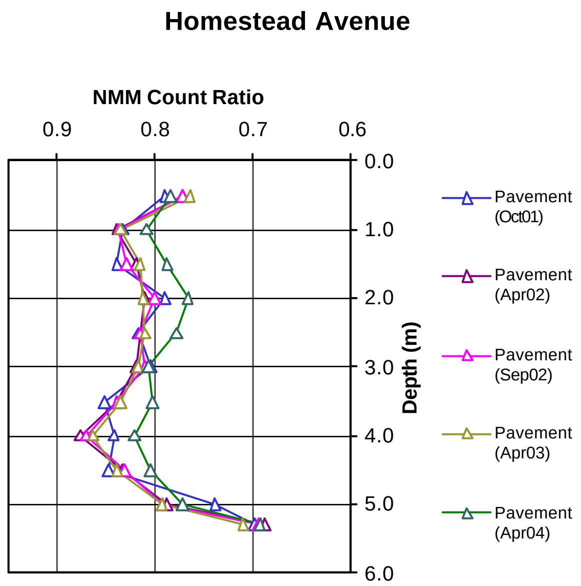
5.2 SOIL DATA

5.2.1 Neutron Moisture Meter

From the neutron moisture meter count ratios recorded over the sites it may be concluded that there has been no obvious drying of the soil due to the street trees. There has not been any substantial difference recorded between the near and “away from tree” boreholes at any of the sites, which could be directly attributed to street tree drying. Many of the sites have been over-irrigated and in all cases the trees are relatively young (less than 4 years old). As illustrated in Figure 8, Homestead Avenue is typical of the NMM data collected for all the sites (data for other sites are provided in Appendix C). Only seasonal moisture changes can be seen in the “away” plots to a depth of 2 m. Near the tree, the count ratios remained high throughout the monitoring period, indicating high moisture contents and the effects of over-irrigation to a maximum effective depth of 1.5m Below the pavement, infiltration is restricted by the asphaltic seal (so long as it remains intact and does not crack). So the soil under the seal remained relatively drier and stable than the other profiles.

It is expected that future summers will provide greater soil moisture changes, with less frequent and effective irrigation by the developer and only supplementally water provided by the household residents.

The NMM count ratio is dependent on soil type and so variations in soil profiles across a site can lead to quite different count profiles as seen in Appendix C (NMM count ratio of 0.9 wetter moving to 0.6 drier). Soil suction is relatively independent of soil type and so soil suction profiles at a site should reflect relative levels of desiccation or wetness. The soil suction profiles are presented in the next section.



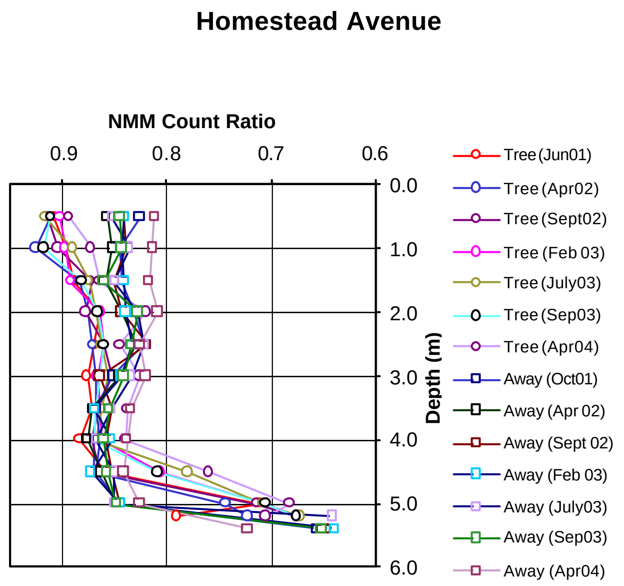


Figure 8: NMM Plots for Homestead Av – 'Near tree', 'pavement' and 'Away from tree' profiles

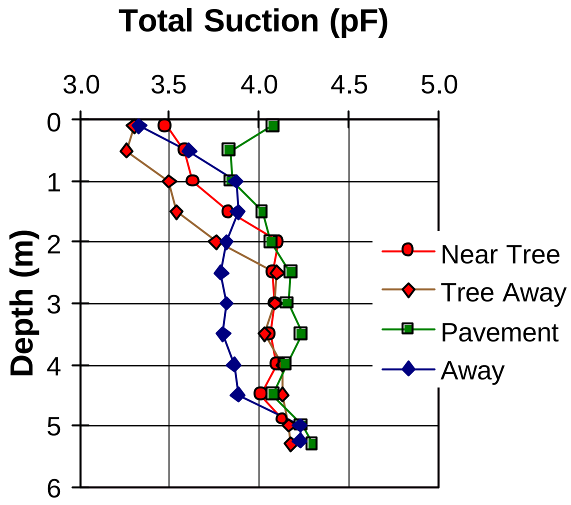
5.2.2 Soil Suction Sampling

Initial soil suction profiles were determined from samples taken from all boreholes made during installation of NMM casing. Six rounds of soil suction monitoring were undertaken subsequently on all sites to appraise the extent of the seasonal wet and dry periods On each site, suction samples to maximum 6.0m depths were taken from BH1 (near tree) and BH4 (away from tree) locations. Each round consisted of approximately 170 soil suction samples. The summary of the initial soil suction for all sites are illustrated in Figure 9. Subsequent suction profiles for the sites near and away from the trees are provided in Appendix E.

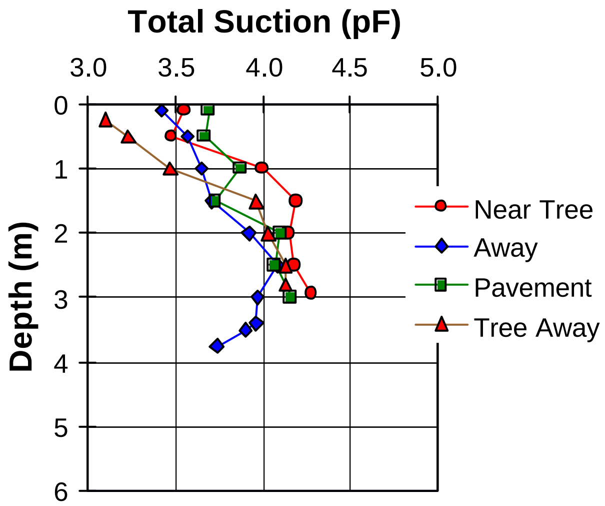
The first observation that can be made is that initial soil suctions were not uniform across the majority of the sites, except for Station Ct. and perhaps Dene St.. Also, sites were generally wet to appreciable depth (2.5m) when established in 2001. A number of road verges at the sites had high initial moisture contents and low suctions due to irrigation, which had commenced well before establishment of the sites. The irrigated sites (HD and LG) have appeared to have been over watered in many cases, which has influenced the short term seasonal drying and wetting patterns of the soils that was subsequently observed.

At the sites that have been irrigated (namely Homestead and Legend Avenue) average total suctions ranged between 0.3 and 0.4 MPa in the top 2 m of the soil profile, while those sites that have not been irrigated, average suctions were slightly higher at 0.7 MPa. The over watering of the irrigated road verge site may account for up to 1.0 MPa change in total suction (wetter) in the top 2.5 m of the near tree borehole when compared to the away from tree and non-irrigated suction profiles.

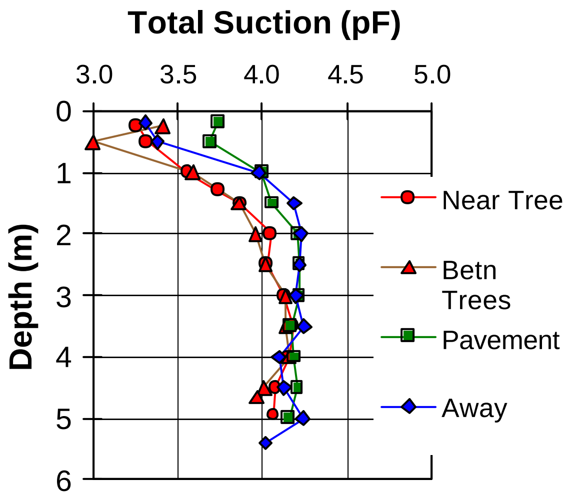
There has been no obvious tree drying as a number of sites have been over irrigated and the trees are relatively young. No substantial difference has been recorded between the near and away from tree boreholes at each site, which could be attributed to street tree drying. Only seasonal suction changes in the top 2 to 3 m of the soil have been recorded to date



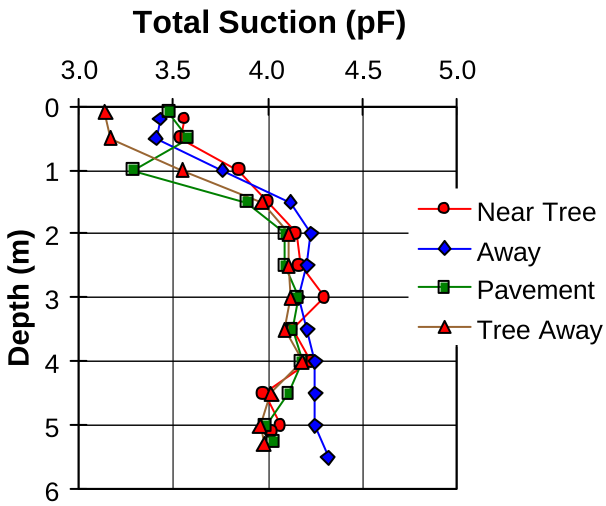
a) Saddle Crescent, Walkley Heights
(22nd Aug 2001)



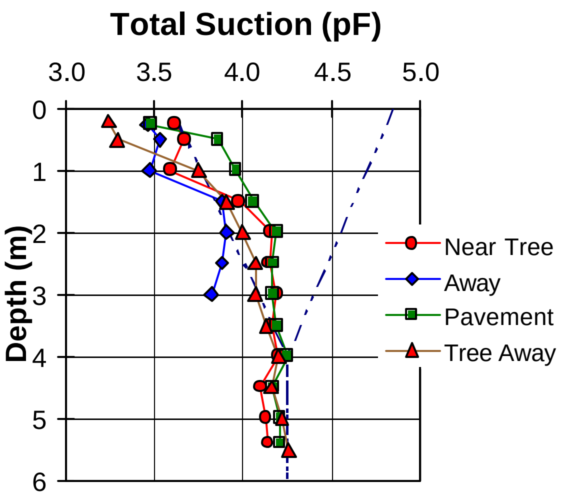
b) Drover Court, Walkley Heights
(28th Aug 2001)



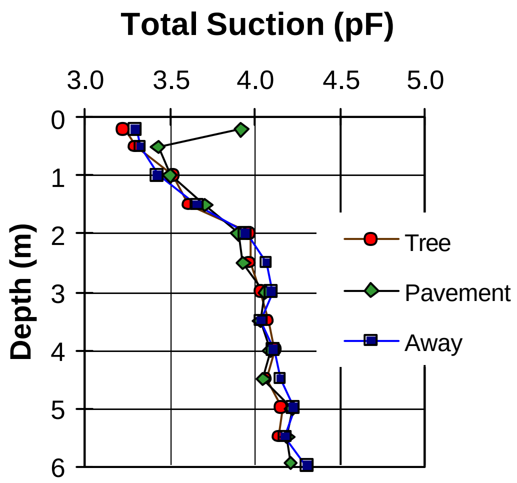
Homestead Av, Walkley Heights
(28th June 01 “tree”, other locations 29th Sept 01)



d) Dene St, Walkley Heights
(19th Sept 01)



e) Legend Avenue, Walkley Heights
(est'd. 28th Sept 01)



f) Station Court, Walkley Heights
(est'd. 28th May 02)

Figure 9: Initial Soil Suction Profiles for all sites

5.3 MOVEMENT ESTIMATES

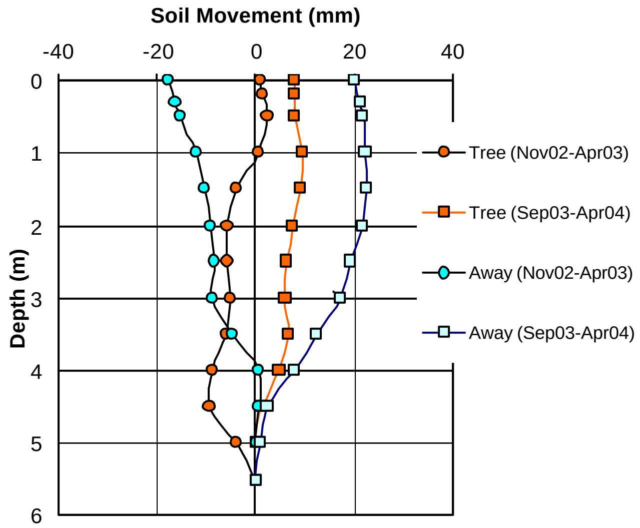
Provided soil profiles are known, soil shrinkage indices have been measured and suction changes predicted, expansive soil movements can be estimated in a similar fashion to consolidation settlements.

Estimates of ground movement were based on the typical shrink-swell profiles for each site, which are provided in Figure 7. Corrections for lateral restraint were made below a depth of three metres, the assumed depth of shrinkage cracking for Adelaide. Movements were estimated between seasons at the routine sampling locations for each site, i.e. near the tree and well away from the tree. Incremental movement estimates have been plotted in Figure 10a for two time periods. These plots have been converted to cumulative movements with time at various depths within the soil profile (refer Figure 10b).

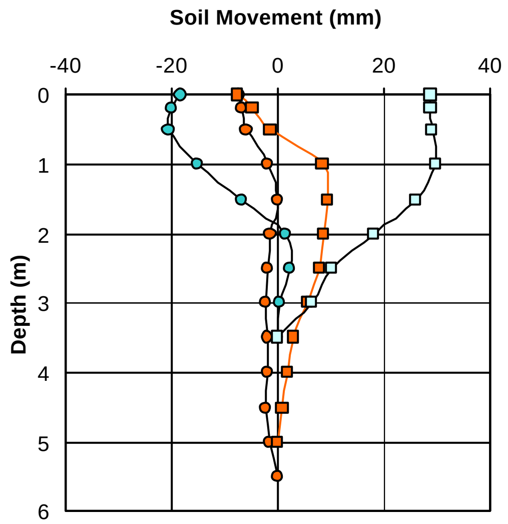
Deep movement was predicted at three of the sites; Homestead Av., Saddle Cres., and to a lesser extent, Station Ct.. At the other sites, the movement was restricted chiefly to the top 2.5 m or so. The suction profiles near the trees were wetter than away from the trees for half the sites. At Saddle Cres., the ground away from the tree was initially wetter, but subsequently was dried, while the soil near the tree became wetter with time. The tree was adjacent to a well-irrigated front-yard, while the away location was not irrigated.

Seasonal activity was not always evident either near or away from the tree. The movement predicted for the away location at Drover Ct. was continuous heave; however this location was below a pavement, although it was near the edge of the pavement. A similar prediction was made for the away location at Station Ct.. The site lies downslope of a small retaining wall, which tends to feed moisture into the adjacent ground.

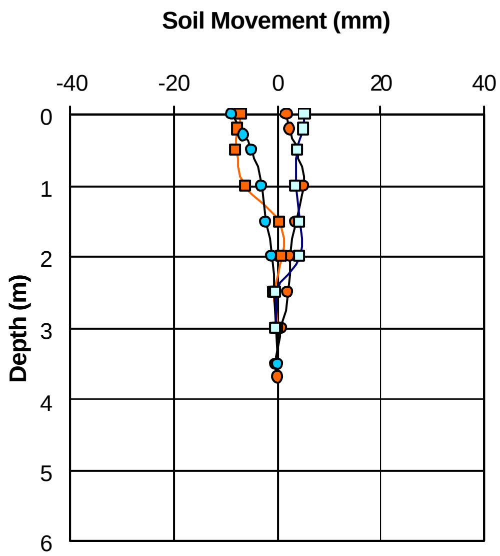
Level survey observations have been imposed on the plots of predicted cumulative movement (indicated as “obs” in the legend) for times corresponding as closely as possible to the dates of soil sampling for total suction determination. Although general trends are reinforced, the correspondence between observed and predicted movements is not strong, which could be due to seasonal movement of temporary, deep benchmarks, or to differences in soil profiles within a site. It should also be noted that movement predictions usually fall within ± 25% of the actual movement (Cameron 1989).



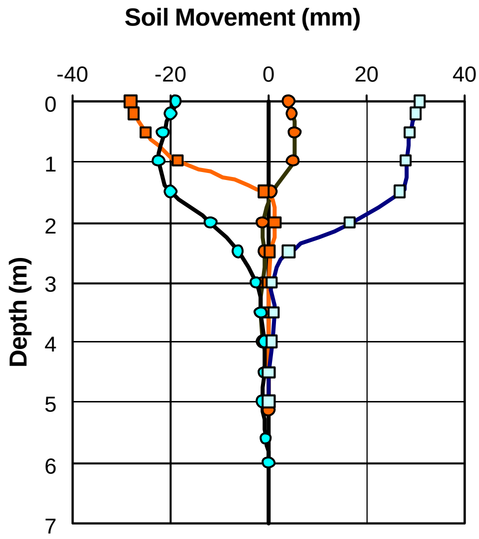
a) Homestead Av



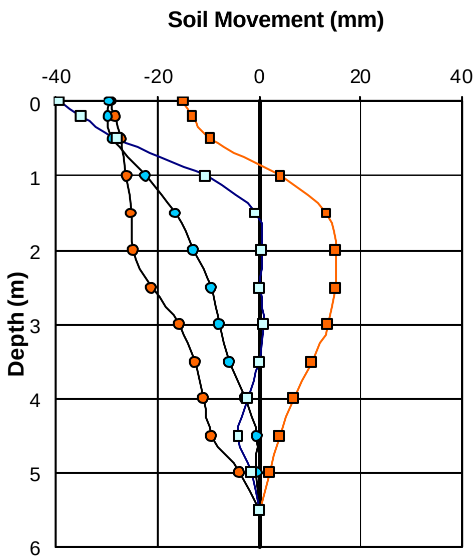
a) Legend Av



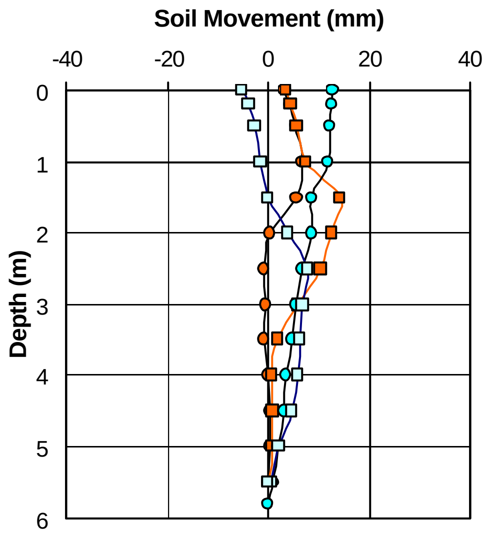
c) Drover Ct



d) Dene St

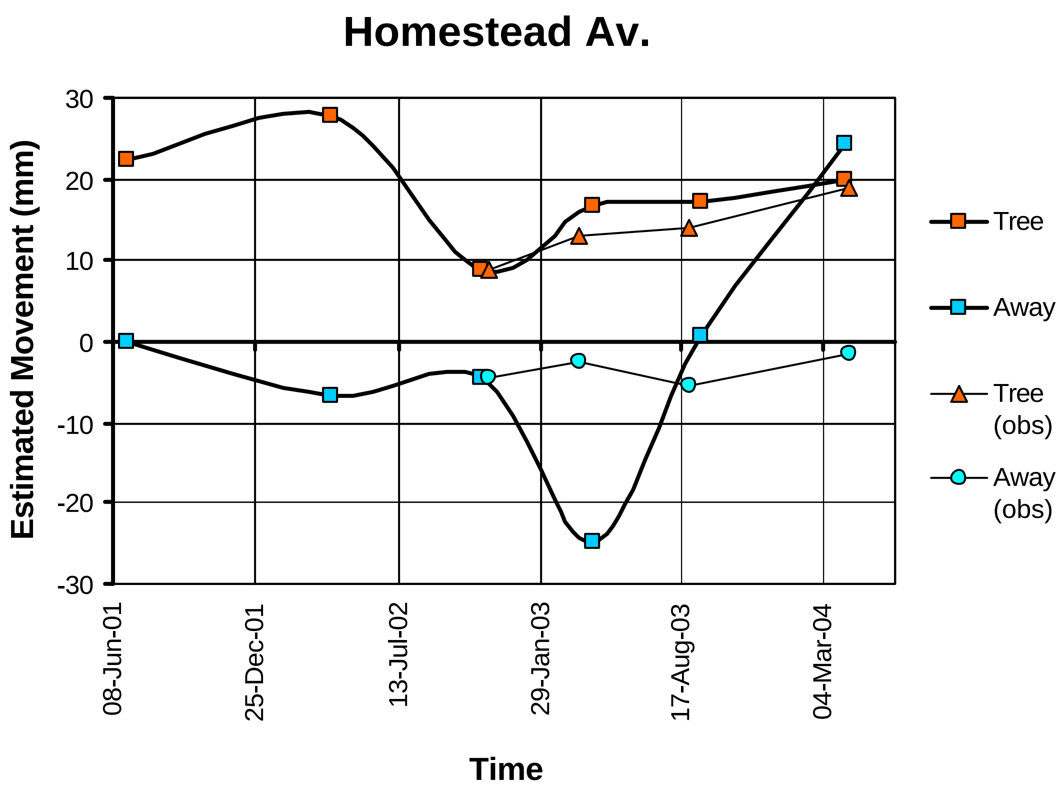


e) Saddle Cr



f) Station Ct

Figure 10a: Near Tree and Away Movement Estimates with Depth for all Six Sites



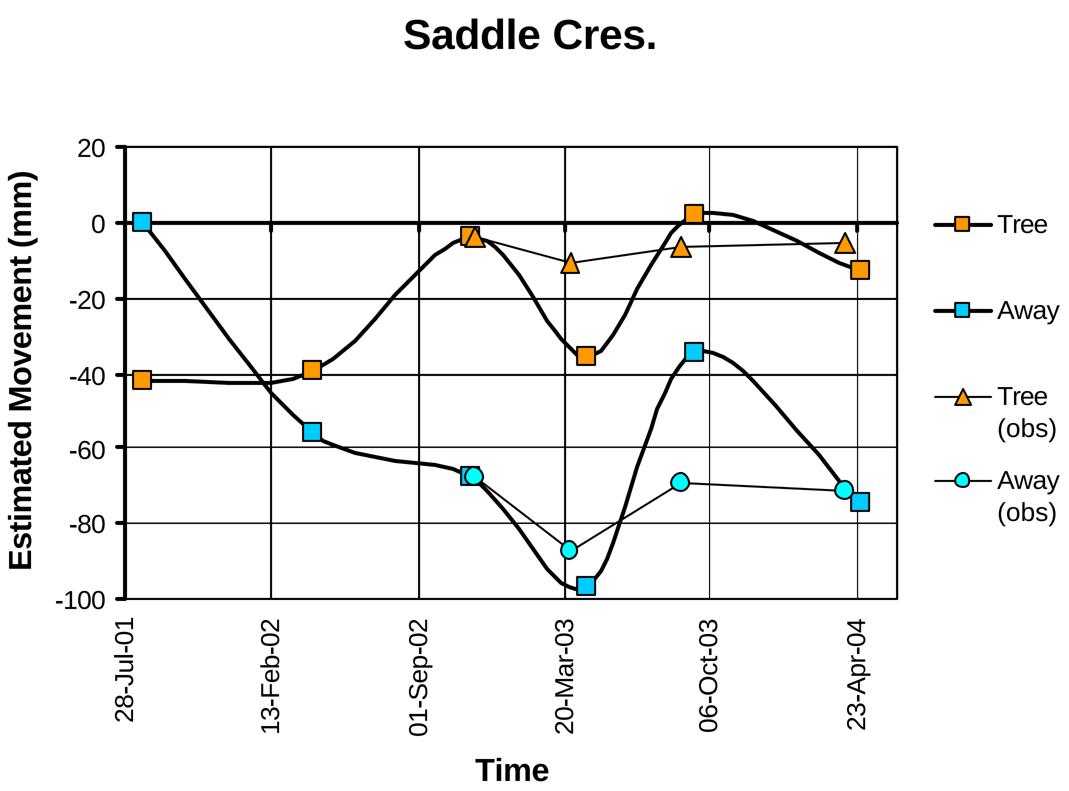
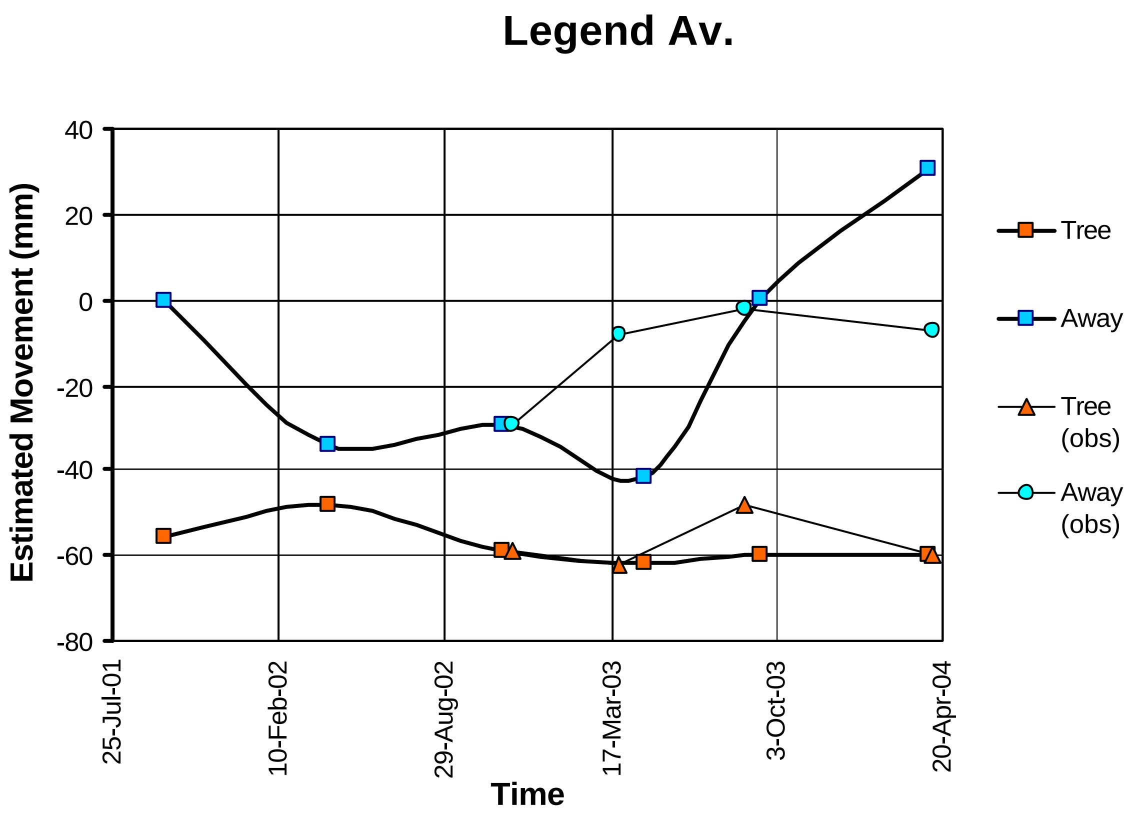


Figure 10b: Movement estimates with time



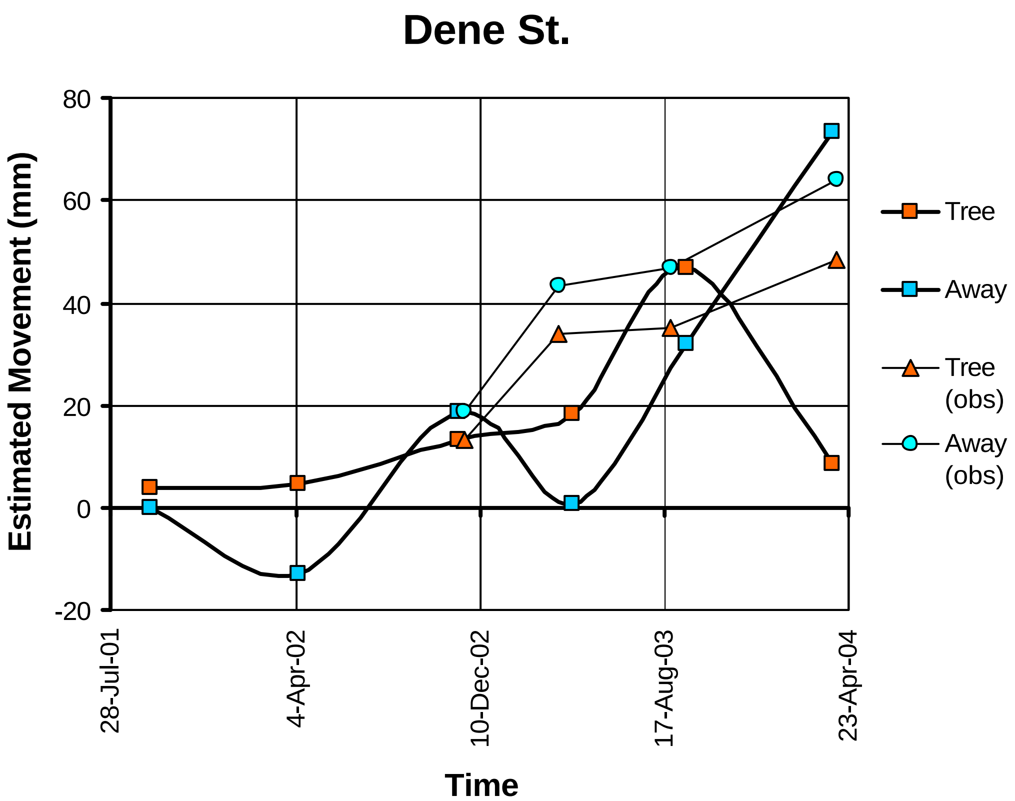
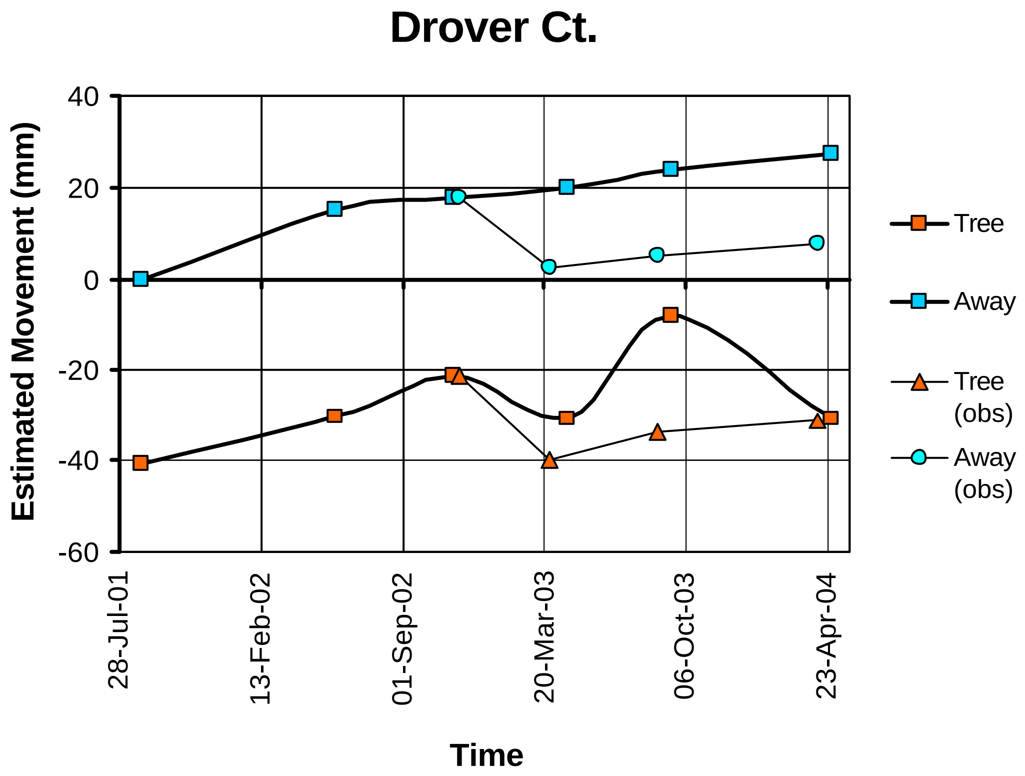


Figure 10b: Movement estimates with time



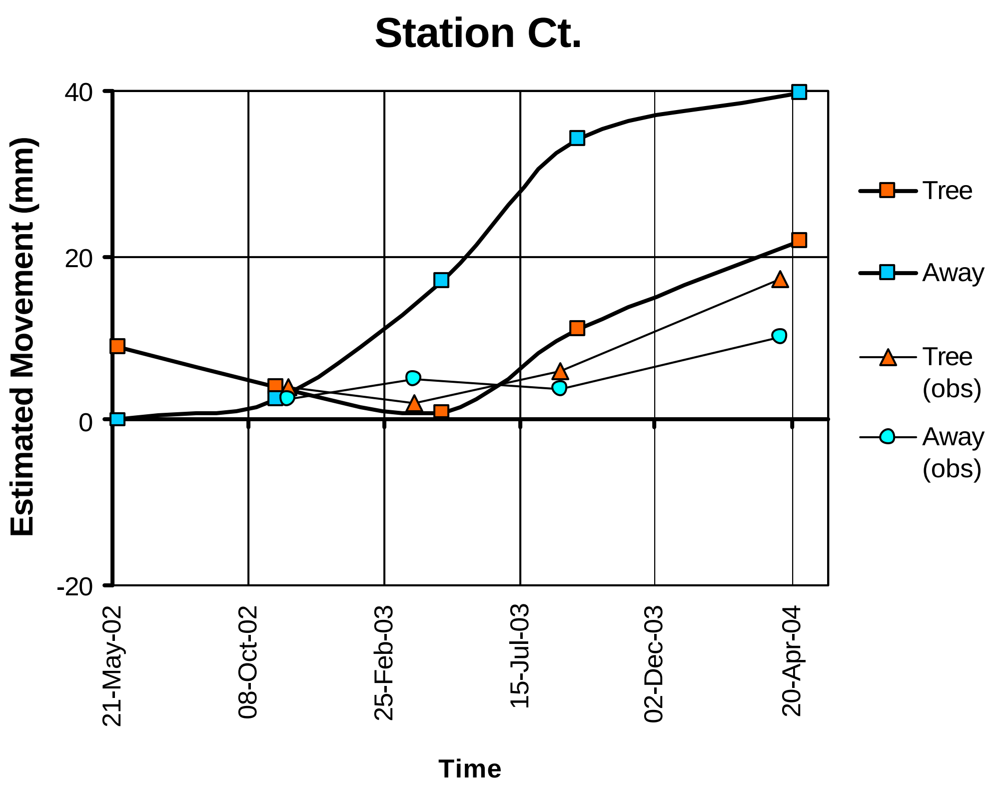


Figure 10b: Movement estimates with time

5.4 LEVEL SURVEYS

5.4.1 Pavement Surveys

Pavement surveys have continued and some substantial movements have been revealed. The highest and lowest pavement profiles (across the pavement surface and including the nature strip) for each site and either near or away from the monitored tree, are presented in Figure 11. All profiles are relative to summer 2002 (February-March), except for Station Court, which was first surveyed in June 2002. It should be noted that the subdivision was partly developed at this stage, with Homestead and Legend Avenues being among the earliest established streets. Consequently the developer had already commenced spray irrigation of the nature strips at these two sites.

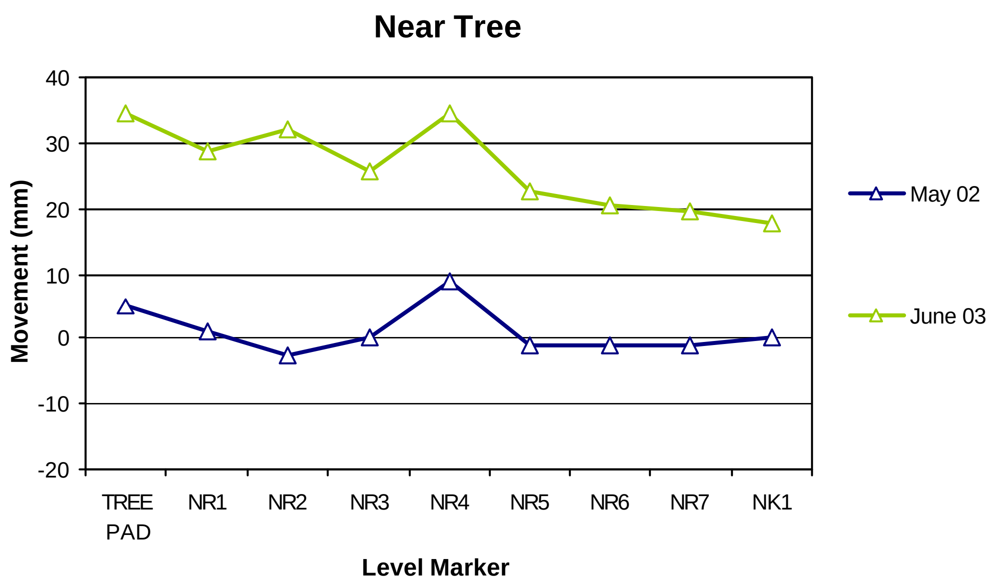
The largest movements were recorded on the surface concrete pads in the nature strip, with movements up to +55 mm. The road movements have ranged from -30 mm to up to +53 mm of movement. Generally the pavements have kept their shape although some relative edge settlement is apparent and may have lead to pavement cracking. However distortion of the pavement at Drover Ct. is clearly evident at the pavement section “away from the tree”.

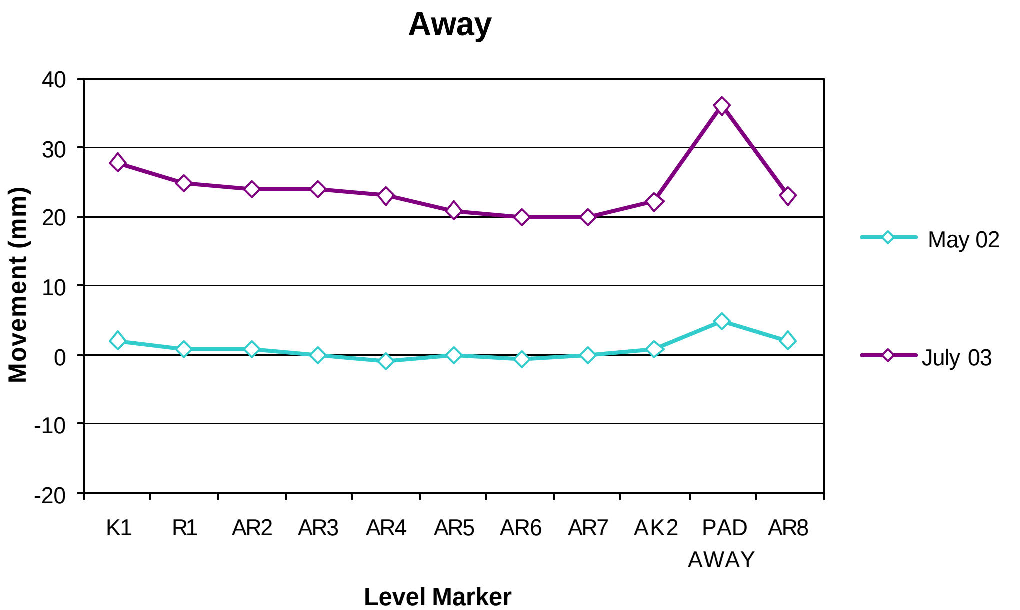
No movements have been directly related to soil desiccation by street trees, as the trees are still young. The movement that has been observed can be considered to be the background movement on an extremely expansive site undergoing urbanization. It is predicted that proceeding summers will dry out the soil profile, reducing levels and probably producing drying settlement (compared to initial levels).

5.4.2 Ground Movement Station

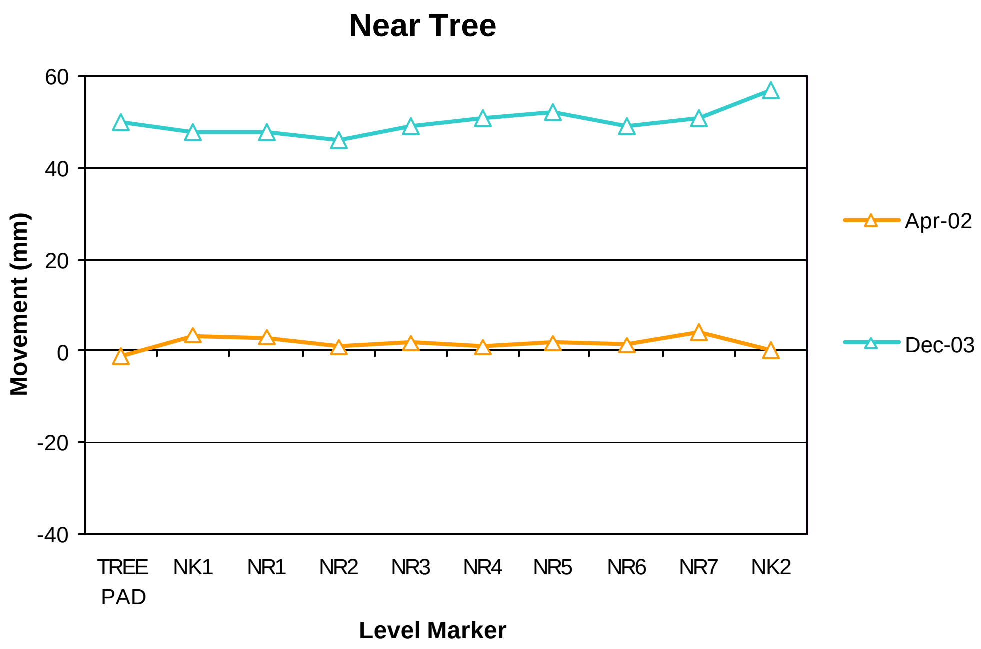
The Ground Movement Station (GMS) has been monitored on a monthly basis since being installed in mid-June 2002 at the top end of Station Crescent, on gently sloping ground in an area devoid of trees. Deep seated movements at 0.5 m, 1.0 m, 1.5 m and 2.0 m depths below the ground surface are being monitored.

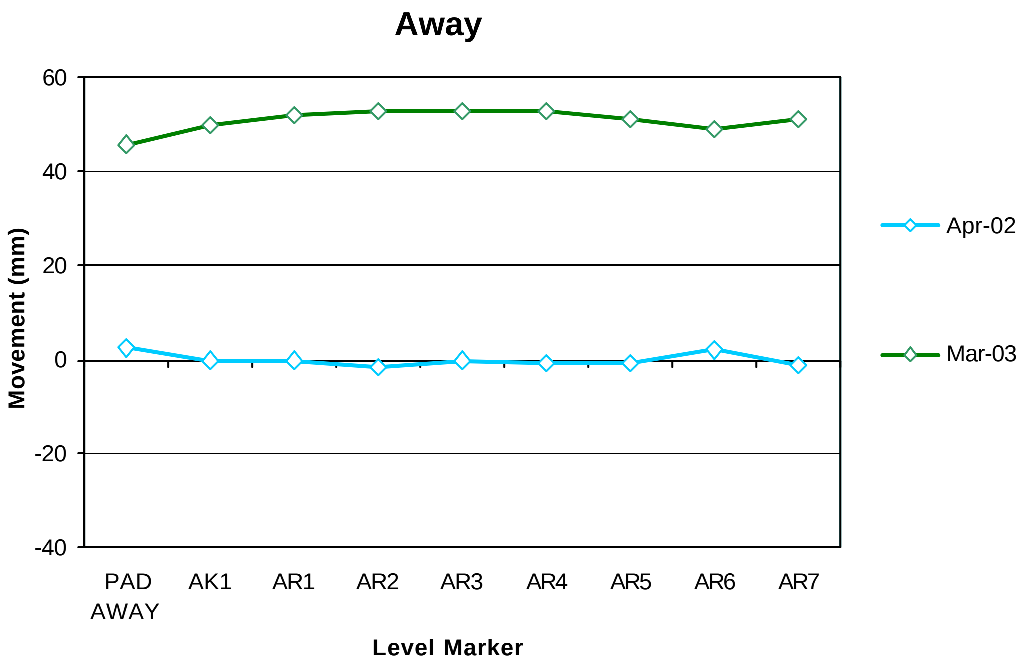
To April 2004, markers at 0.5 and 1.0 m have moved +11 mm since installation and surface concrete pads have moved a maximum of +10 mm. The 1.5 m and 2.0 m markers have remained relatively constant since installation with only +2 mm of movement measured. It was expected that the 0.5 and 1.0 m markers would move more than the deeper 1.5 and 2.0 m markers, due to greater seasonal soil moisture and suction changes near the surface. However inspection of the soil profile for this site revealed that the overlying soil layers to a depth of two metres are of low reactivity (1 %/pF). Consequently, no significant movements from the GMS have been recorded to date. The blanketing of movement at this site is also evident in the maximum pavement levels, which are about half of most of levels recorded at the other sites.


Near Tree
40
30
20
10
0
-10
-20
Movement (mm)
TREE PAD
NR1
NR2
NR3
NR4
NR5
NR6
NR7
NK1
Level Marker
May 02
June 03


Away
40
30
20
10
0
-10
-20
Movement (mm)
K1
R1
AR2
AR3
AR4
AR5
AR6
AR7
AK2
PAD AWAY
AR8
Level Marker
May 02
July 03

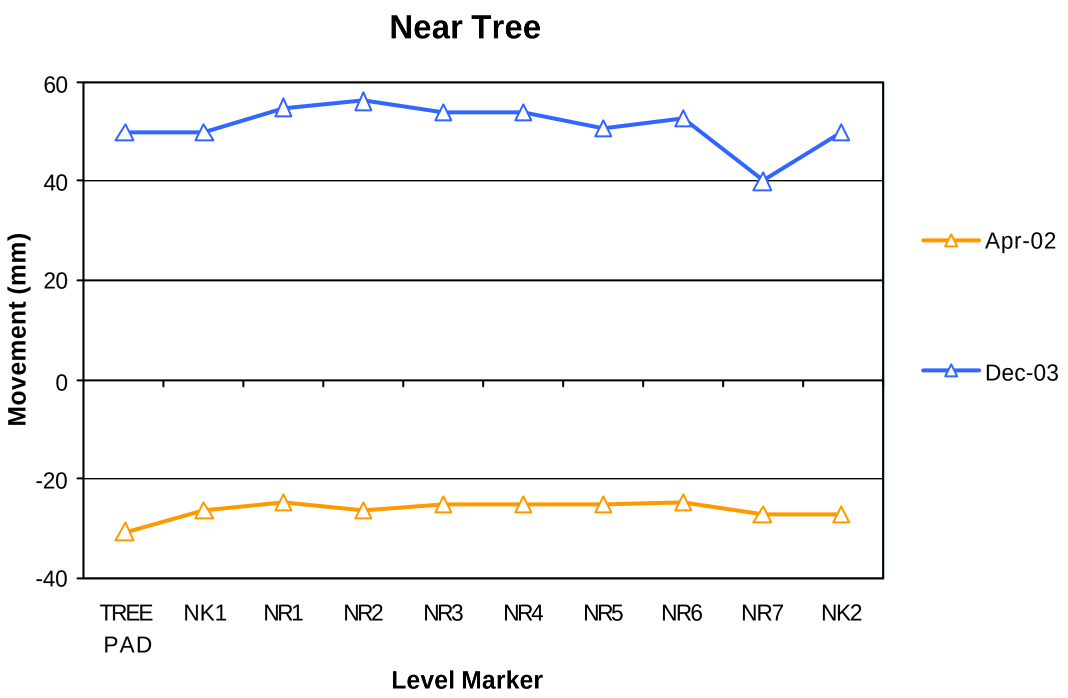
(a) Saddle Cr

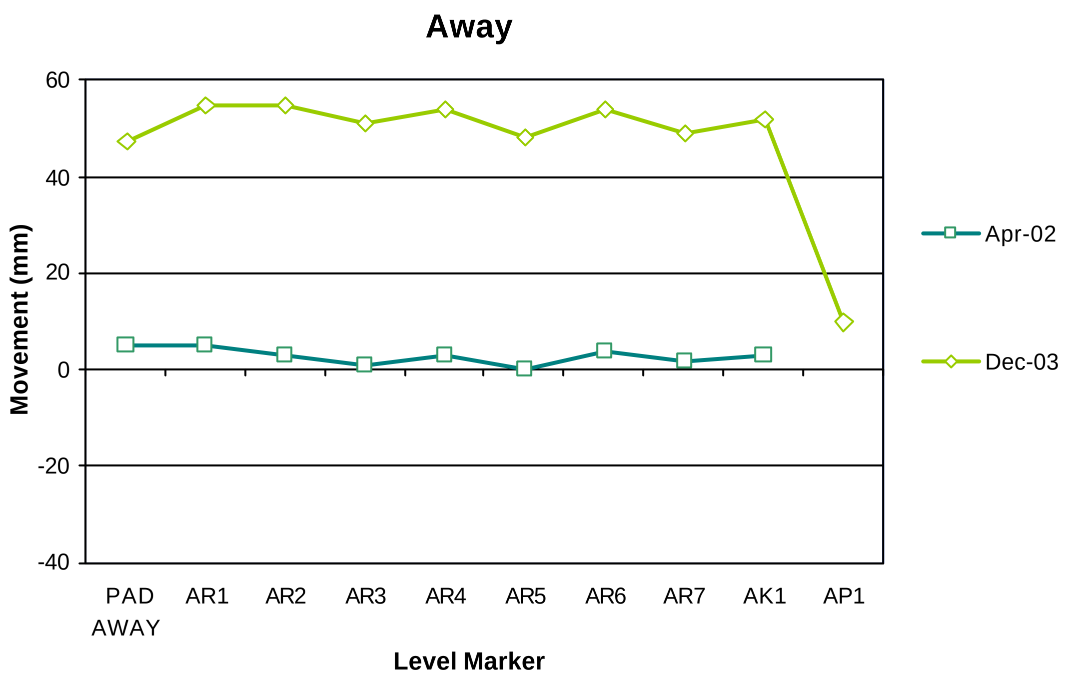




b) Homestead Av

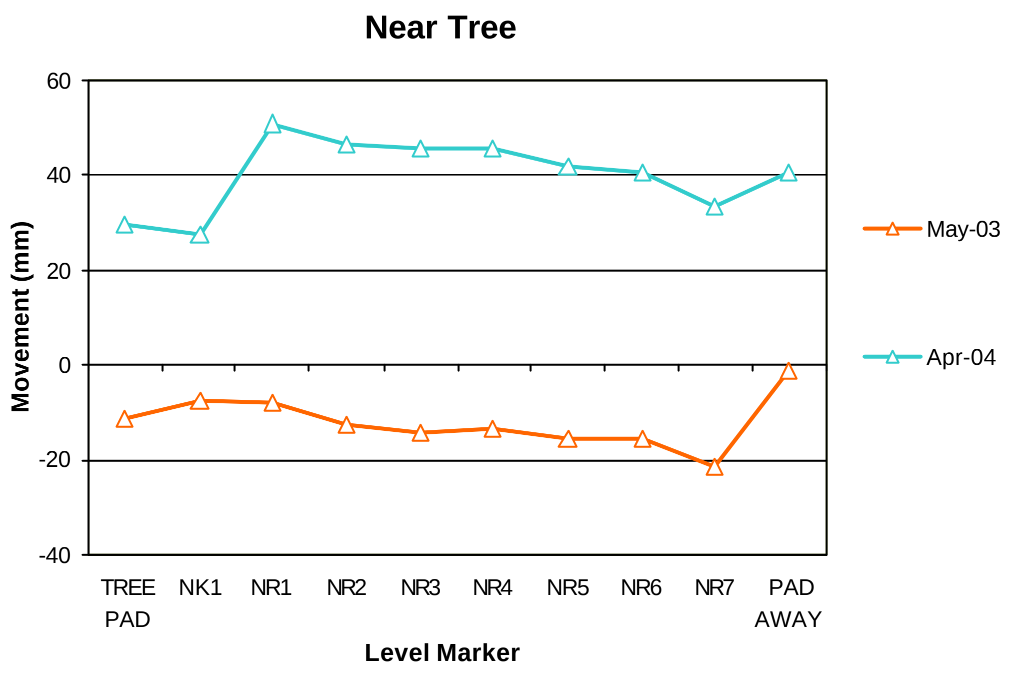
Figure 11: Pavement Survey Max. and Min. Movements for all sites

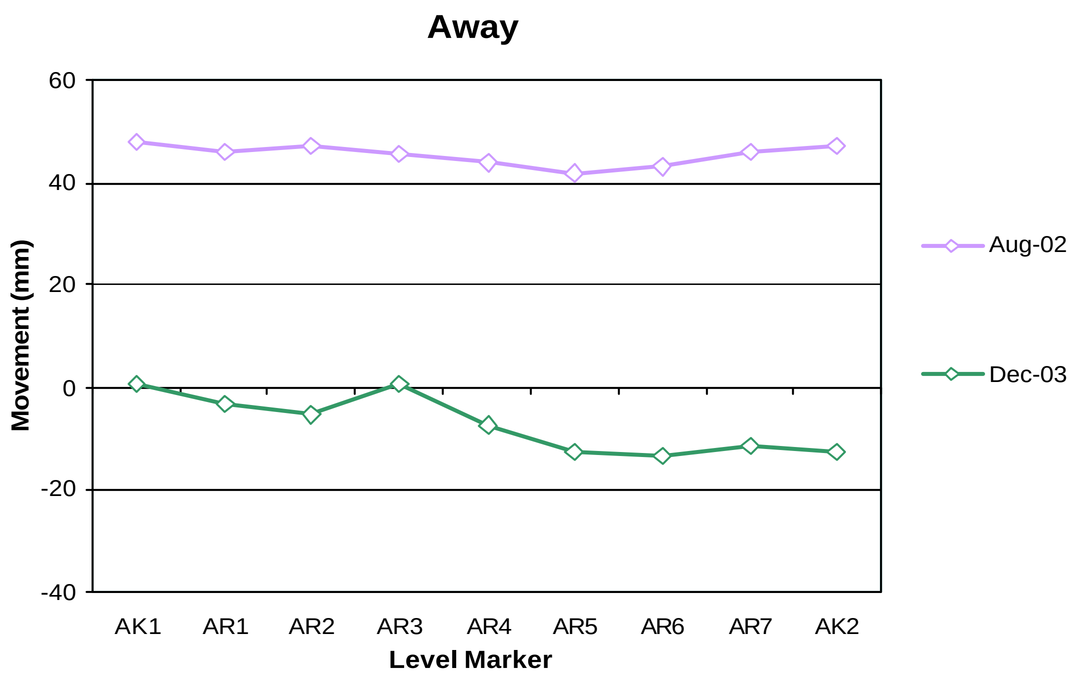




c) Legend Av

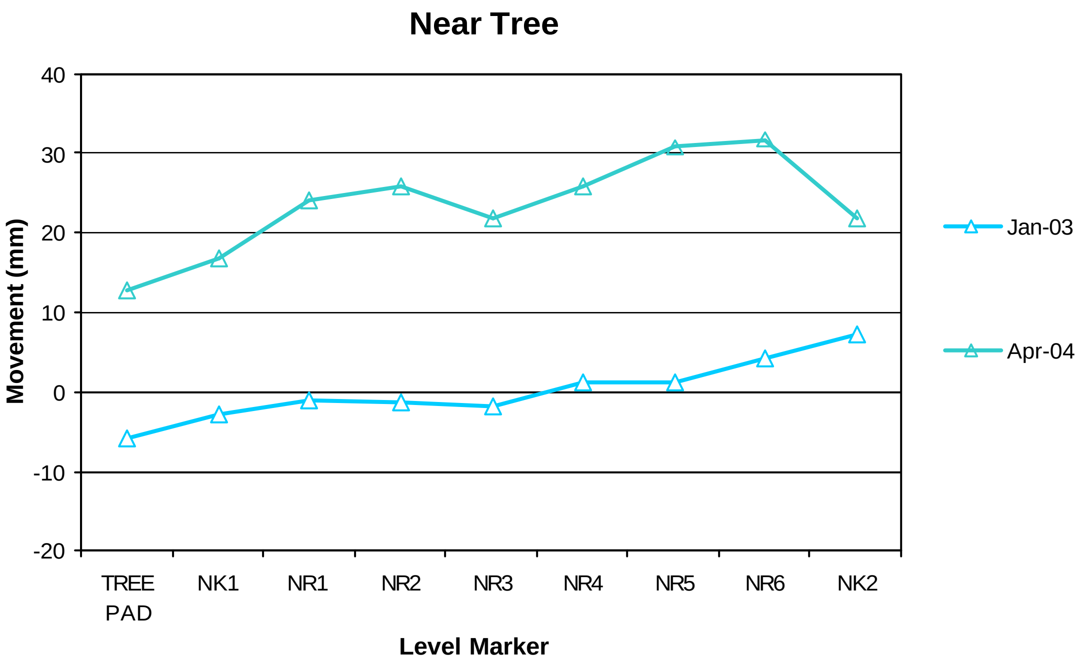
Figure 11: Pavement Survey Max. and Min. Movements for all sites





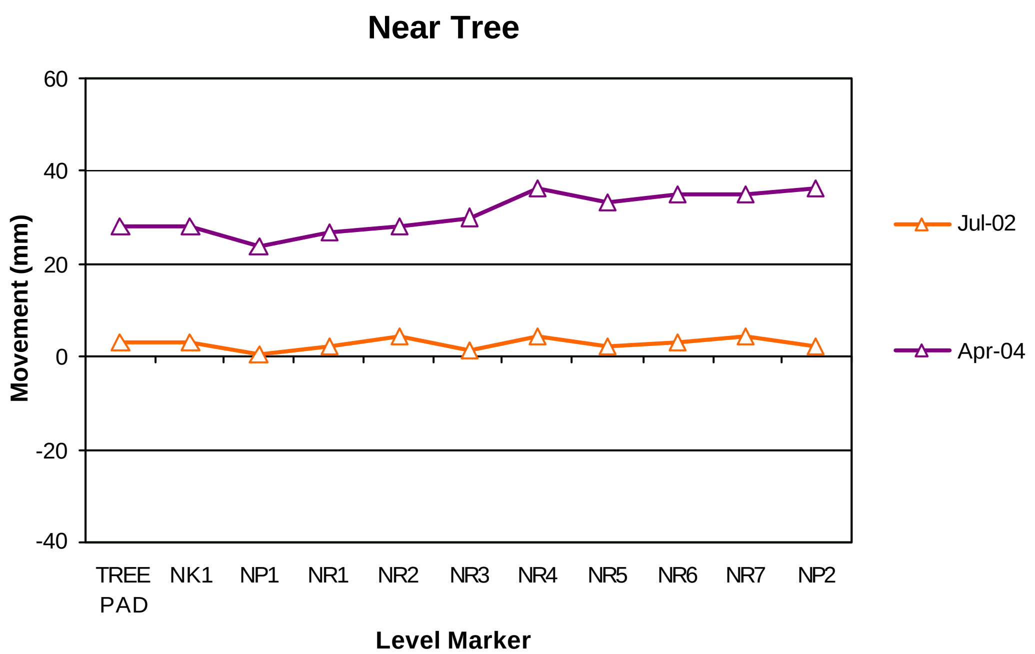
d) Dene Street

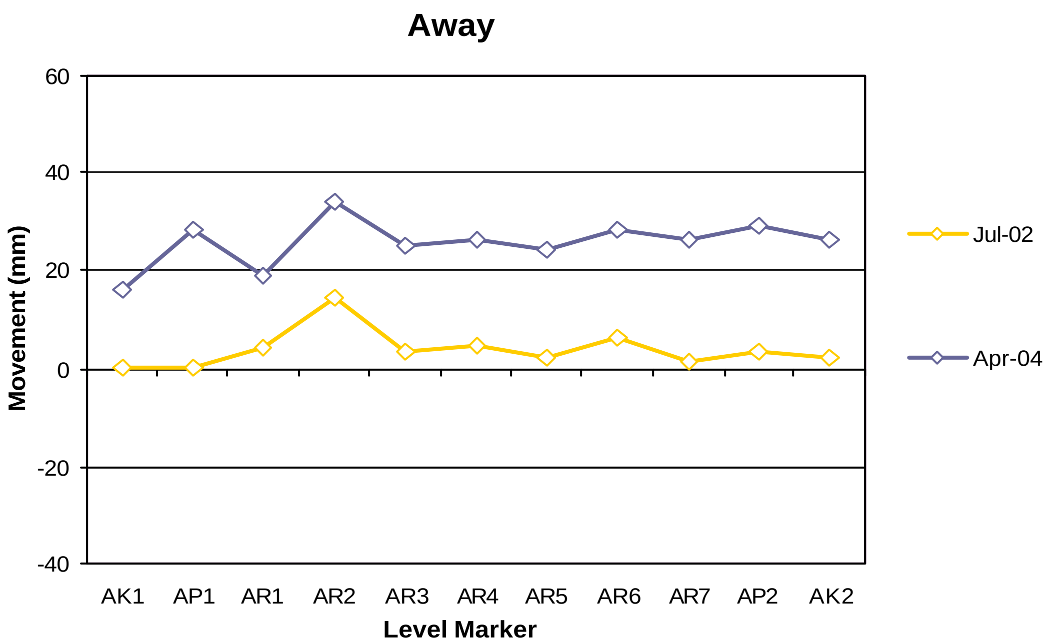
Figure 11: Pavement Survey Max. and Min. Movements for all sites



e) Drover Ct

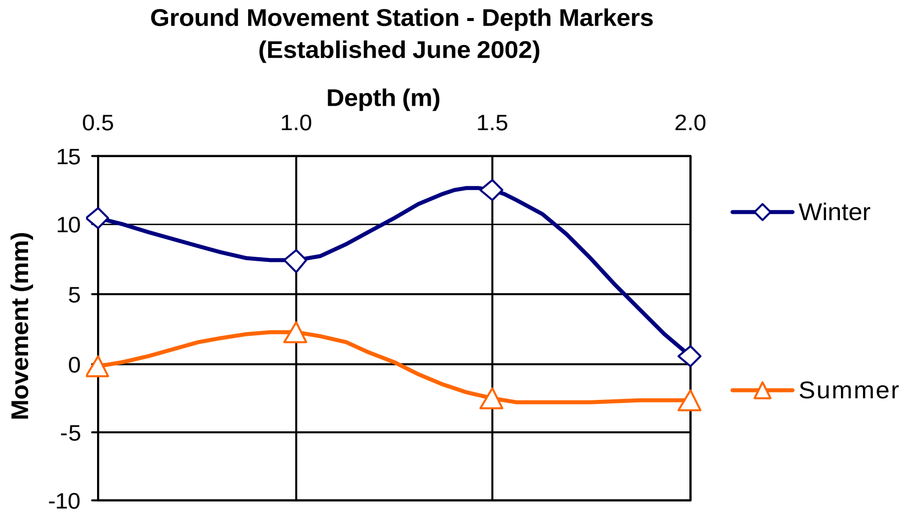
Figure 11: Pavement Survey Max. and Min. Movements for all sites





f) Station Ct

Figure 11: Pavement Survey Max. and Min. Movements for all sites



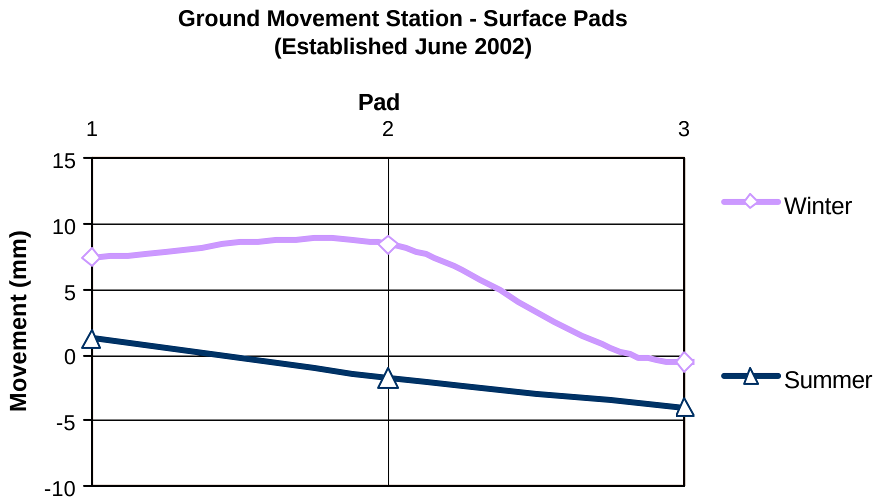


Figure 12: GMS Surface and Sub-Soil Movements

5.4.3 House Surveys

5.4.3.1 House designs and footing designs

Houses in the development are comprised of articulated masonry veneer walls supported on conventional raft slabs, which have been designed for the estimated soil movements over the life of the footing (50 yrs), under normal soil conditions (not close trees, good site drainage, etc). The general depth of beams for raft slabs in the area of the subdivision under investigation ranged between 0.6 to 0.8 m deep. Some South Australian Housing Trust homes in the subdivision have been further stiffened against anticipated tree effects, so these homes commonly have slabs with 1.0 m deep beams.

The SA Housing Trust designed footings for their houses (pre 2001) to take account of tree-related effects using a 'proximity ratio' or D:H of 0.5, where D is the distance of the tree (of height, H) to the proposed structure. Proximity is used in South Australia in conjunction with site classification and number of trees to estimate the extra soil suction change at depth, caused by tree drying. Accordingly, the design site surface movement is increased and footings are designed for extra centre heave movement. Consequently, Trust homes in the subdivision have typically 1.0 m deep beams reinforced with deformed bar with nominal diameters of 20 to 28 mm compared with other house which have typically 0.6 m deep beams and 16 mm diameter reinforcement bars.

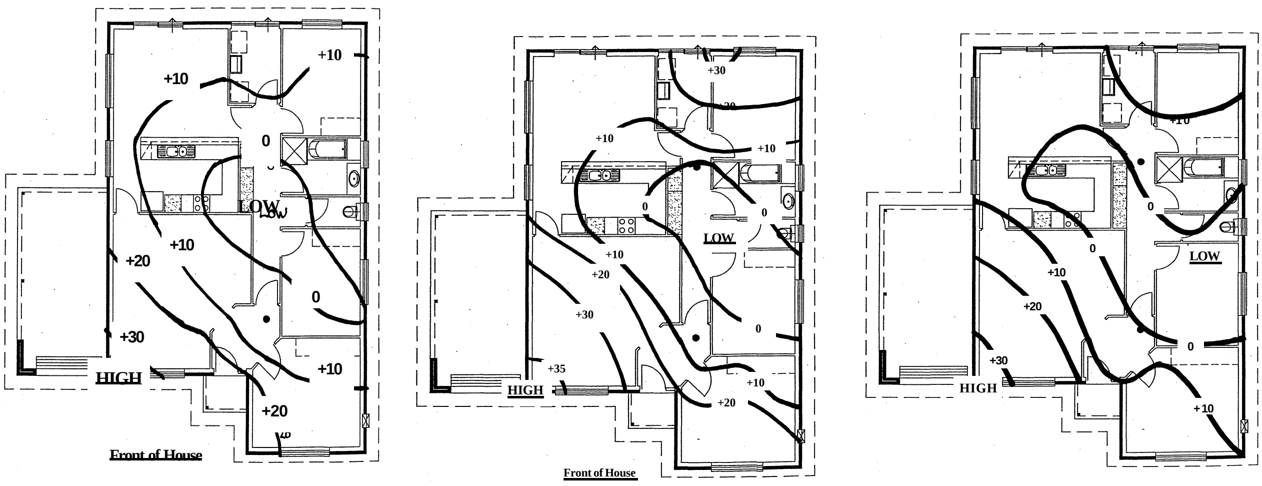
At selected research sites, a number of houses were chosen for internal and exterior level surveys. These surveys will be used to gauge the performance of different footing designs and tolerances of construction, by monitoring the development of movements across the slabs, in relation to nearby ground movements. Initial surveys have provided background levels that can be compared to future level surveys of the house floors. As well, level surveys were performed on four newly constructed slabs to gauge the general construction tolerance of floor construction. The maximum difference in level observed across a newly poured floor was just +/-10 mm.

Soil mound development beneath raft slabs can take considerable time, for example Mitchell (1988) reported persistent edge heaving in a house 10 years after construction. Ultimately the pattern of distortion will be centre heave. A few residents within the subdivision have reported noticeable movements of their walls and outside footpaths and pavements since their houses have been built. Most of these houses are less than five and a half years old and are built as conventional raft slabs (deep beams, spaced a minimum of 4 m apart).

In Figure 16 contour plots for all four of the internally surveyed houses are displayed. Each house contour pattern is distinctively different as are the changes of the movement patterns with time. The highest differential movement observed has been +40 mm at 3 Legend Avenue in June 2003 and +35 mm on Saddle Crescent in March 2003.

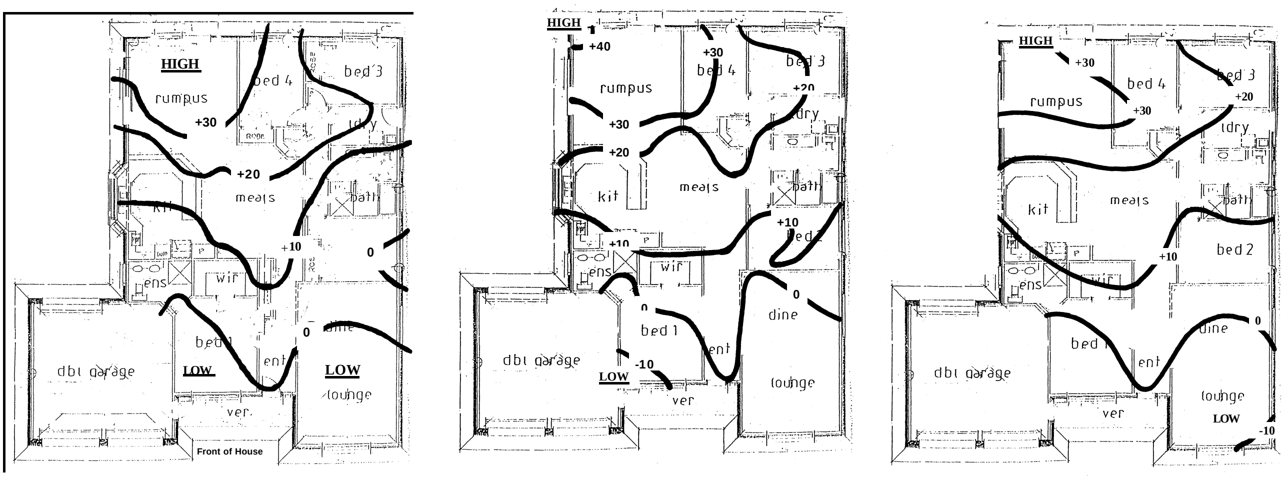
The contour plot of an SA Housing Trust house in Saddle Crescent can be seen in Figure 13a. Levelling surveys were conducted in August 2002, March 2003 and October 2003. An inspection of the house on the first visit revealed minor cracking, 1 to 2 mm wide above two inner walls; these cracks have since widened slightly to 2 to 2.5 mm. The house has experienced 35 mm of edge heave or dishing, with the lowest point near the centre of the slab. The highest levels were recorded around the perimeter of the slab. The slab is expected to eventually progress to centre heave, or doming, which will be most pronounced in the drier months. This house is not performing as well as other houses, which are routinely surveyed in this project. It is interesting to note that 3 Legend Avenue house, which has experienced slightly greater movement, has not suffered any visual internal cracking.

The lowest edge heave distortion of all surveyed houses has been 8 Dene Street, with level differences across the slab within 10 to 15 mm. This has been the best performing house with minimal changes in contour movements across the house floor over time with re-surveys. This appears to be related to the sites soil profile.



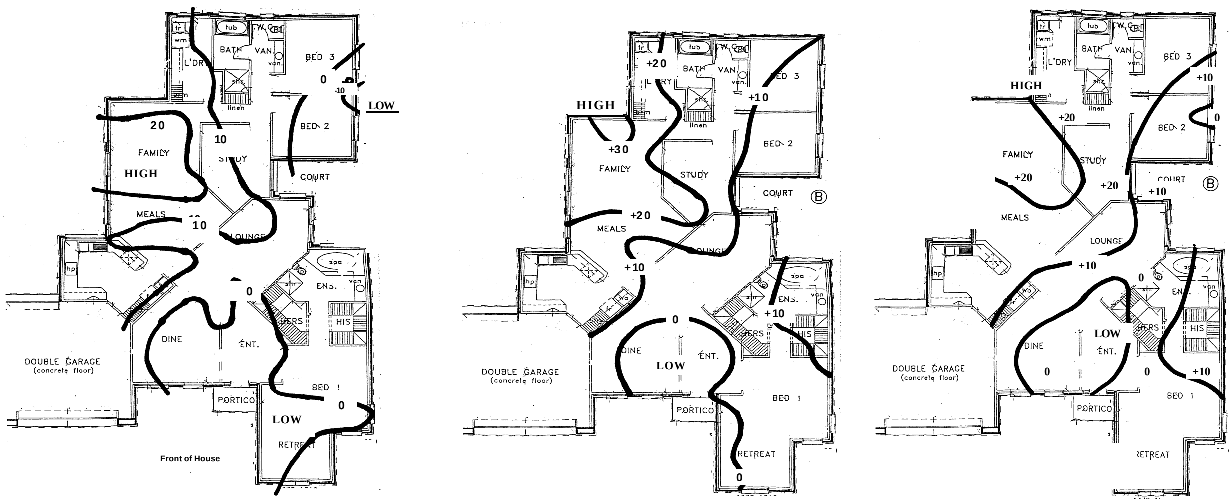
August 2002 | March 2003 | October 2003

Figure 13a: 8 Saddle Crescent



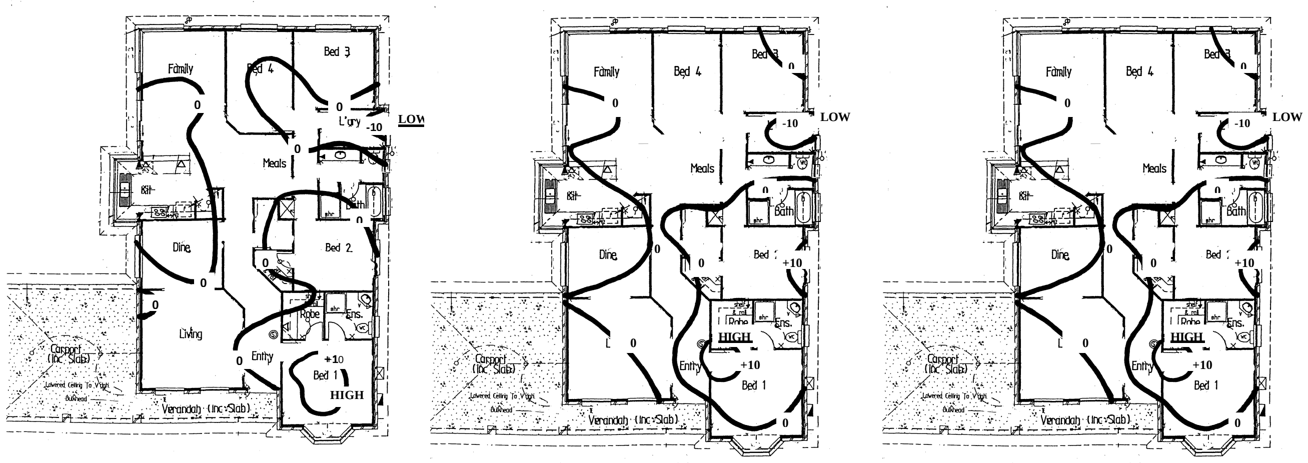
October 2002 | June 2003 | December 2003

Figure 13b: 3 Legend Av



October 2002 | June 2003 | December 2003

Figure 13c: 16 Legend Avenue



September 2002 **March 2003** **December 2003**

Figure 13d: 8 Dene Street

Figure 13: Internal House Floor Contours

5.5 TREE DATA

5.5.1 Leaf Water Potential and Xylem pressures

A major aim of this project to evaluate the relationship between leaf and xylem potential and the tree species water relations (water demand). Leaf water potentials and xylem (or stem or sap) pressures have been monitored continuously (apart during leaf fall) for over twenty months. Average water relations are summarized for all species in this section. Higher values of water potential mean the tree is under greater stress, which usually occurs during the warmer months. Lower values or low suctions occur during the colder, wetter months, as there is a high availability of water in the soil. All the data have been summarized in the plots in Figure 14 of plant water potential against time.

The golden raintree had an average suction difference of 0.10 MPa between leaf and sap values, with the leaf suctions being consistently lower for the period to June 2003. Using only the sap suction measurements, the overall trend for this particular species' water relations is a maximum suction of 1.95 MPa during February and a minimum suction of 1.1 MPa recorded in the next month. Thereafter suction increased to 1.5 to 1.7 MPa for the remaining period.

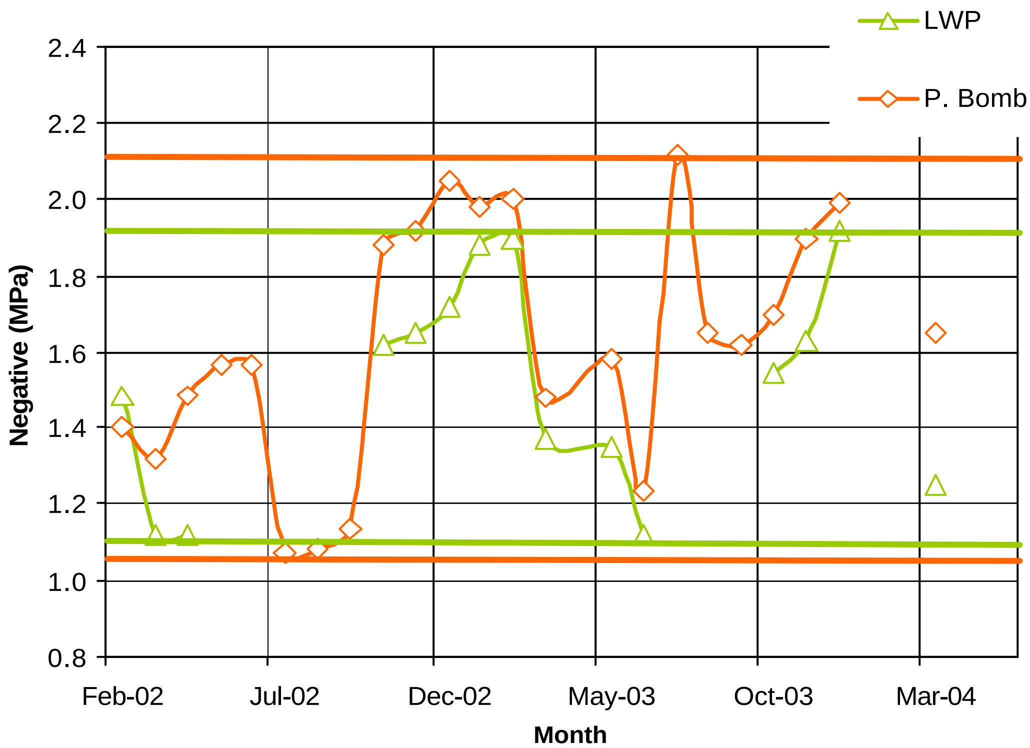
The pyrus species on the other hand demonstrated a closer relationship between leaf and sap suction, but leaf suctions were still lower than sap suctions. This species' highest sap suction was also measured in February (2.2 MPa) at the end of summer. Subsequently, measurements fell considerably to a low of 0.9 MPa in July 2003.

Leaf suction measurements ceased in July 2003 for both trees, as the Pyrus and golden raintree are both deciduous species. After July, both trees' suctions increased slightly as the weather warmed up and the trees began to shoot new buds and leaves. It may be concluded that the patterns of moisture demand vary markedly between the two species.

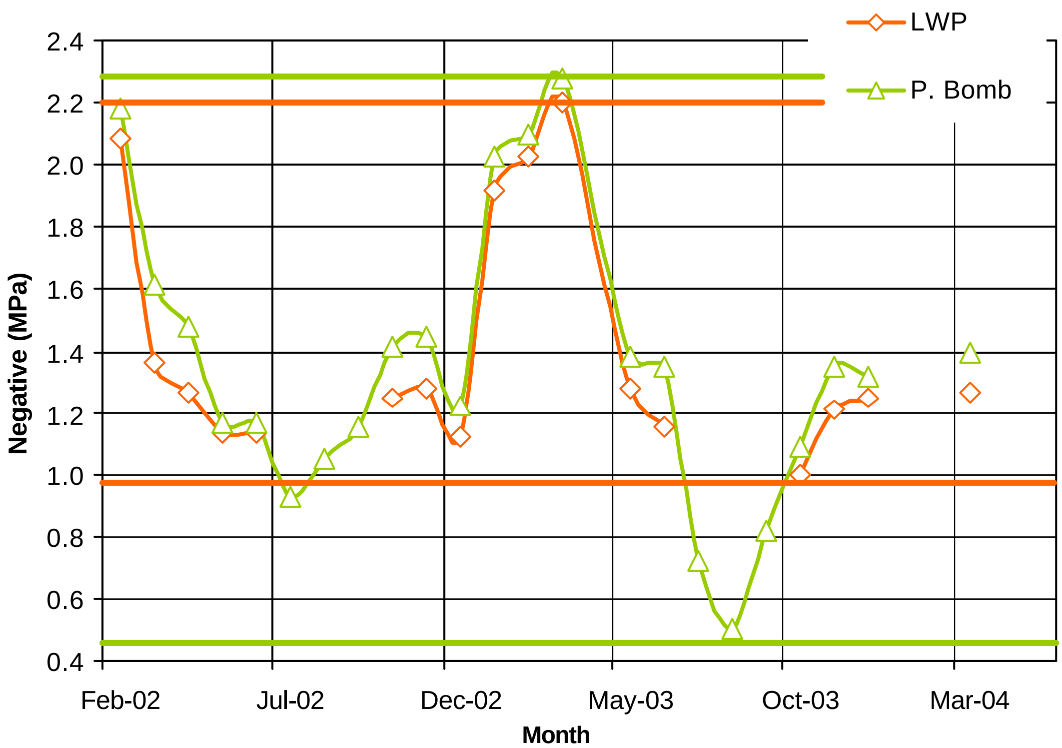
Measurements on the Chinese Elm tree indicated an average suction difference between leaf and sap values ranging between 0.10 and 0.40 MPa. Sap suctions measurements revealed the continuous trend for this species' water relations, with a maximum of 2.05 MPa during December 2002 and a minimum suction of 1.07 MPa recorded in the winter of June 2002. The Chinese Elms species were located on a site that had been heavily irrigated by the developer in the early stages of subdivision. The tree was stressed by the over-irrigation and somewhat prevailing saline conditions which caused large increases in water relations between the winter leaf fall months and warmer growing summer months.

5.5.2 Water Demands of Native and Exotic Trees (using water potential and xylem suctions)

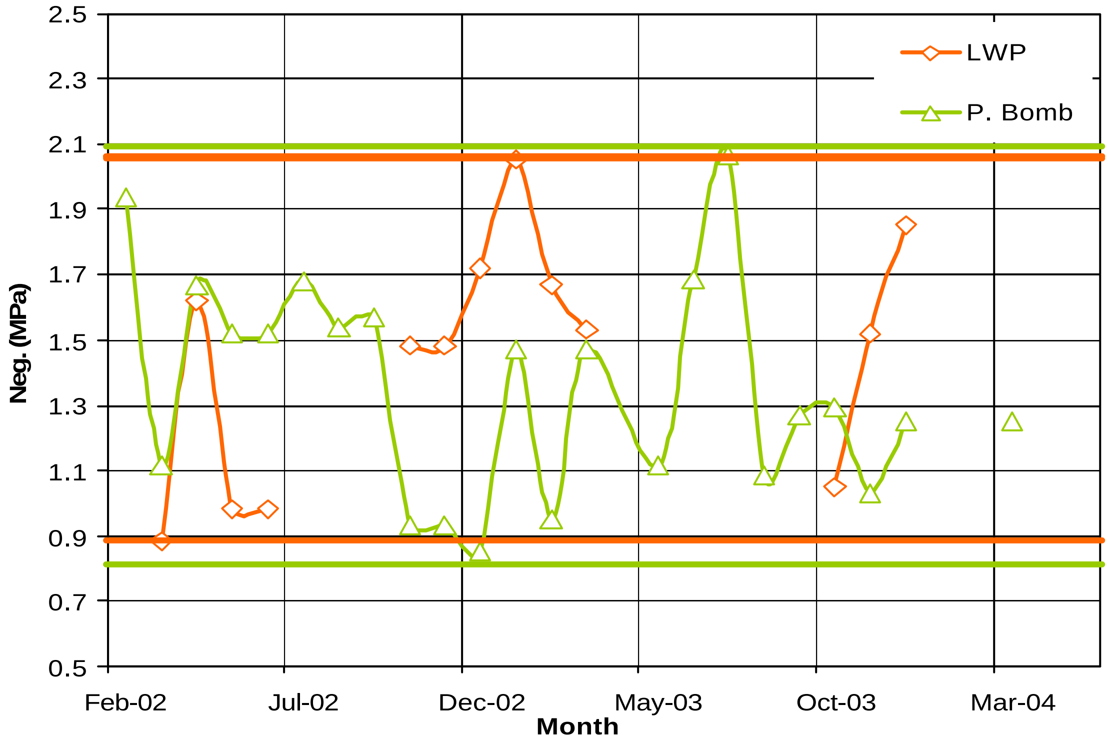
It is difficult to make a conclusive comparison between the native and exotic tree species researched in this project as only one native species is represented, the Coral Gum on Station Ct., and the three exotic trees were all quite different. A preliminary observation from the data in Figures 18 is that the native tree's suctions tended to be higher overall throughout the year and dropped only marginally during the winter months. The highest recorded suction reading of 2.3 MPa was taken from both the native coral gum and the Pyrus tree on Legend Avenue. The patterns of plant suctions with the seasons were very similar over most of the years except when the exotic trees lost their leaves and suction values dropped considerably in the cooler months. Therefore it can be said for all the exotic tree species which tend to have their highest suction values during the summer months and drop considerably during leaf fall in the cooler months of the year.



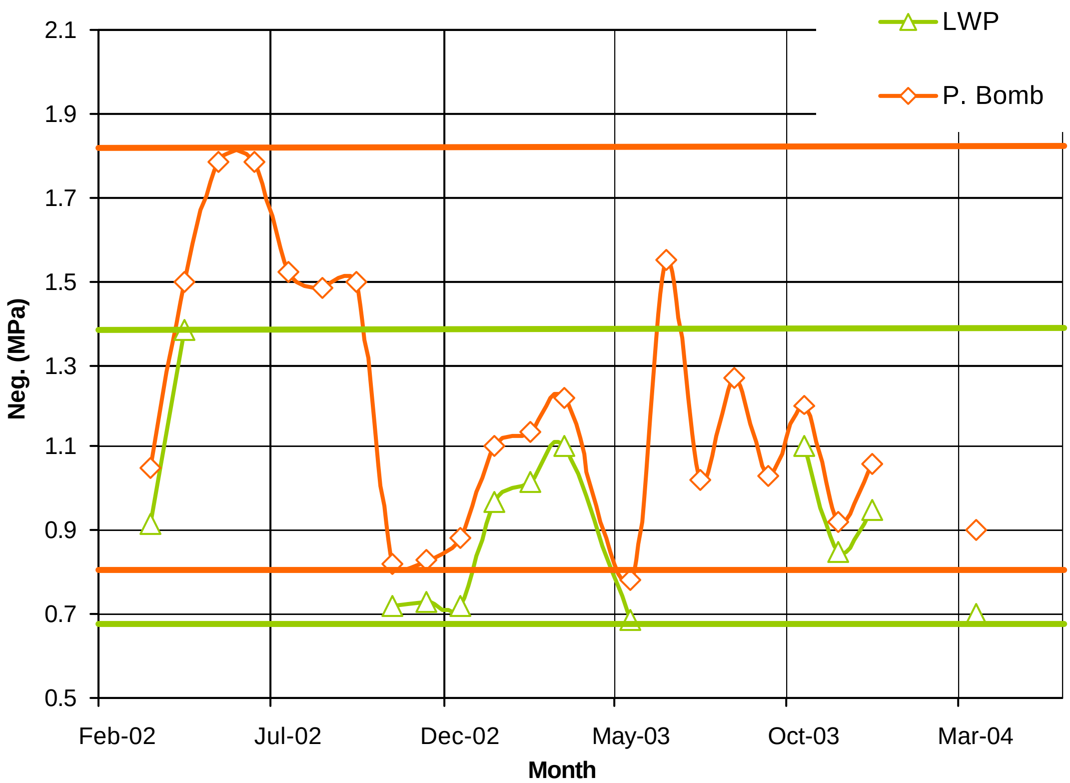
Homestead Av (Chinese Elm)



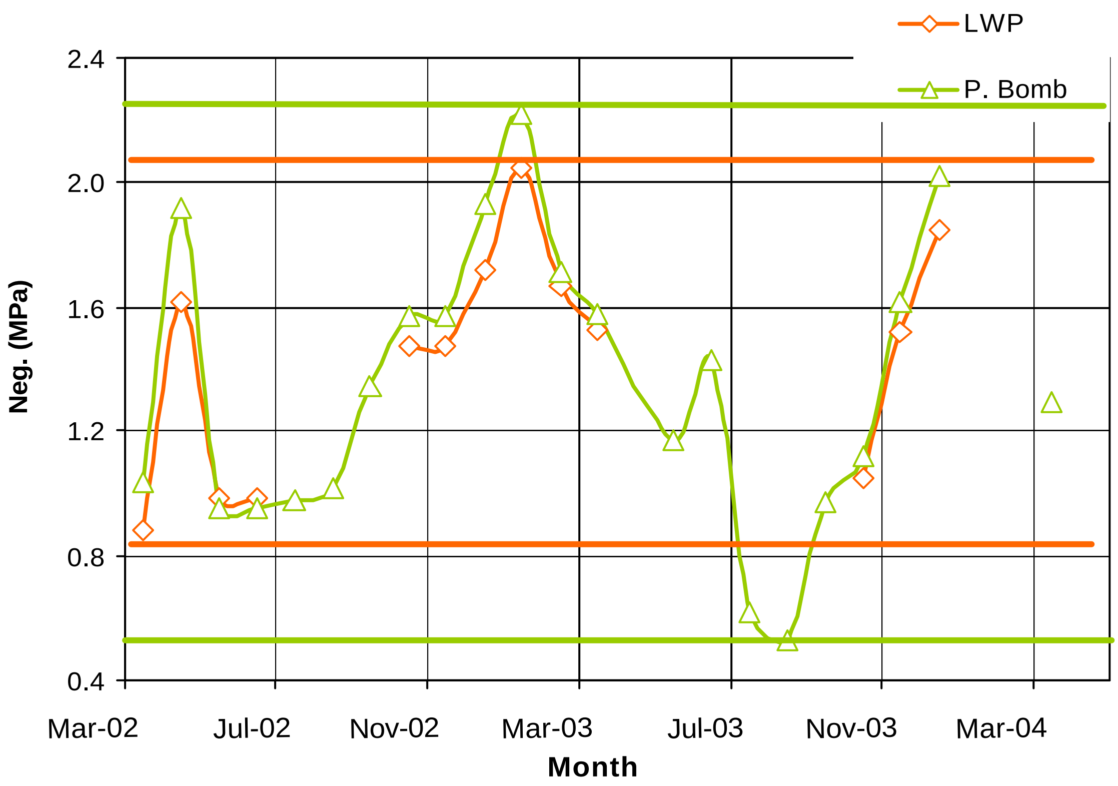
Legend Av (Ornamental Pear)



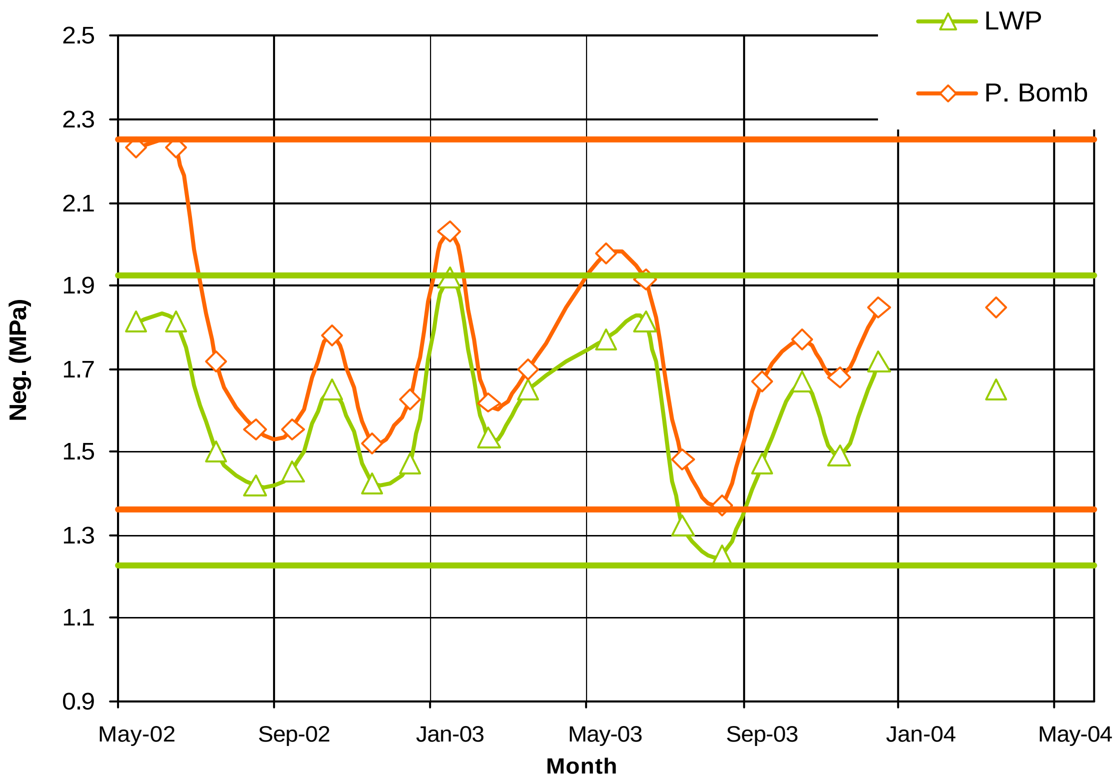
Saddle Cr (Golden Raintree)



Drover Ct (Golden Raintree)



Dene Street (Ornamental Pear)



Station Ct (Coral Gum)

Figure 14: Tree Water Relations for All Sites – LWP and Xylem Pressure

6. DISCUSSION OF RESULTS

The project is preliminary both in its conclusions and research outcomes, although short term goals have been reached and the research has been communicated (refer section 9). It is clear that further research is needed on this project, particularly as the trees mature and have a greater influence on the surrounding soil moisture patterns near infrastructure. It is expected that the City of Salisbury will continue to support the project over the forthcoming years, as far as practical.

Background soil moisture patterns, soil movements and water demands from the collection of data during the project can be used to predict future moisture patterns and movements. This information will be used and compared to future data collected and analyses of these data from the Walkley Heights research sites, as the trees mature.

A short summary of the findings of the current research follow.

<u>Neutron Moisture Meter</u>

From the analysis of the field data, there was no distinct difference in the NMM readings between the "near tree" and "away from tree" profiles at any of the sites that could be directly attributed to street tree drying. This observation may be due to the immature nature of the street trees, the irrigation regime in the early stages of the development and possibly the change in land use from open paddock to a built environment. However, seasonal moisture changes in the top two metres of the soil profile have been observed in the NMM profiles.

The summer monitoring period of April 2004 (subsequent to the LGA-funded period) revealed the start of some near tree soil drying at most sites in the top 2.0 to 2.5 m of the profile, as water irrigation has been reduced since late 2003 through to early 2004. The researchers predict this process may take a number of seasons, depending on weather conditions and the watering regimes applied at these sites by homeowners and the City of Salisbury.

<u>Soil Suctions</u>

Similar results to the NMM data were found for soil suction profile development at the sites. Maximum and minimum trends for each of the sites have been presented in Figures 10a and 10b of this report.

Distinct seasonal suction changes been noted between near and away holes, but only in the top two metres of the profile. The monitoring period in April 2004 showed minor soil drying across the subdivision, with the highest suction values (lowest moisture) recorded, paradoxically, at the "away from tree" sites. Again it is expected that the long term moisture distributions will be significantly different.

<u>Tree Water Demands</u>

A good correlation was found between the xylem pressure bomb and Wescor in-situ leaf water potential meter instruments for the tree species of this study. The xylem pressure approach has the distinct benefit of allowing measurement of tree water demand during periods of leaf fall.

A comparison between the native and exotic tree species was limited by planting restrictions imposed by the developer and the community. Only one native tree species was represented in this project. Interestingly, each tree tended to have its own water demand, even trees of the same species. This may be due to a number of interacting factors, such as:

- different sourced stock
- tree locations within the subdivision
- different growth patterns
- additional watering by the developer/householder/local government authority

Preliminary indications suggest that all tree species could achieve the same level of water demand; however the water demands of both the golden raintree and the ornamental pear decreased markedly in the deciduous period, when compared to the other two tree species. This observation suggests that the golden raintree and ornamental pear may be better street trees, based solely on the annual water demand and not on ecological considerations or other factors.

Pavement Surveys

Each site tended to have its own patterns of movement over the monitoring period, with the more heavily watered sites having the highest swelling movements, probably due to over watering of the nature strip (Homestead and Legend Avenue). Generally pavements have kept good shape despite the observed background movement.

Pavement movements can not be related to tree drying, as yet, since the trees are relatively young (less than 4 yrs old). The data recorded from the 2004 summer period did not illustrate any clearer a picture. The effect of turning off the developer's irrigation system may take a number of seasons to achieve an equilibrium soil moisture state.

The suction changes and the soil reactivities were combined to estimate ground movements along the nature strip at each site.

House Floor Contours – House Surveys

All houses showing edge heave movements with the greatest movements seen in the Saddle and Legend Avenue house sites. Greatest movements were +40mm. All houses showed some seasonal movements +/- although the Dene Street house site has shown the least amount of differential seasonal movement across all house sites. This site seems to be fairly stable at this stage with only a height change of 0-5mm of movement across the slab between seasonal re-surveys. The remaining house showed edge movements between 10 mm and 35 mm.

7. OUTCOMES

The project has been unique in that it has incorporated the disciplines of both civil engineering (geotechnical) and environmental science. The research has added information to the body of knowledge in civil, geotechnical and environmental engineering, thereby contributing to the better understanding of reactive soils, street tree species physiology (and water uses), street tree suitability, soil moisture patterns, soil movements and house footing designs in urban environments. However it is clear that the research is not all encompassing and so further work will be required to achieve all the objectives of the program.

The outcomes of the research to date are as follows:

- Trees require water and are able to apply suctions within each tree system to extract water from the soil
- The level of suction has been measured both within the xylem and in the leaves over a period of two years
- The maximum level of suction achieved in each tree was similar for each species (about 2 MPa)
- Xylem pressure measurements indicated that deciduous trees still require water during leaf fall
- Of the deciduous trees, the ornamental pear had the least persistent water demand – sap suctions fell significantly during leaf fall
- Despite the observed tree water demands, the influence on the ground was not apparent – the immature trees had not caused significant desiccation
- Soil moisture and total suction monitoring indicated that many nature strips had been over-irrigated to the point that trees were stressed
- Ground movements were significant beneath pavements and reflected the very high reactivity within the soil profiles
- Well-designed stiffened rafts in the subdivision commonly deflected 30 to 40 mm differentially in edge heave distortion, as expected in the early years after construction, and little or no damage was evident to house superstructures

8. FURTHER RESEARCH

To fully realise the objectives of the project, further research is essential. The sites have been established and monitoring protocols have been determined. The influence of the trees was less than expected, due to late plantings in some cases, tree immaturity and often over-irrigation of the nature strip. As the trees become more established and the irrigation program is taken over by the City of Salisbury, tree-related ground movements will become more apparent.

Ultimately a numerical model needs to be developed, which will reasonably predict soil movements and the direct influence on adjacent infrastructure. Such a model is being developed in another research project in a completely different context, which the senior author of this report is involved with. The model needs good climatic data for the site and an indication of transpiration rates of the tree species. With such data the model may be validated for general application in streets.

9. COMMUNICATION OF RESULTS

UniSA School Presentation

6th October 2002
17th October 2003
2nd November 2004
8th November 2005

City of Salisbury
University researchers Don Cameron and Aaron O'Malley presented an updated summary of the project to the City of Salisbury in March 2004 and November 2004.

Project Reports
Initially quarterly reports were presented to the industry partner to update new and innovative research findings and preliminary results on a regular basis. It was mutually agreed that the reports be prepared on a six-monthly basis in the latter half of the project.

UNSAT JAPAN– November 2003

University researchers Don Cameron and Aaron O'Malley have authored a research paper for the 2nd Unsaturated Soil Conference (UNSAT 03) in Japan. This international conference is to be held from the 10-12th November 2003 in Osaka, Japan. The authors attended and presented at this conference.

Gardening Australia – ABC TV – November 2003 (Aired 14th May 2004)

Don Cameron and Aaron O'Malley participated in the shooting of a 4-5 minute segment on the ABC show, "Gardening Australia". Don was interviewed by Malcolm Campbell on the influence of trees on reactive sites and the design of houses on reactive sites. The research monitoring of street trees at the Walkley Heights subdivision supported by both the City of Salisbury and the Local Government Association was captured on film in this segment.

Research Articles

International Conferences
2nd Asian Unsaturated Soils Conference, Japan, Osaka, Japan, November 2003

National Conferences
TREENET (Tree and Roadway Experimental and Educational Network) September 2001

Papers and presentations
Local Conferences / Seminars
Footings Group/Australian Geomechanics Society (SA) seminar (June 2003 & October 2005)
Footings Group/Australian Geomechanics Society (SA) seminar on "Trees in the Built Environment" (Sept 2004)
University seminars and local engineering conferences

Local Newsletters (University, Private Papers and Council Newsletters)
The research was publicised in community papers, Messenger press and newsletters in order to publicise the collaboration between the University and Local Government on this research and its benefits and outcomes.

Standards Australia
The Chief Investigator is a member of committee BD25 (responsible for AS2870). The results of the research will be communicated through the committee and through Standards Australia seminars, as the opportunity arises. Likewise meetings of the Footings Group (SA) will be used to communicate findings of the research.

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11. APPENDICES

Appendix A - List of Particularly Thirsty Tree Species

Appendix B – Soil Borelogs and Free Swells

Appendix C – All Site NMM Summary Plots

Appendix D – Surface Movements (ys values)

Appendix E – Summary of Soil Suctions Profiles for all Sites

Appendix F – Site Overviews

APPENDIX A

List of Particularly Thirsty Tree Species

from Cameron, D. A. and Earl, I. (1982). Trees and Houses: a Question of Function. Cement and Concrete Association of Australia, 20 pp.

Botanical Name	Common Name	Mature Height H(m)
Angophora costata	Smooth-barked apple	15-24
Araucaria heterophyla (and similar species	Norfolk Island pine	30-60
Casuarina cunninghamiana	River sheoak	12-30
Casuarina glauca	Swamp sheoak	12-15
Cedrus species	Cedars	Variable
Cupressus species	Cypress	Variable
Eucalyptus bridgesiana	But-but	-
Eucalyptus camaldulensis	River red gum	24-30
Eucalyptus citridora	Lemon-scented gum	To 15
Eucalyptus cladocalyx	Sugar gum	15-30
Eucalyptus cornuta	Yate	9-18
Eucalyptus diversicolor	Karri	To 60
Eucalyptus globulus	Tasmanian blue gum	30-60
Eucalyptus leucoxylon	Yellow gum	4.5-7.5
Eucalyptus maculata	Spotted gum	18-30
Eucalyptus occidentalis	Flat-topped yate	-
Eucalyptus rubida	Candlebark	9-30
Eucalyptus viminalis	Manna gum	9-60
Ficus species	Figs	To 30
Fraxinus oxycarpa	Desert ash	9-15
Fraxinus "Raywood" (unless grafted or budded onto a rootstock of Fraxinus ornus (Manna ash)	Claret ash	9-15
Grevillea robusta	Southern silky oak	15-30
Phoneix species	Date palms	Variable
Pinus species	Pines	To 30
Platanus species	Planes	15-36
Populus nigra (and similar species)	Black poplar	To 24
Quercus robur (and similar species)	English oak	To 20
Robinia pseudoacacia	False acacia, Black locust	9-15
Salix babylonica (and similar species)	Weeping willow	9-15
Salix chilensis "Fastigiata"	Chilean willow	-
Schinus molle	Pepper tree	6-15
Tamaris aphylla	Athel tree	To 6
Ulmus procera (and similar species)	English elm	To 30

The information in this table has been derived from:

- Baker, P.D.: Tree root intrusion into sewers – Progress Report No. 2: Analysis of root chokes by species. Engineering and Water Supply Department, SA, Sewerage Branch, August 1978.
- Lord, E.E. (1970). 'Shrubs and Trees for Australian Gardens'. 4th Edition. (Lothian Publishing Co.: Australia).

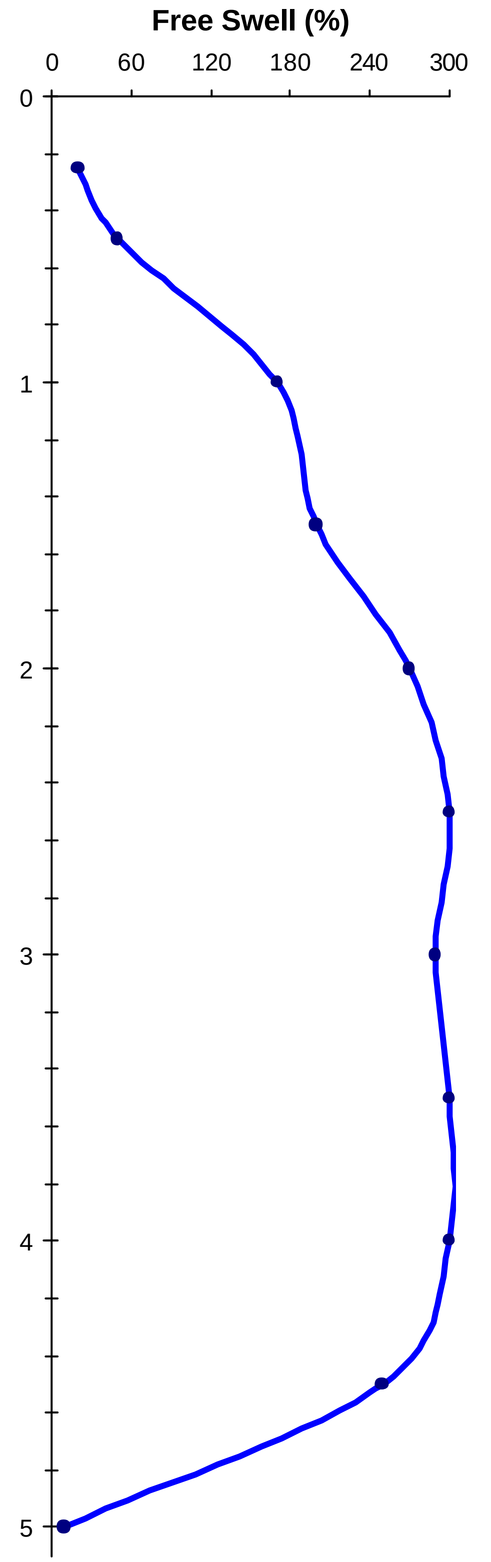
APPENDIX B

Soil Borelogs and Free Swells

Homestead Avenue, Walkley Heights

BH 1 'Near Tree'

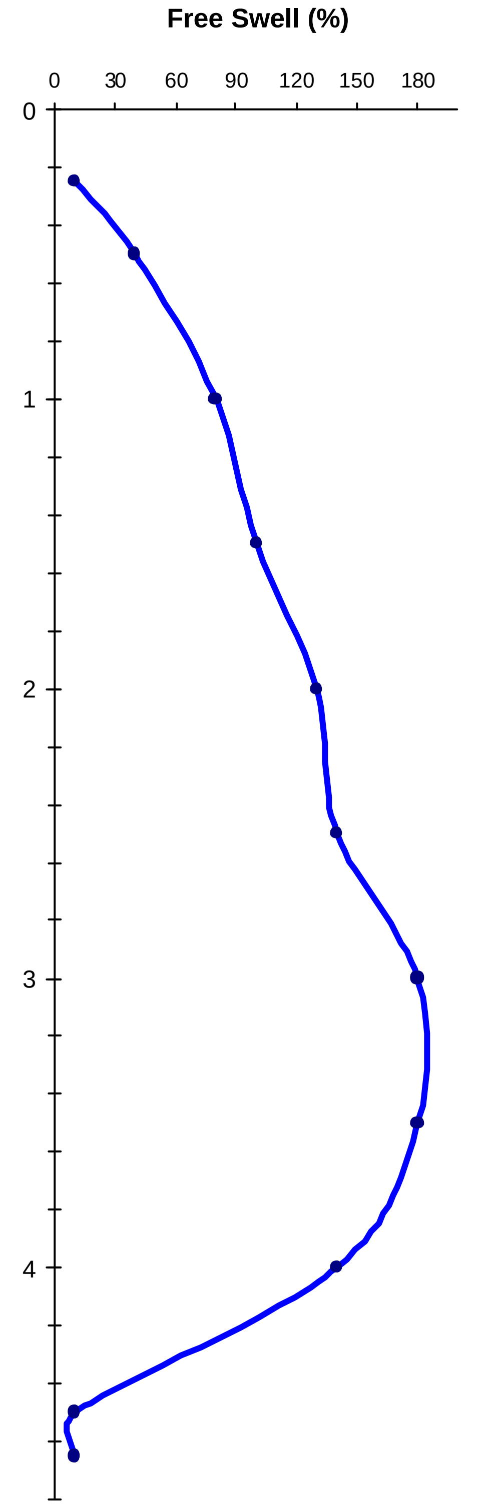
Soil Depth (m)	Description and Classification
0.0 - 0.15	Sandy silt (SM), fill, roots present light brown
0.15 - 0.5	Clay-silt (CL) yellowish red, grey tinge (5YR 5/5) medium-high plasticity, 55 kPa, free swell 20% (slightly expansive)
0.5 - 0.85	Clay-silt, (CI) light reddish brown (5YR 6/3) highly calcareous, 60 kPa free swell 50% (moderately expansive)
0.85 - 1.25	Clay, silty, sand (fine) (CH) light reddish brown (5YR 6/4) Calcareous pockets, high plasticity, 85 kPa, free swell 170% (extremely expansive)
1.25 - 1.5	Clay, (CH) light reddish yellow (5YR 6/5) highly calcareous, high plasticity free swell 200% (extremely expansive)
1.5 – 2.0	Clay, (CH) light reddish brown (tan) (5YR 6/4) calcareous pockets, free swell 270% (*extremely expansive)
2.0 – 2.5	Clay, (CH) slightly calcareous, mottled reddish yellow brown (5YR 5/4) high plasticity, 110 kPa, free swell 300% (*extremely expansive)
2.5 – 4.6	Clay (CH), shear faces (slickensides) mottled reddish yellow grey (5YR 5/3) very stiff, 120 kPa, free swell 300-250% (*extremely expansive)
4.6 – 5.1	Clay-silt, (CL) yellowish brown (5YR 5/2.5) slightly calcareous, free swell 10% (slightly expansive)



Homestead Avenue, Walkley Heights

BH 2 'Between Trees'

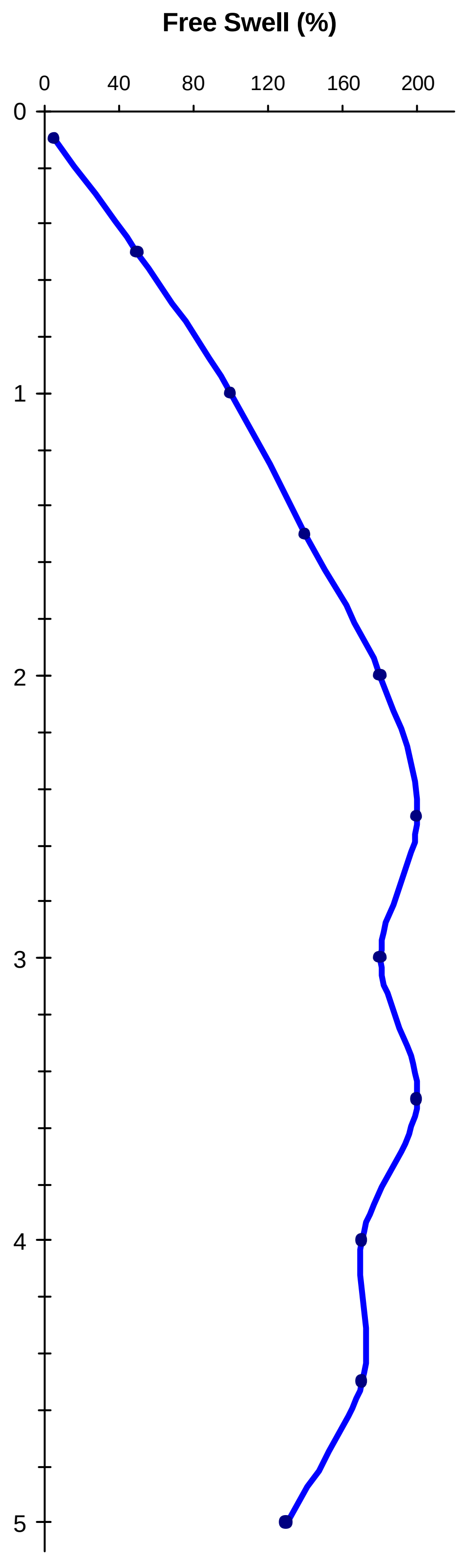
Soil Depth (m)	Description and Classification
0.0 - 0.2	Clay fill, (CL) light pinkish brown and strong brown (5YR 7/4) free swell 10% (slightly expansive)
0.2 - 1.5	Clay, (CI)reddish yellow and light brown (7.5YR 6/6) highly calcareous free swell 50-100% (moderately to highly expansive)
1.5 - 2.6	Clay, (CH) strong brown to light olive brown (7.5YR 5/6, 2.5Y 6/3) Calcareous free swell 100-140% (highly expansive)
2.6 - 4.2	Clay, (CH) mottled red and light grey (2.5YR 4/8, 2.5Y 7/2) slickensides free swell 180-140% (extremely to highly expansive)
4.2 - 4.65	Silt clay, (ML) very pale brown to white (10YR 7/3) free swell 10% (slightly expansive)



Homestead Avenue, Walkley Heights

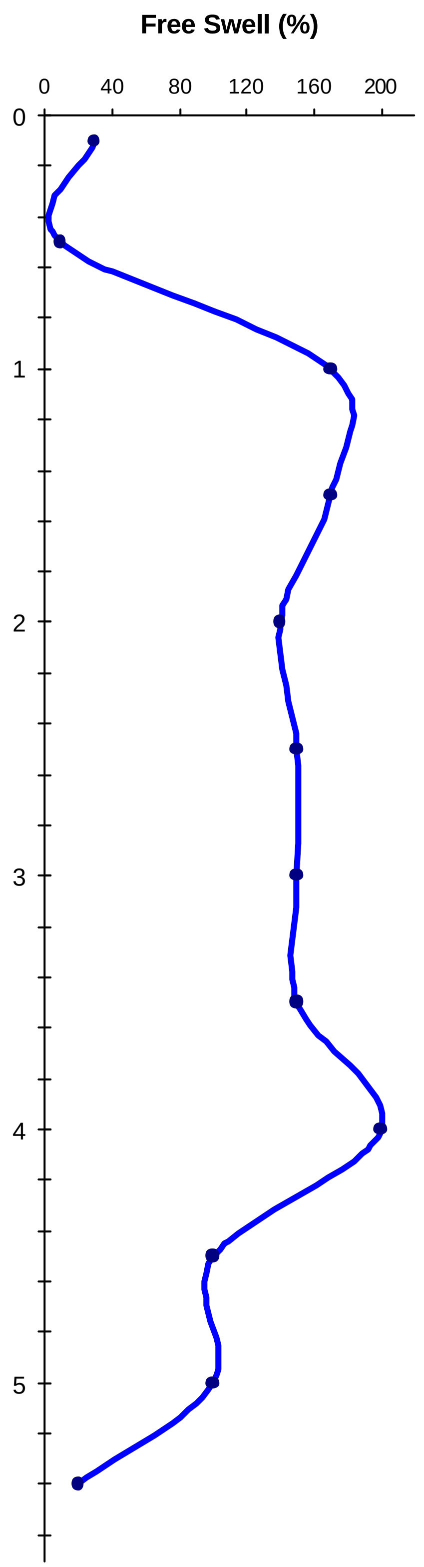
BH 3 'Pavement'

Soil Depth (m)	Description and Classification
0.0 - 0.5	Road rubble fill and bitumen, grey (5YR 6/1) free swell 5% (slightly expansive)
0.5 - 1.0	Clay, (CI) light pinkish brown (5YR 7/4) free swell 50-100% (moderately to highly expansive)
1.0 - 2.0	Clay, (CH)yellowish brown (2.5Y 6/4) free swell 100-180% (highly to extremely expansive)
2.0 - 5.0	Clay, (CH) mottled grey red (2.5Y 7/2 and 10R 5/6) slickensides free swell 130-200% (highly to extremely expansive)



Homestead Avenue, Walkley Heights

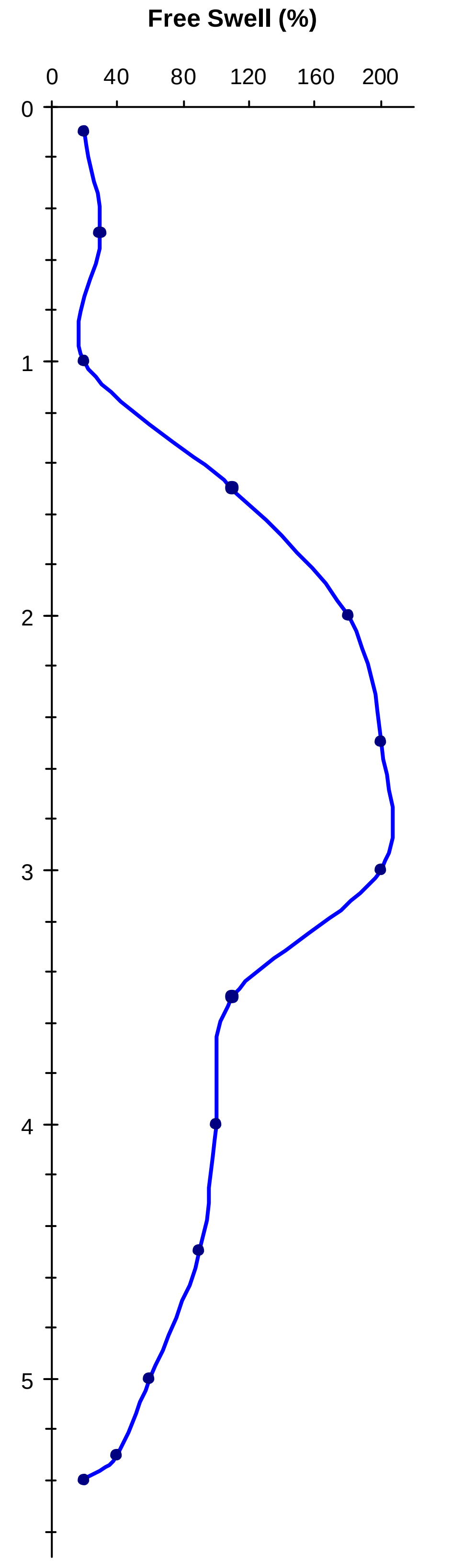
BH 4 ‘Away’

Soil Depth (m)	Description and Classification	
0.0 - 0.2	Organic clay, dark brown (7.5YR 3/4) calcareous, free swell 30% (slightly expansive)	
0.2 - 0.6	Clay fill, pinkish grey (7.5 YR 7/2) highly calcareous free swell 10% (slightly expansive)	
0.6 - 1.6	Clay, (CI-CH)yellowish brown (10YR 5/5) calcareous free swell 170% (extremely expansive)	
1.6 - 5.2	Clay, (CH) mottled grey to strong red (2.5Y 7/2 and 10R 5/6) slickensides 2.8 - 4.0m free swell 100-200% (highly to extremely expansive)	
5.2 - 5.4	Silty, (ML) white (10YR 8/1) free swell 20% (slightly expansive)	

Legend Avenue, Walkley Heights

BH 1 'Near Tree'

Soil Depth (m)	Description and Classification
0.0 - 0.15	Fill, grey and reddish yellow (5YR 4/1, 5YR 6/6) free swell 20% (slightly expansive)
0.15 - 0.55	Clay, (CL) strong light brown (7.5YR 5/8) calcareous free swell 30% (slightly expansive)
0.55 - 1.2	Fill, light grey (2.5YR 7/1) highly calcareous free swell 20% (slightly expansive)
1.2 - 3.1	Clay, (CH) light olive brown (2.5Y 5/4) calcareous, slickensides free swell 110-200% (highly to extremely expansive) slickensides 1.8m - 4.7m
3.1 - 4.7	Clay, (CH) mottled reddish brown grey (2.5YR 5/4) calcareous, slickensides, blocky nature free swell 100% (highly expansive)
4.7 - 5.4	Clay, silt, (CL) mottled dark red, grey, reddish brown yellow (5YR 7/2) calcareous free swell 60-20% (moderately to slightly expansive)

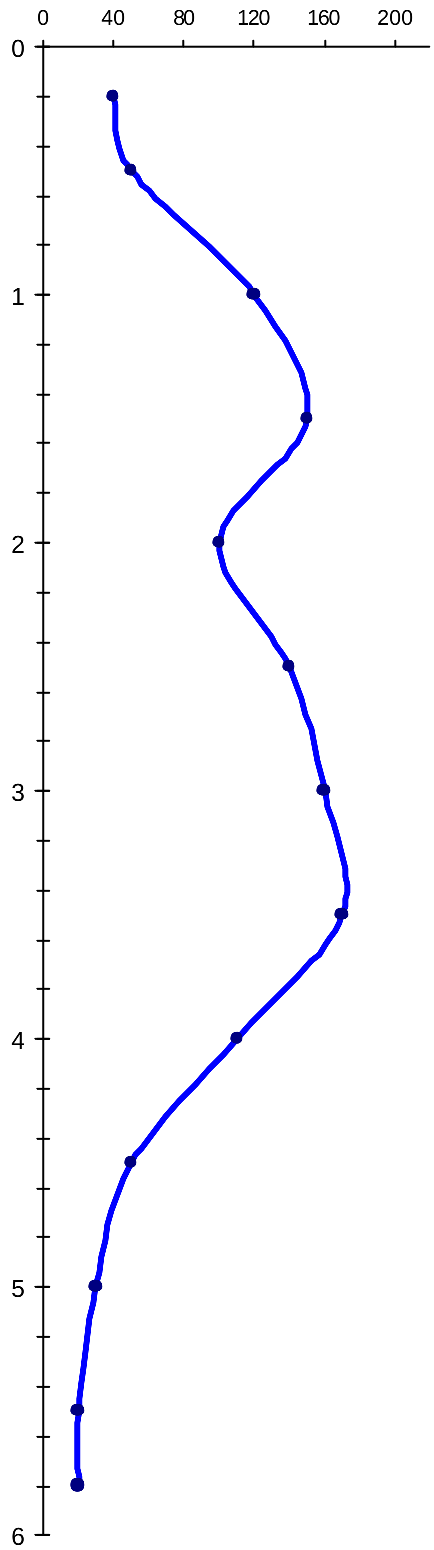


Legend Avenue, Walkley Heights

BH 2 'Tree Away'

Soil Depth (m)	Description and Classification
0.0 - 0.2	Organic fill, strong brown (7.5YR 4/6) free swell 40% (slightly expansive)
0.2 - 0.85	Clay, (CI) light strong brown (7.5YR 4/6) highly calcareous free swell 50% (moderately expansive)
0.85 - 2.5	Clay, (CI)dark yellowish brown (10YR 4/6) calcareous free swell 120-150% (highly to extremely expansive)
2.5 - 4.5	Clay, (CH) mottled red and light yellowish grey brown (2.5YR 4/8, 2.5Y 6/3) slickensides 2.7 - 4.7m free swell 170-110% (extremely to highly expansive)
4.5 - 5.8	Clay, silt, (CL) red clay and pale yellow-grey silt (2.5YR 4/8, 2.5Y 7/2) free swell 50-20% (moderately to slightly expansive)

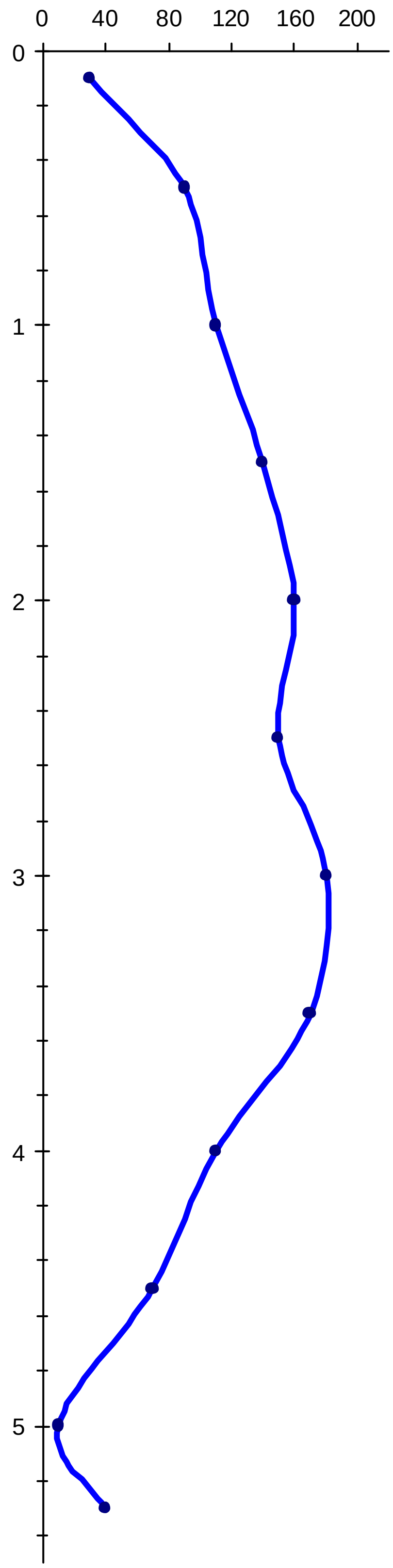
Free Swell (%)



Legend Avenue, Walkley Heights BH 3 'Pavement'

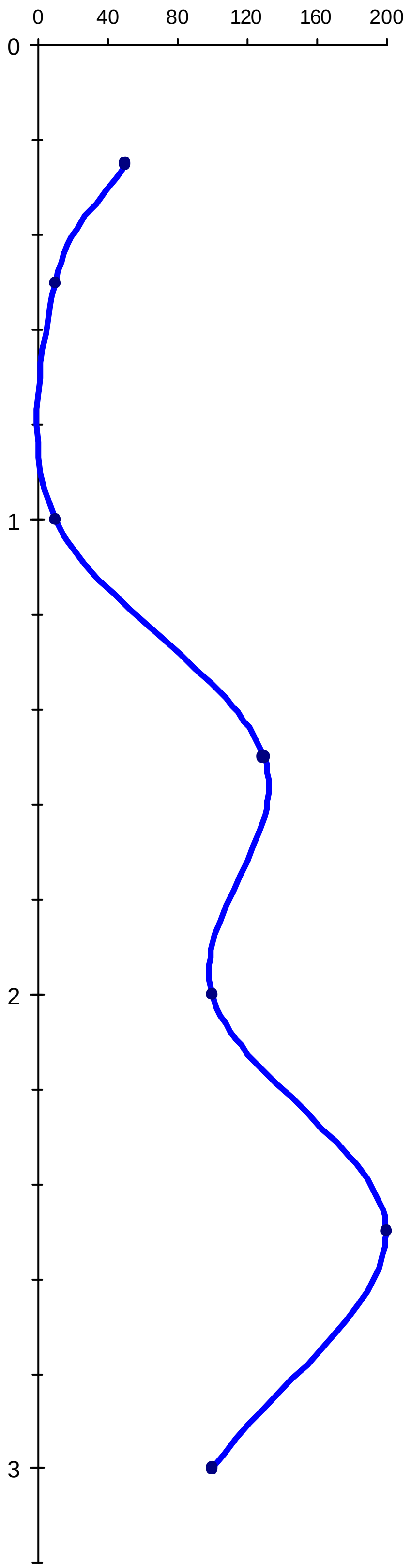
Soil Depth (m)	Description and Classification
0.0 - 0.4	Rubble fill, grey (7.5YR 6/1) calcareous small stones to gravel, free swell 30% (slightly expansive)
0.4 - 0.8	Clay, (CI) light strong brown and yellow (7.5YR 5/7) highly calcareous, 0.75m (100mm of fine sand) free swell 90% (moderately expansive)
0.8 - 3.0	Clay, (CH) light olive brown (2.5Y 5/6) Slickensides, free swell 110-180% (highly to extremely expansive)
3.0 - 4.0	Clay, (CH) mottled reddish grey (2.5Y 4/8) free swell 180-100% (extremely to highly expansive)
4.0 - 4.5	Clay, silt, (CI) mottled reddish grey (2.5Y 4/8) and yellowish red brown (2.5YR 5/6) free swell 90% (moderately expansive)
4.5 - 5.0	Clay, silt, (CI) yellowish red brown (2.5Y 5/6) free swell 70% (moderately expansive)
5.0 - 5.2	Silt, (ML) dark red (iron rich) (10R 5/6) free swell 10% (slightly expansive)
5.2 - 5.3	Silt, light grey (10YR 7/2) free swell 10% (slightly expansive)

Free Swell (%)



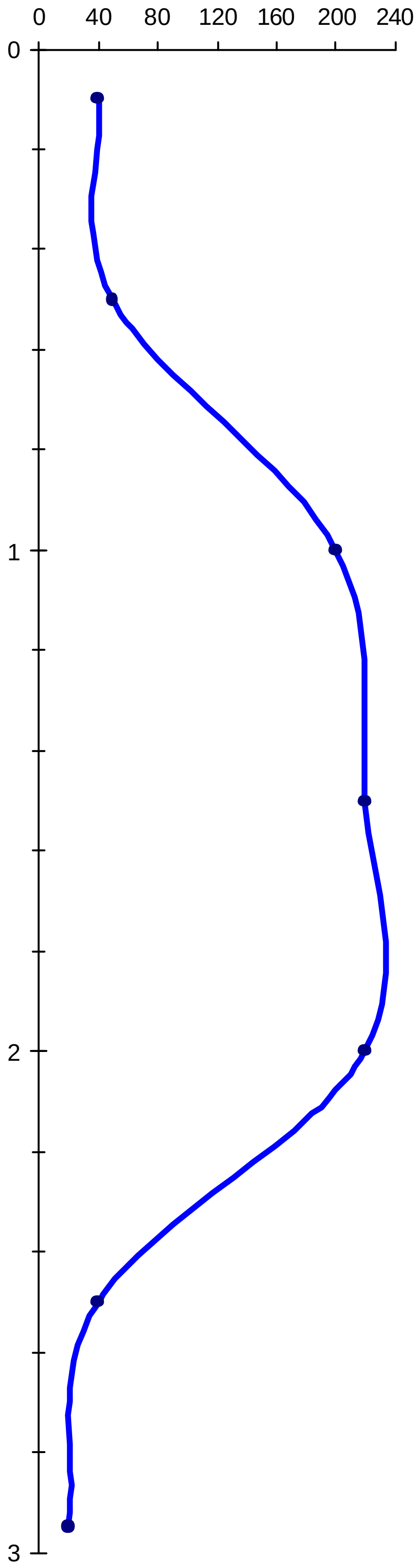
Legend Avenue, Walkley Heights

BH 4 'Away'

Soil Depth (m)	Description and Classification	Free Swell (%)
0 - 0.3	Organic fill, (OL) strong brown (10YR 5/6) calcareous free swell 50% (moderately expansive)	
0.3 - 0.6	Rubble road fill, dark grey (10YR 4/1) calcareous free swell 5% (slightly expansive)	
0.6 - 1.2	Sand, (SP) yellow (10YR 4/8) free swell 0% (non expansive)	
1.2 - 2.0	Clay, (CI) dark yellowish brown (10YR 4/6) slightly calcareous free swell 130% (highly expansive)	
2.0 - 3.0	Clay, silt, (CI-CH)light olive brown and pale yellow grey (2.5Y 5/4, 2.5Y 7/2) slightly calcareous free swell 100-200% (highly to extremely expansive)	

Drover Court, Walkley Heights

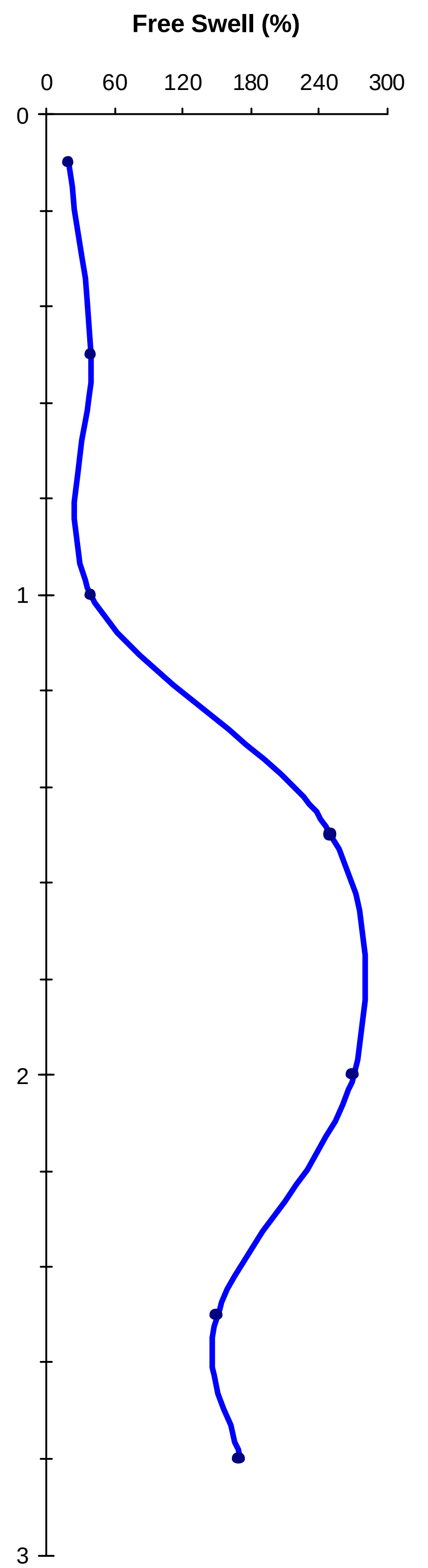
BH 1 'Near Tree'

Soil Depth (m)	Description and Classification	Free Swell (%)
0 - 0.25	Fill, dark grey (2.5YR 4/1) highly calcareous free swell 40% (slightly expansive)	
0.25 - 0.75	Clay, (CI) yellowish brown (10YR 6/7) highly calcareous free swell 50% (moderately expansive)	
0.75 - 2.5	Clay, (CH) dark yellowish brown (10YR 4/6) calcareous free swell 200-220% (extremely expansive)	
2.5 - 2.95	Clay, (CL) light olive brown (2.5Y 5/5) Calcareous free swell 40-20% (slightly expansive)	

Drover Court, Walkley Heights

BH 2 'Behind Kerb'

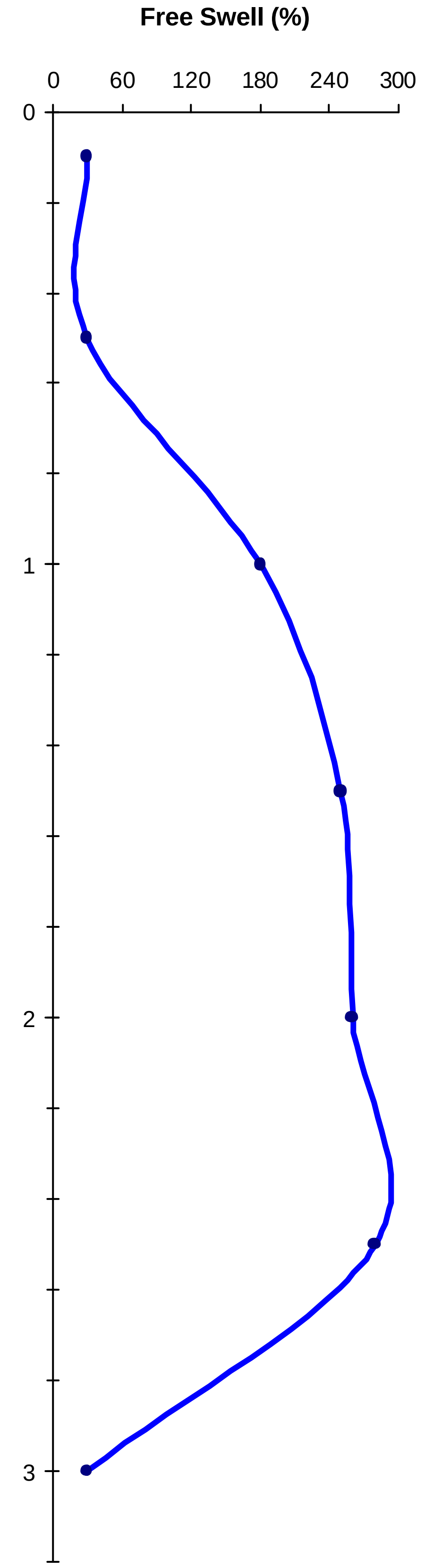
Soil Depth (m)	Description and Classification
0 - 0.5	Clay fill, strong brown (7.5YR 5/8) highly calcareous free swell 20% (slightly expansive)
0.5 – 1.0	Clay, (CL) brown (7.5YR 5/4) calcareous free swell 40% (slightly expansive)
1.0 - 1.8	Clay, (CH) light olive brown (2.5Y 5/4) calcareous free swell 250% (*extremely expansive)
1.8 - 2.3	Clay, (CH) light olive brown (2.5Y 5/6) free swell 270% (*extremely expansive)
2.3 - 2.8	Clay, (CH) light olive brown with white silty outer (2.5Y 5/6) free swell 170-150% (extremely expansive)



Drover Court, Walkley Heights

BH 3 'Pavement'

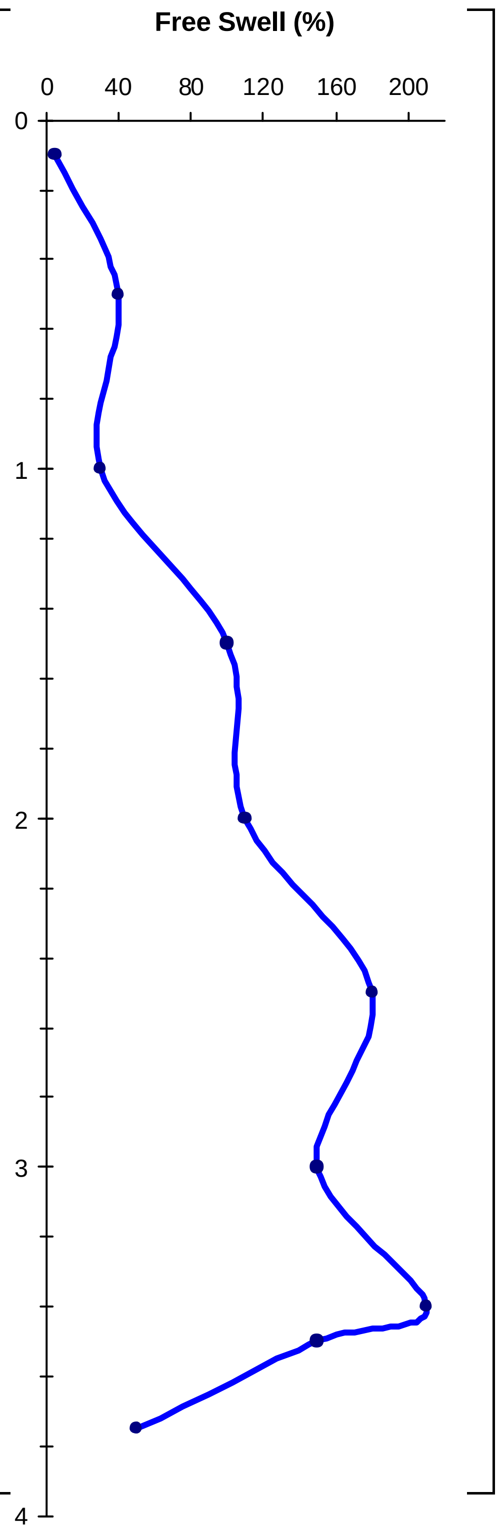
Soil Depth (m)	Description and Classification
0 - 0.5	Fill, light brown grey (2.5YR 6/2) highly calcareous free swell 30% (slightly expansive)
0.5 - 1.0	Clay, (CL) with grey fill yellowish brown (10YR 6/7) highly calcareous free swell 30% (slightly expansive)
1.0 - 2.5	Clay, (CH) light olive brown to olive (2.5Y 5/4, 5Y 5/4) slightly calcareous free swell 180-290% (*extremely expansive)
2.5 - 3.16	Silt, clay, (CL) reddish yellow (7.5YR 6/6) free swell 30% (slightly expansive)



Drover Court, Walkley Heights

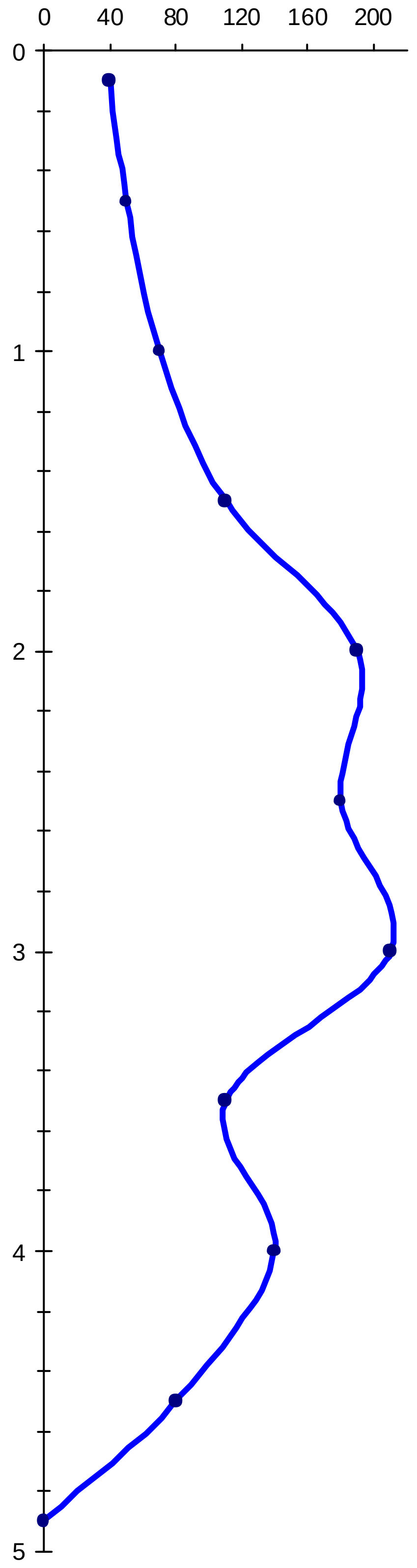
BH 4 "Away"

Soil Depth (m)	Description and Classification
0 - 0.4	Fill, dark grey (2.5Y 4/1) highly calcareous free swell 5% (slightly expansive)
0.4 - 1.25	Clay, (CL) yellowish brown to light pinkish brown (10YR 6/7, 7.5YR 6/4) highly calcareous free swell 40% (slightly expansive)
1.25 - 2.0	Clay, (CI) dark yellowish brown (10YR 4/6) calcareous free swell 100% (highly expansive)
2.5 - 3.5	Clay, (CH) light olive brown (2.5Y 5/5) slightly calcareous free swell 150-210% (extremely expansive)
3.5 - 3.75	Silt, clay, (ML) light yellowish brown (10YR 6/5) free swell 50% (moderately expansive)



Saddle Court, Walkley Heights

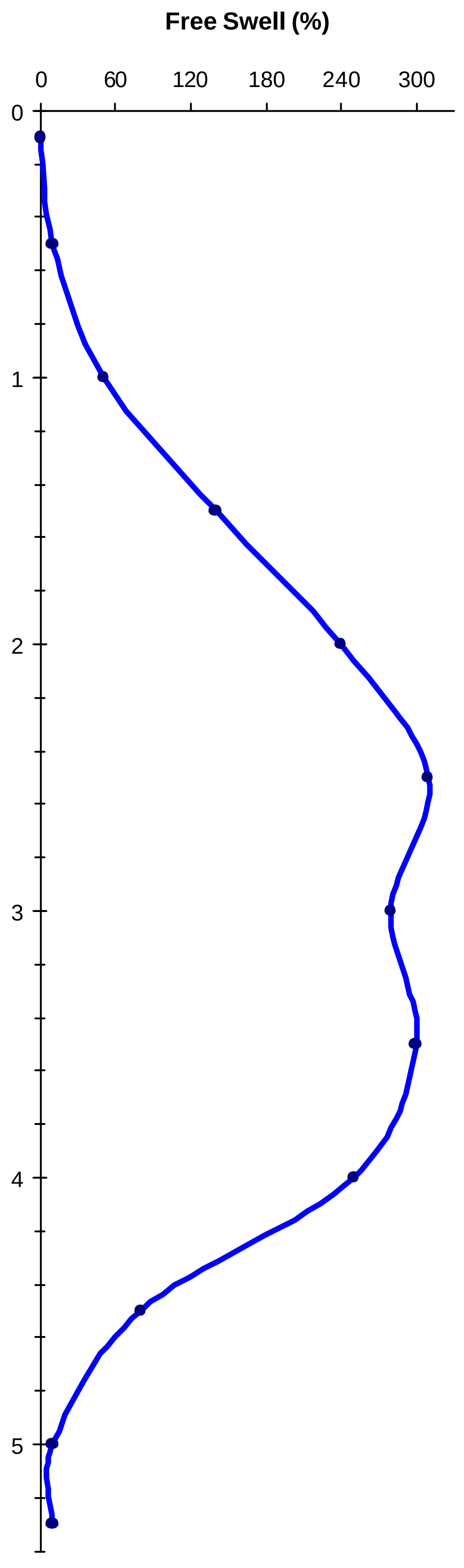
BH 1 ‘Trees’

Soil Depth (m)	Description and Classification	Free Swell (%)
0.0 - 0.1	Fill sandy clay, yellowish brown (10YR 5/4) calcareous, free swell 40% (slightly expansive)	
0.1 - 0.5	Clay,(CL) pinkish white grey (7.5YR 7/1) gravelly, highly calcareous free swell 50% (moderately expansive)	
0.5 - 1.0	Clay, (CI) pinkish grey brown (5YR 6/2) highly calcareous free swell 70% (moderately expansive)	
1.0 - 3.5	Clay, (CH) yellowish brown to light olive brown (10YR 6/4, 2.5Y 5/4) calcareous free swell 110-210% (highly to extremely expansive)	
3.5 - 4.4	Clay, (CH) mottled light olive reddish brown (2.5Y 5/4) free swell 110-140% (highly expansive)	
4.4 - 4.9	Clay-silt, (CI-CL) sand, light brown grey to dark reddish yellow (2.5Y 6/2, 2.5Y 3/6) free swell 80-0% (moderately to non-expansive)	

Saddle Court, Walkley Heights

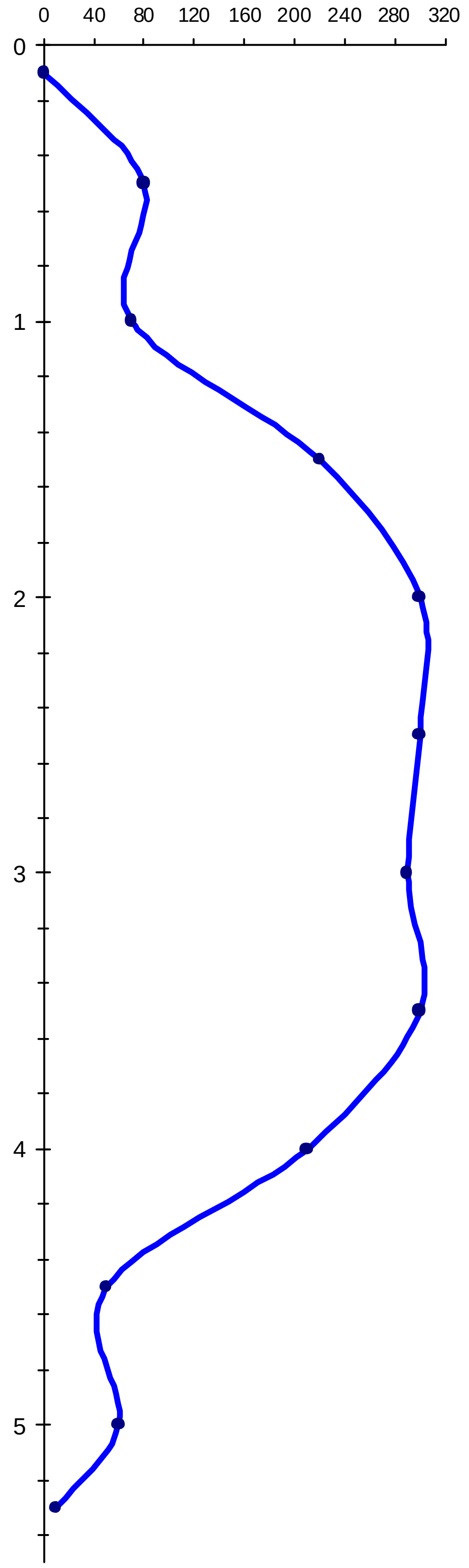
BH 2 'Tree Away'

Soil Depth (m)	Description and Classification
0.0 - 0.3	Fill sandy clay, yellowish brown (10YR 5/4) highly calcareous, non-expansive
0.3 - 0.9	Fill, gravely rubble, grey (7.5YR 5/1) Calcareous, free swell 10% (slightly expansive)
0.9 - 1.5	Clay, (CI) pale brown grey (10YR 7/3) highly calcareous 100 kPa ,free swell 50-140% (moderately to highly expansive)
1.5 - 4.3	Clay, (CH) reddish olive brown (10YR 5/4) calcareous, slickensides 2.7-3.9m 1.5m 100 kPa 2.0m 95 kPa 2.5m 110 kPa 3.0m 120 kPa 3.5m 150 kPa 4.0m 210 kPa free swell 240-310% (*extremely expansive)
4.3 - 5.3	Clay, silt, (CL) reddish pale yellow grey to white (5YR 5/6, 5YR 7/1) free swell 80-10% (moderately to slightly expansive)

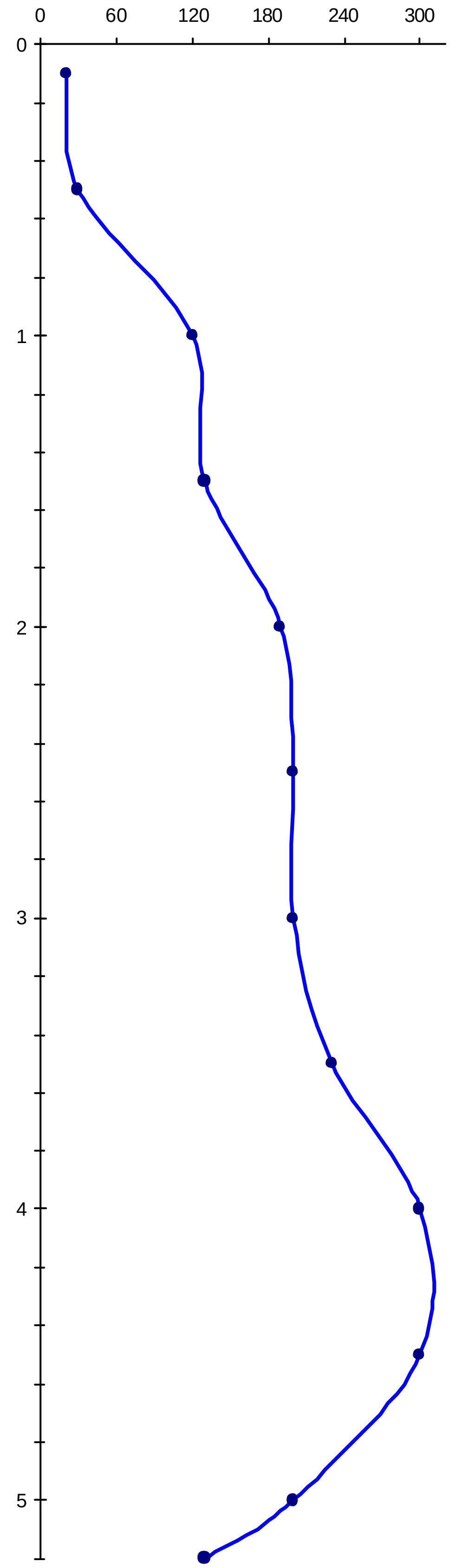


Saddle Court, Walkley Heights

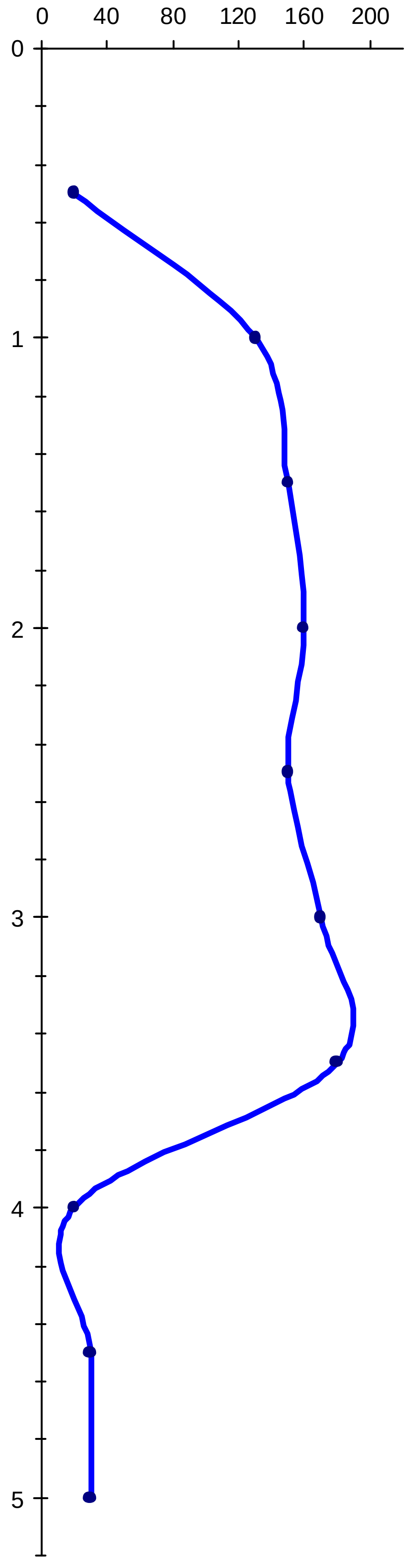
BH 3 "Pavement"

Soil Depth (m)	**Description and Classification**	**Free Swell (%)**
0.0 - 0.5	Fill, silty-gravelly, grey (10YR 6/1) highly calcareous free swell 0-40% (non - slightly expansive)	
0.5 - 1.5	Clay, (CI) pinkish grey to light olive brown (10YR 5/6, 2.5Y 5/4) highly calcareous free swell 80% (moderately expansive)	
1.5 - 4.0	Clay, (CH) light olive brown (2.5Y 5/4) slightly calcareous slickensides 2.2-3.7m free swell 210-300% (*extremely expansive)	
4.0 - 5.3	Clay, silt, (CI-CL) reddish brown and grey (2.5Y 4/6) free swell 60-10% (moderately to slightly expansive)	

Saddle Court, Walkley Heights BH 4 "Away"

Soil Depth (m)	Description and Classification	Free Swell (%)
0.0 - 0.7	Organic fill, dark brown (10YR 3/2) highly calcareous, roots present free swell 30% (slightly expansive)	
0.7 – 1.5	Clay, (CH) yellowish brown (7.5YR 4/6) highly calcareous free swell 130% (highly expansive)	
1.5 - 4.9	Clay, (CH) light olive brown to yellowish brown red (2.5Y 5/4. 2.5 6/3) Slightly calcareous free swell 190-300% (*extremely expansive)	
4.9 - 5.2	Clay, (CH) mottled red and grey (10R 3/3, 10YR 7/2) free swell 200-130% (extremely to highly expansive)	

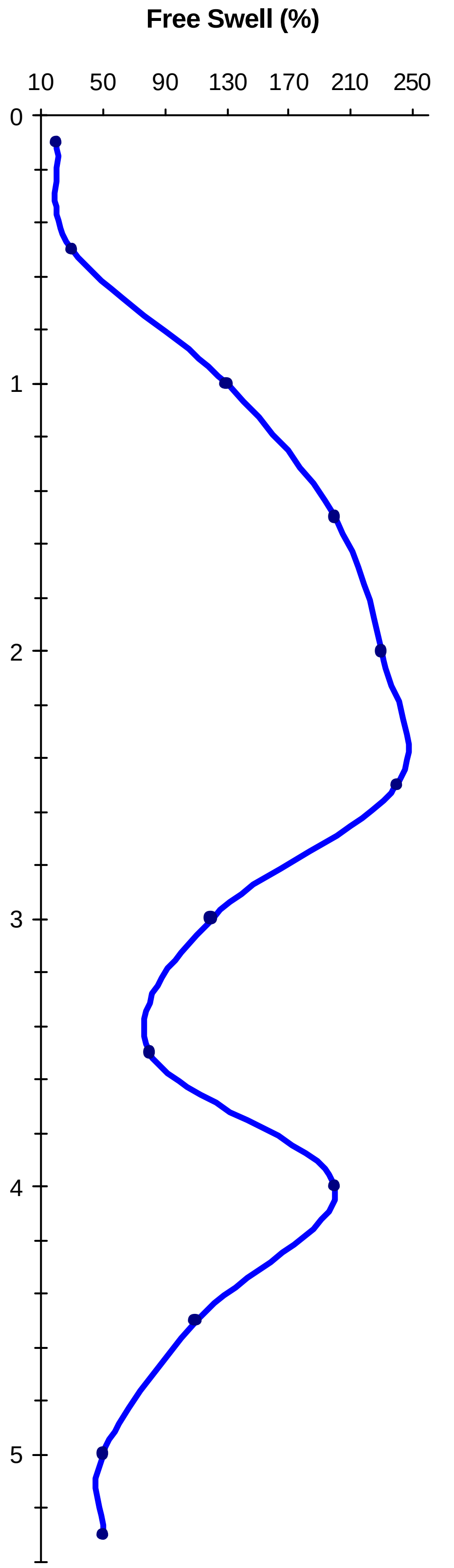
Dene Street, Walkley Heights BH 1 'Near Tree'

Soil Depth	Description and Classification	Free Swell (%)
0.0 - 0.1	Fill, brown (10YR 4/3) highly calcareous, free swell 10% (slightly expansive)	
0.1 - 0.8	Clay, (CL) yellowish brown (10YR 5/6) highly calcareous free swell 20% (slightly expansive)	
0.8 - 2.4	Clay, (CH) red (2.5YR 4/6) calcareous pockets, blocky fractures free swell 130-160% (highly to extremely expansive)	
2.4 - 3.7	Clay, silt, (CH) yellowish red brown (5YR 5/8) free swell 150-180% (extremely expansive)	
3.7 - 4.8	Silty clay, (ML) yellowish brown (10YR 6/8) 4.0m fine yellow sand with quartz (10YR 7/8) free swell 20% (slightly expansive)	
4.8 - 5.1	Silty Clay, (ML) reddish yellow to orange (7.5YR 6/8) free swell 30% (slightly expansive)	

Dene Street, Walkley Heights

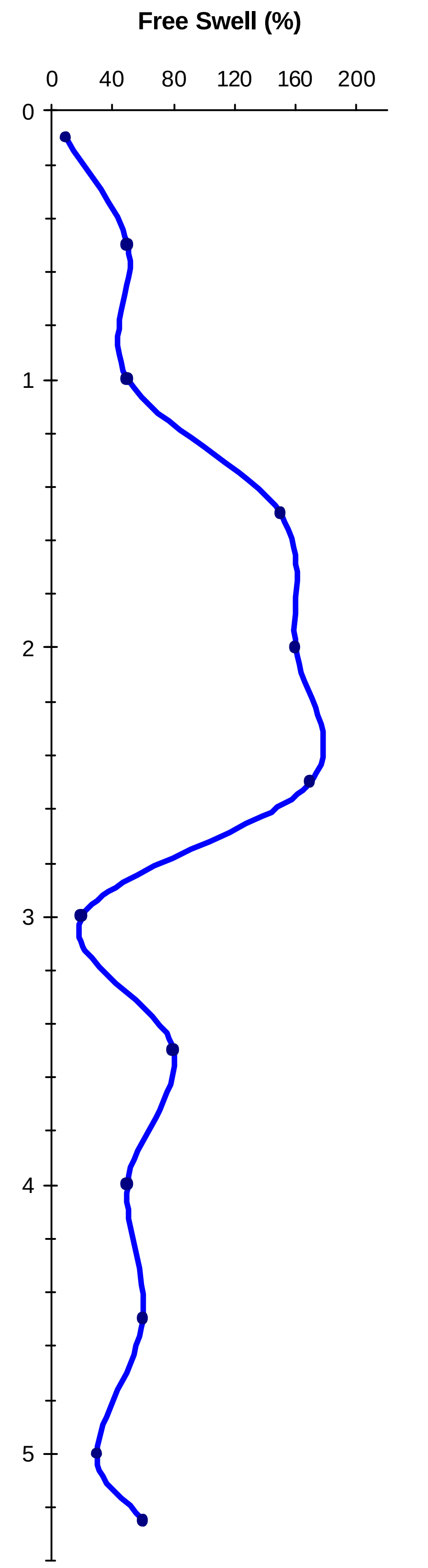
BH 2 'Tree Away'

Soil Depth (m)	Description and Classification
0.0 - 0.25	Clay fill, light brown to brown (5YR 3/3) highly calcareous, free swell 20% (slightly expansive)
0.25 - 1.0	Clay fill, brown to light brown (5YR 4/3) Calcareous, free swell 30% (slightly expansive)
1.0 - 1.75	Clay, (CH) reddish brown (2.5YR 4/5), calcareous free swell 130-200% (highly to extremely expansive)
1.75 - 2.8	Clay, (CH) mottled red and light olive brown grey (10R 4/6, 2.5Y 6/3) free swell 230-240% (*extremely expansive)
2.8 - 3.9	Clay silt, (CI) white and pale yellow (2.5Y 8/1) free swell 120-80% (highly to moderately expansive)
3.9 - 4.5	Clay, silt, (CH) reddish yellow (2.5YR 3/6) free swell 200% (extremely expansive)
4.5 - 4.7	Clay, silt, (CI) yellowish brown (10YR 5/8) free swell 110% (highly expansive)
4.7 - 5.3	Silt, clay, pale yellowish brown (10YR 7/4) free swell 50% (moderately expansive)



Dene Street, Walkley Heights **BH 3 'Pavement'**

Soil Depth (m)	Description and Classification
0.0 - 0.5	Fill, grey (7.5YR 6/1) bitumen 25mm thick, gravelly, highly calcareous free swell 10% (slightly expansive)
0.5 - 1.2	Clay, (CI) light pinkish brown (5YR 7/4) highly calcareous free swell 50% (moderately expansive)
1.2 - 2.8	Clay, (CH) mottled grey and reddish brown (2.5YR 4/6) calcareous free swell 150-170% (extremely expansive)
2.8 - 3.0	Sand, clay, (SC) yellowish red (5YR 5/8) free swell 20% (slightly expansive)
3.0 - 3.3	Clay, (CI) mottled reddish brown and grey (2.5YR 4/6) silt at depth, free swell 80% (moderately expansive)
3.3 - 4.5	Sand, clay, (SM) yellowish red (5YR 5/8) free swell 60-80% (moderately expansive)
4.5 - 5.25	Silt, (ML) brownish yellow to reddish yellow (10YR 6/8, 7.5 6/8) free swell 30-60% (moderately-slightly expansive)

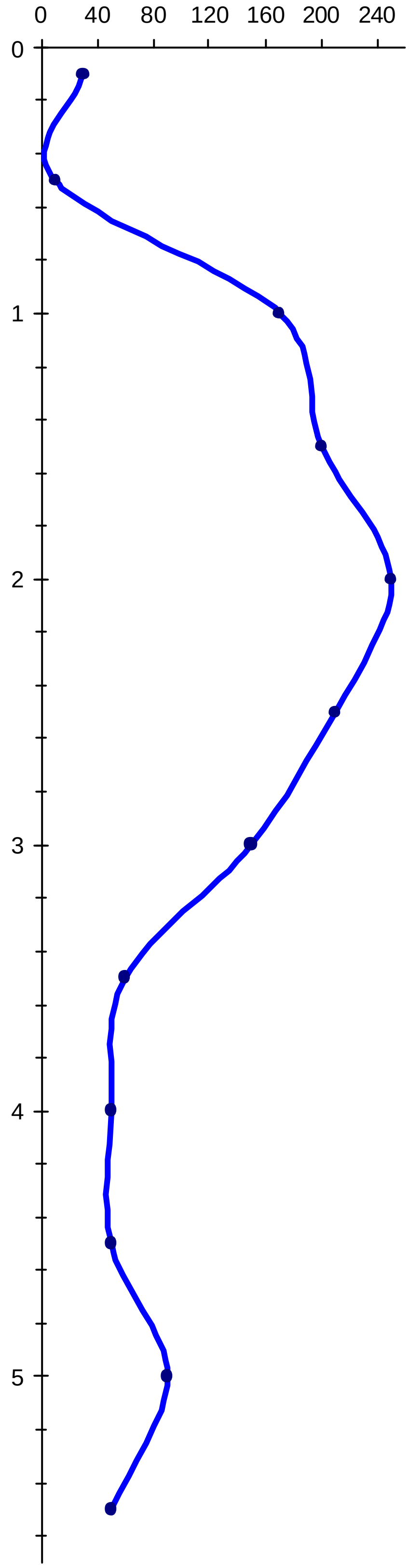


Dene Street, Walkley Heights

BH 4 'Away'

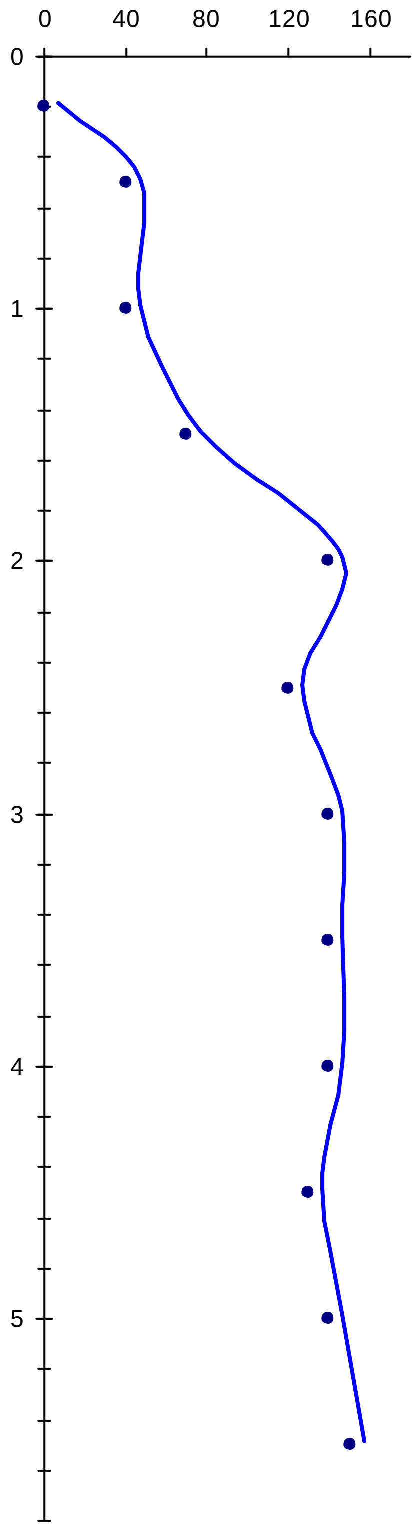
Soil Depth (m)	Description and Classification
0.0 - 0.3	Organic fill, dark greyish brown (10YR 3/2) Calcareous, free swell 30% (slightly expansive)
0.3 - 0.7	Fill, gravelly, dark grey (10YR 4/1) calcareous, free swell 10% (slightly expansive)
0.7 - 0.9	Clay, (CH) light brown (7.5YR 5/5) calcareous free swell 120% (highly expansive)
0.9 - 2.0	Clay, (CH) mottled reddish brown and grey (2.5YR 4/4) slightly calcareous, blocky nature free swell 170-200% (extremely expansive)
2.0 - 3.1	Clay, (CH) mottled dark reddish brown and grey (2.5YR 4/4) slickensides 1.5 - 3.0m free swell 250-150% (extremely expansive)
3.1 - 5.5	Clay-sand, (CI-SM) yellowish orange red (5YR 5/8) free swell 90-40% (moderately to slightly expansive)

Free Swell (%)



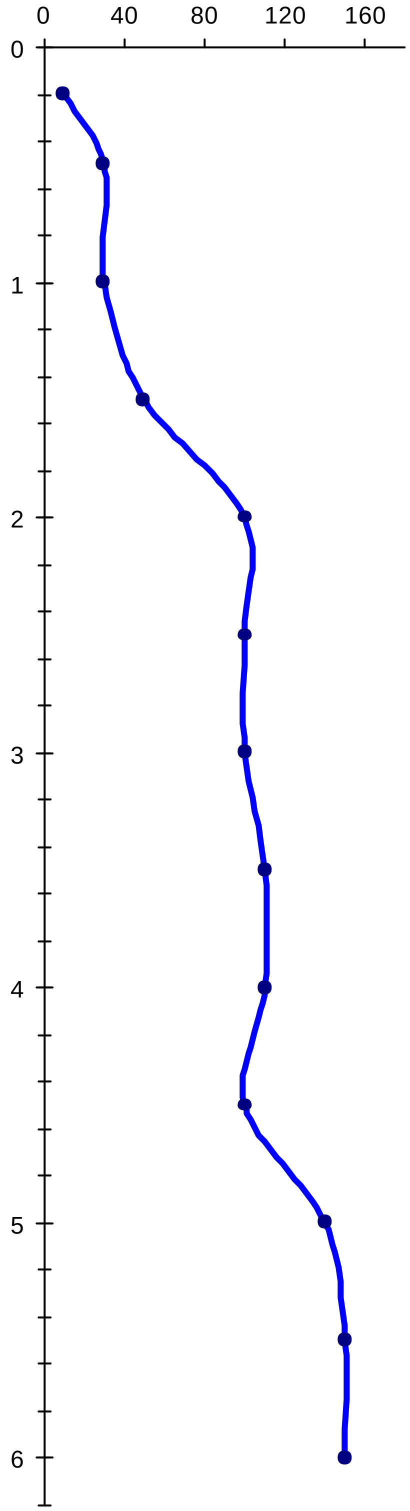
Station Court, Walkley Heights (May 02)

BH 1 (Near Tree)

Soil Depth (m)	Description and Classification	Free Swell (%)
0.0 – 0.20	Loam fill, grass and roots, brown (10YR 4/4)	
0.20 – 1.80	Clay, (CL) light cream brown (7.5YR 6/7) highly calcareous	
1.80 – 3.00	Clay, (CH) light olive brown (2.5Y 5/6) blocky nature	
3.00 – 5.60	Clay, (CH) grey with red-brown and yellow mottling (2.5Y 6/2) Blocky nature, slickensides	

Station Court, Walkley Heights (May 02)

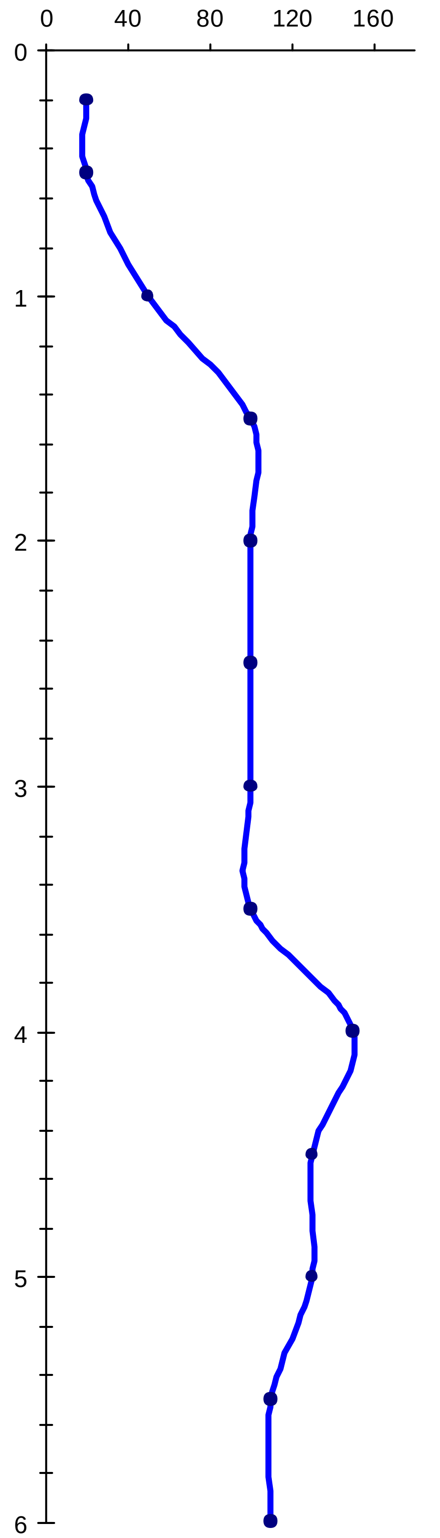
BH 3 (Pavement)

Soil Depth (m)	Description and Classification	Free Swell (%)
0.00 – 0.15	Pavement fill, grey (7.5YR 6/1) gravelly highly calcareous, non-expansive	
0.15 – 0.50	Gravelly fill, light brown and grey (7.5YR 6/3) highly $CaCO_3$, free swell 10-30%	
0.50 – 1.50	Clay, (CI) light cream brown to light yellowish brown (7.5YR 7/2, 10YR 6\4) calcareous, free swell 30-50% (slightly to moderately expansive)	
1.50 – 2.80	Clay, (CH) olive brown to light olive brown (2.5Y 4/4) slightly calcareous free swell 100% (highly expansive)	
2.80 – 3.10	Clay with decomposed matter, old root, black (7.5YR 2.5/1) and greenish grey (2.5Y 6/2)	
3.10 – 6.00	Clay, (CH) greyish green brown with reddish yellow mottling (2.5Y 6/2) blocky nature, slickensides at 3.2 m free swell 100-150% (highly to extremely expansive)	

Station Court, Walkley Heights (June 02)

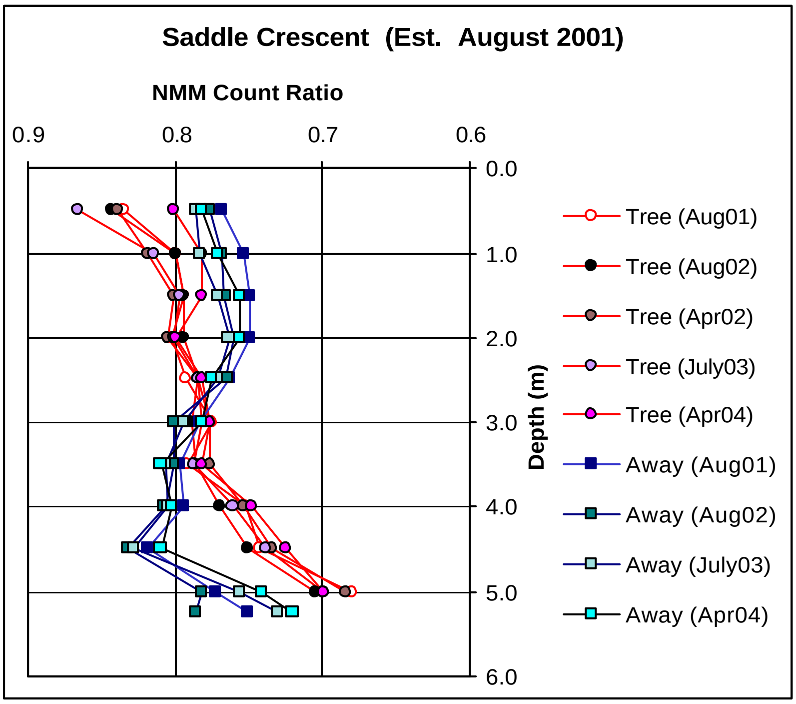
BH 4 (Away in Ground Movement Station)

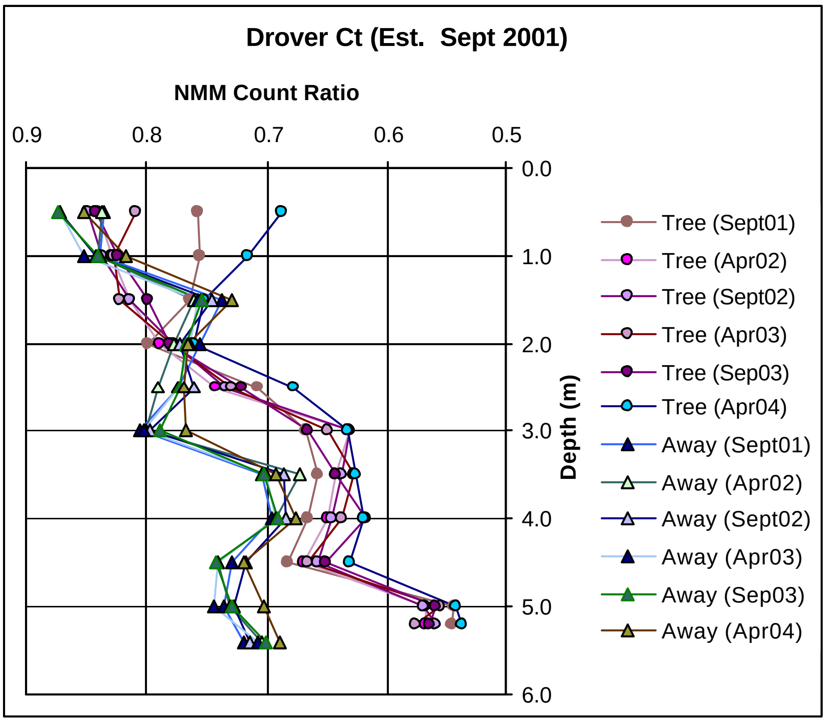
Soil Depth (m)	Description and Classification	Free Swell (%)
0.0 – 0.30	Organic Clay, highly calcareous, dark brown (7.5YR 3/3) free swell 20% (slightly expansive)	
0.30 – 1.50	Clay, light reddish yellow brown (7.5YR 6/6) highly calcareous free swell 50-100% (moderately to highly expansive)	
1.50 – 2.00	Clay, mottled reddish yellow and cream brown (7.5YR 6/4) calcareous free swell 100% (highly expansive)	
2.00 – 6.00	Clay, greenish grey with some reddish yellow (2.5Y 7/2) Blocky nature Grey and yellow (silt) increasing at depth free swell 100-150% (highly to extremely expansive)	

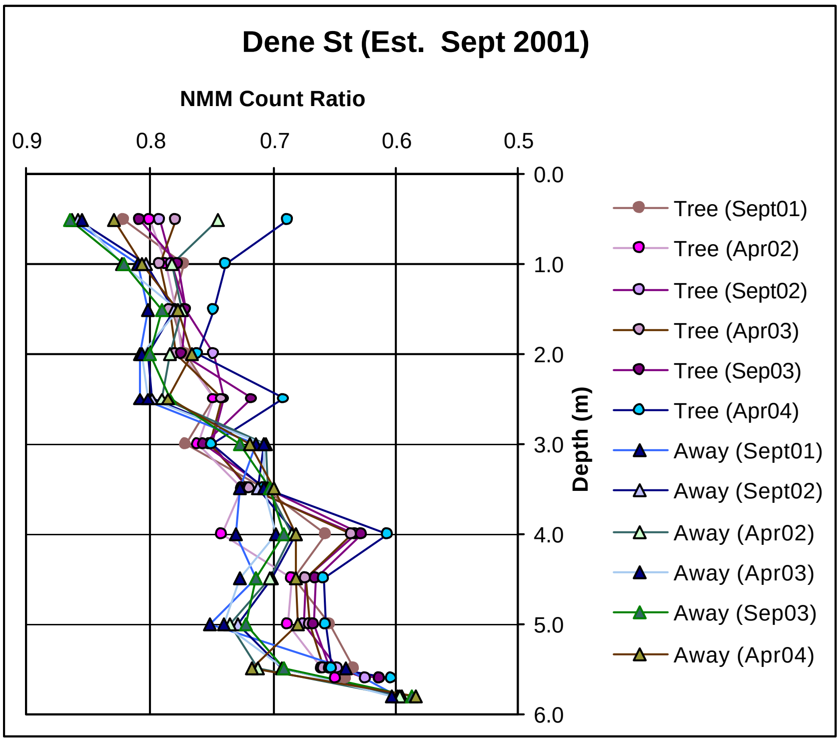


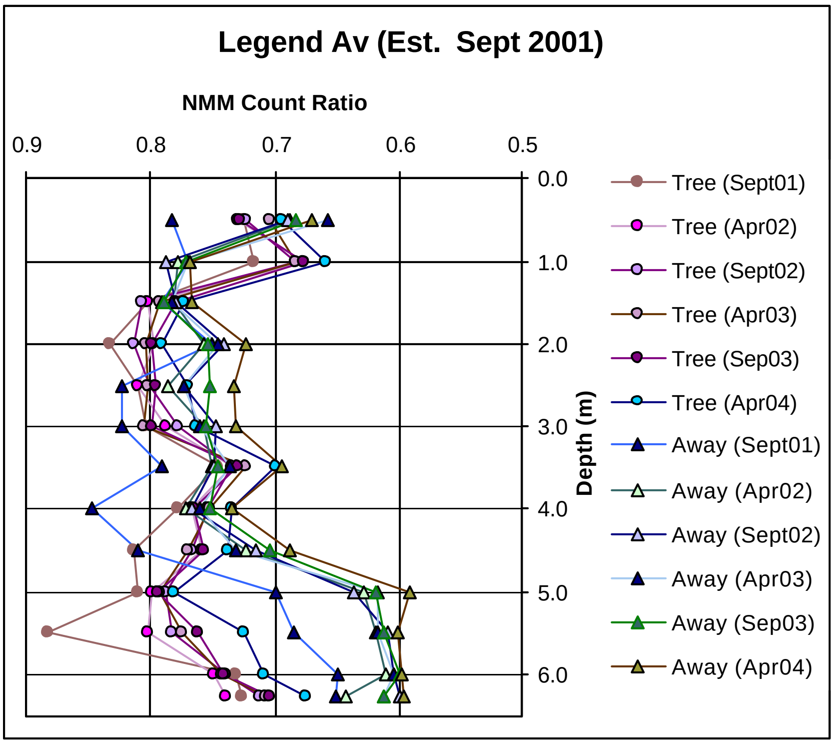
APPENDIX C

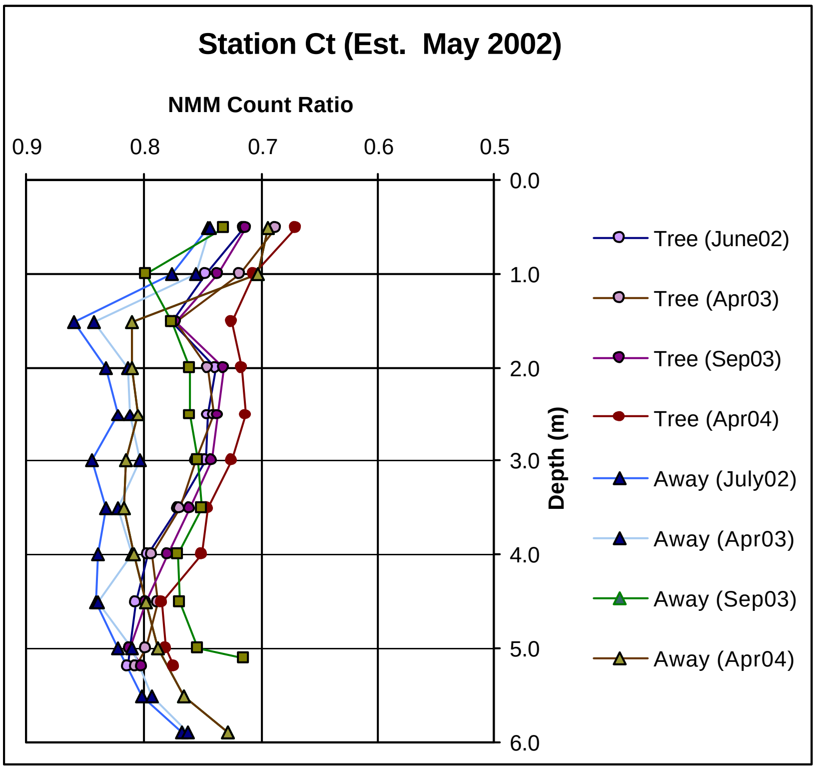
ALL SITES NMM SUMMARY PLOTS





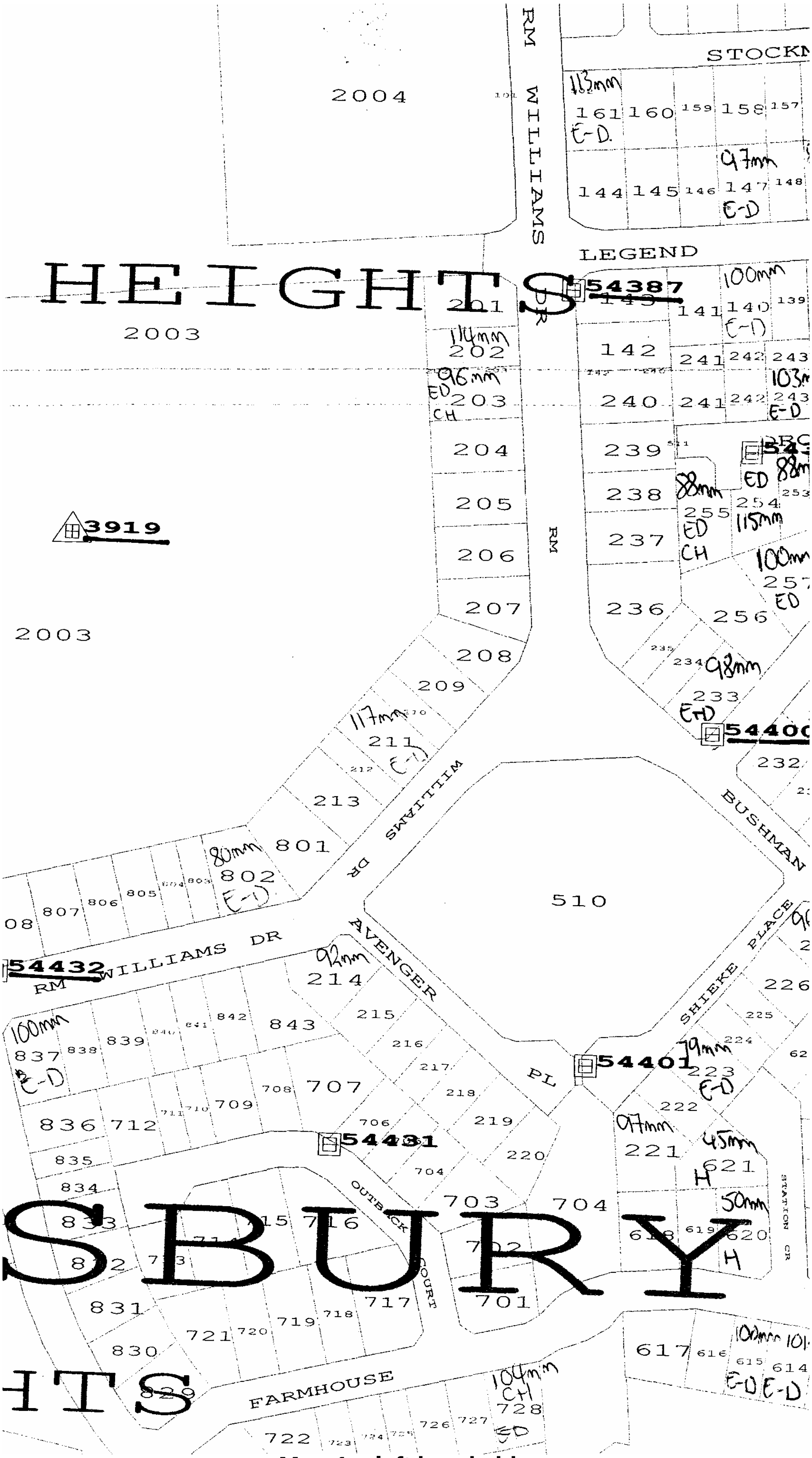

Dene St (Est. Sept 2001)
NMM Count Ratio
0.9
0.8
0.7
0.6
0.5
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Depth (m)
Tree (Sept01)
Tree (Apr02)
Tree (Sept02)
Tree (Apr03)
Tree (Sep03)
Tree (Apr04)
Away (Sept01)
Away (Sept02)
Away (Apr02)
Away (Apr03)
Away (Sep03)
Away (Apr04)


Legend Av (Est. Sept 2001)
NMM Count Ratio
0.9
0.8
0.7
0.6
0.5
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Depth (m)
Tree (Sept01)
Tree (Apr02)
Tree (Sept02)
Tree (Apr03)
Tree (Sep03)
Tree (Apr04)
Away (Sept01)
Away (Apr02)
Away (Sept02)
Away (Apr03)
Away (Sep03)
Away (Apr04)

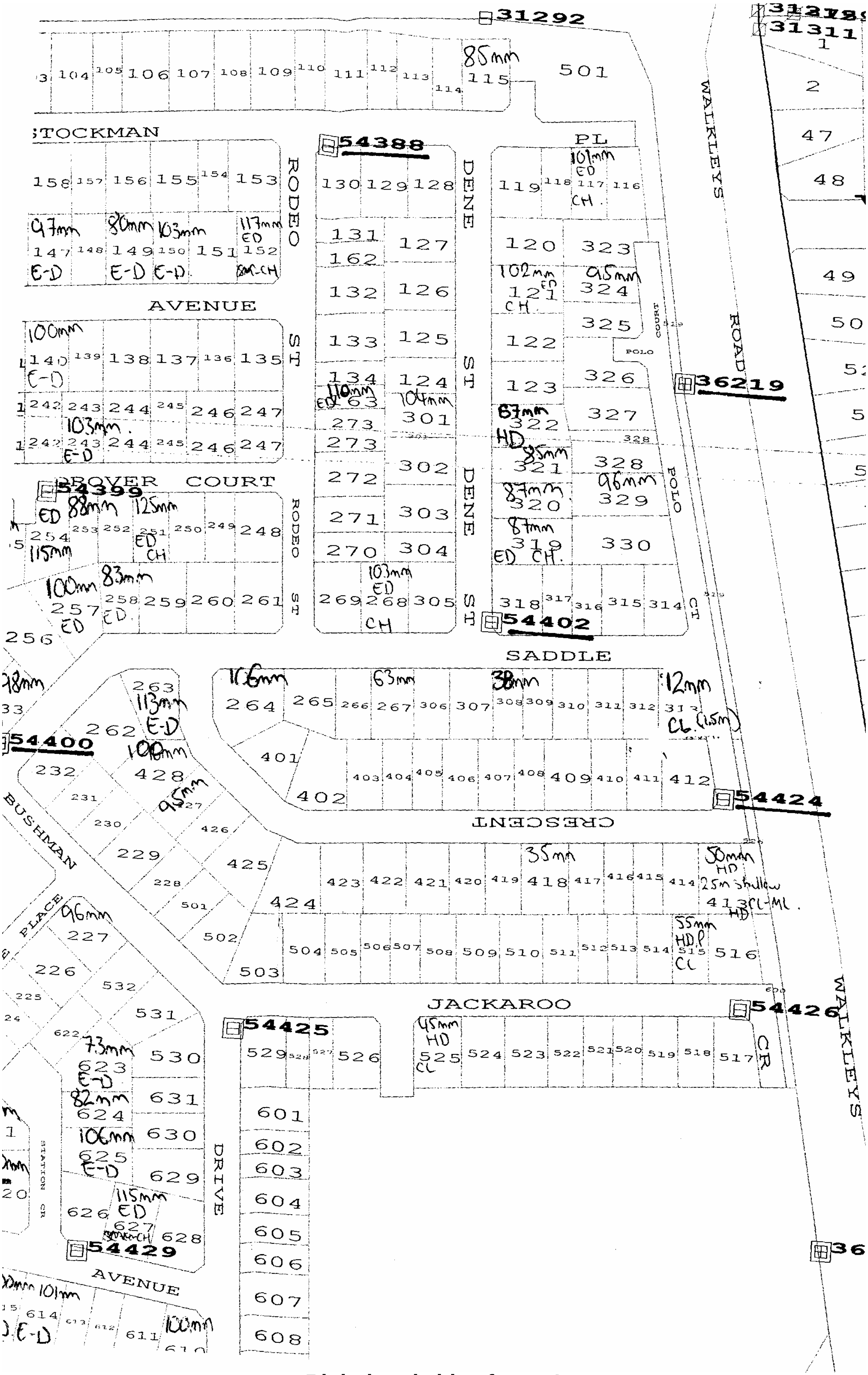

Station Ct (Est. May 2002)
NMM Count Ratio
0.9
0.8
0.7
0.6
0.5
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Depth (m)
Tree (June02)
Tree (Apr03)
Tree (Sep03)
Tree (Apr04)
Away (July02)
Away (Apr03)
Away (Sep03)
Away (Apr04)

APPENDIX D

Surface movements y_s values



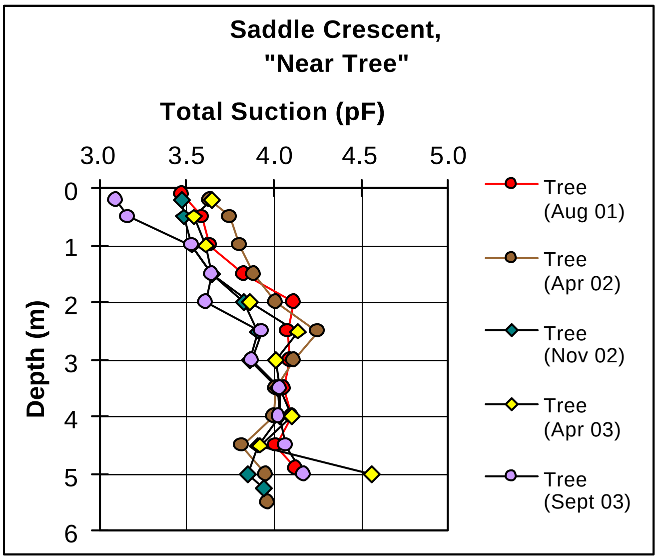
Map 1 – left hand side

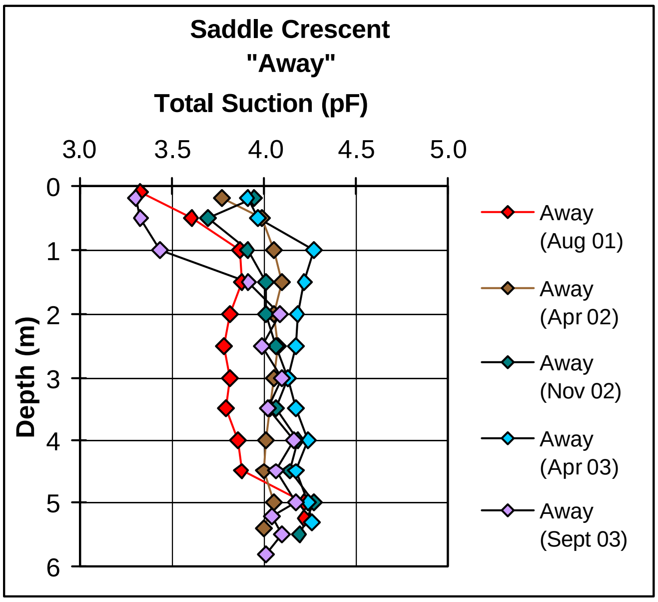


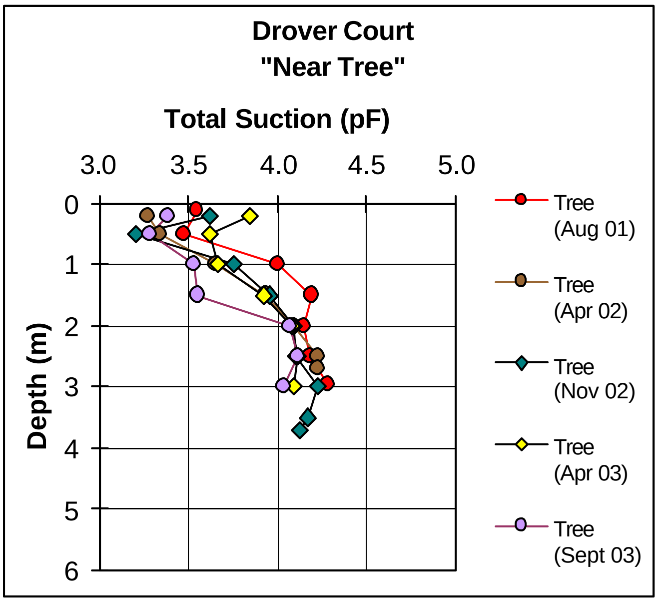
Right hand side of map 1

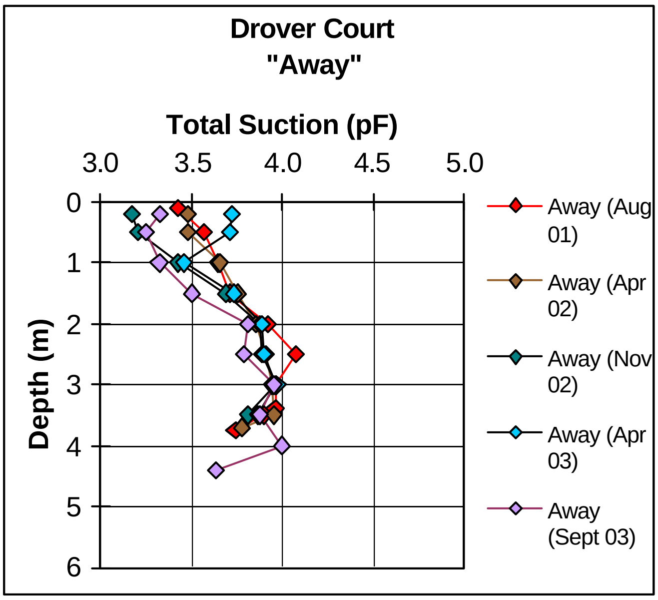
APPENDIX E

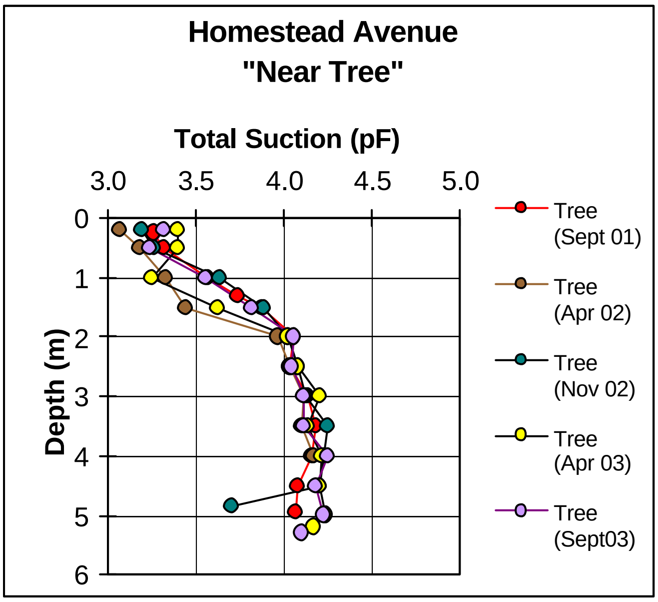
Summary of Soil Suction Profiles for all Sites

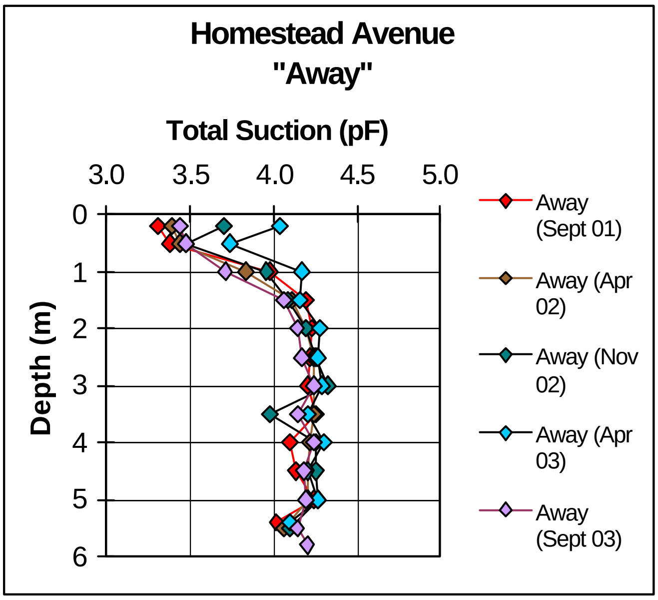


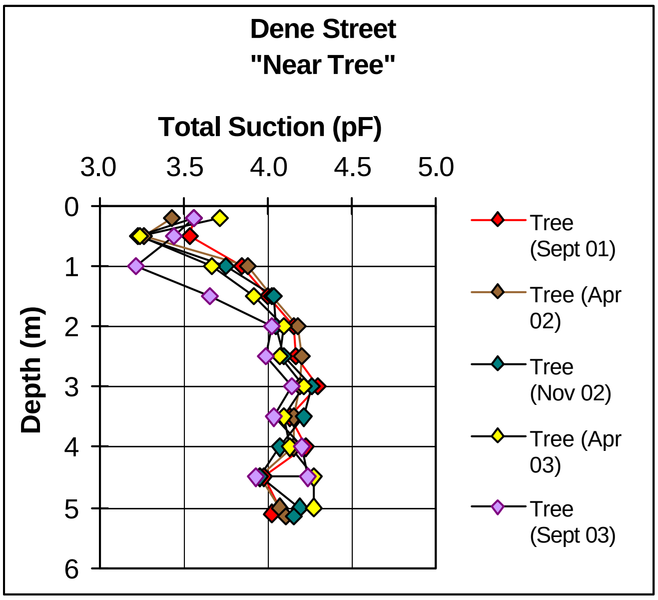


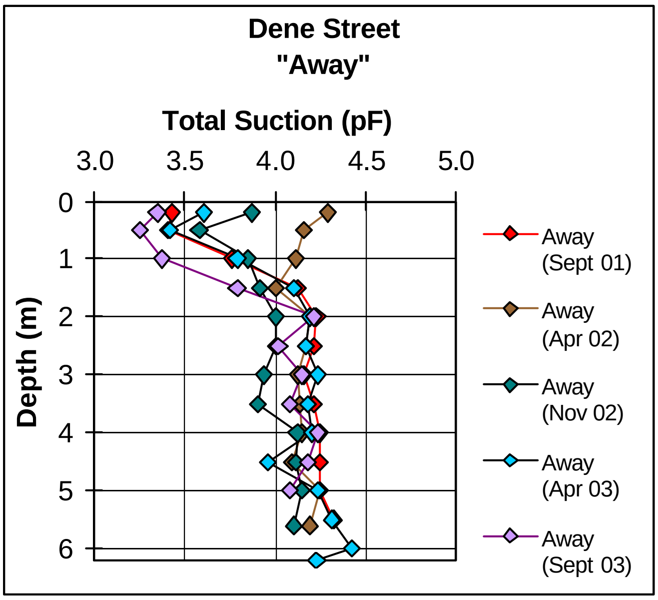


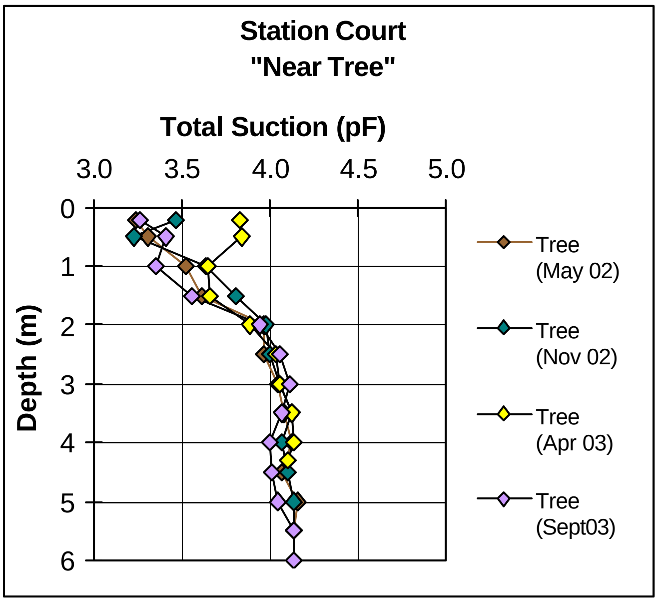


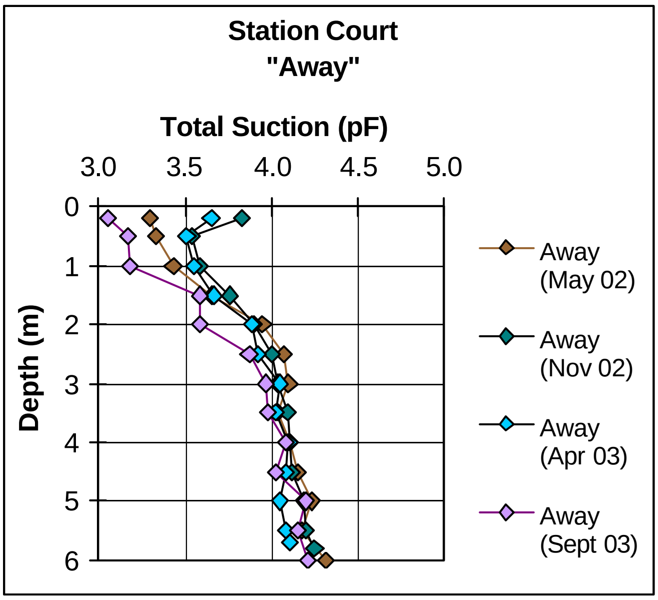

Homestead Avenue
"Near Tree"
Total Suction (pF)
3.0 3.5 4.0 4.5 5.0
Depth (m)
0 1 2 3 4 5 6
Tree (Sept 01)
Tree (Apr 02)
Tree (Nov 02)
Tree (Apr 03)
Tree (Sept03)

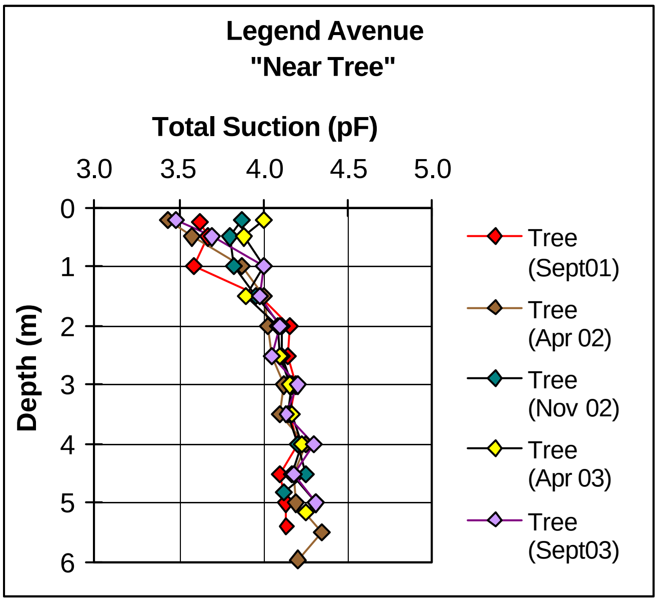

Homestead Avenue
"Away"
Total Suction (pF)
3.0 3.5 4.0 4.5 5.0
Depth (m)
0 1 2 3 4 5 6
Away (Sept 01)
Away (Apr 02)
Away (Nov 02)
Away (Apr 03)
Away (Sept 03)

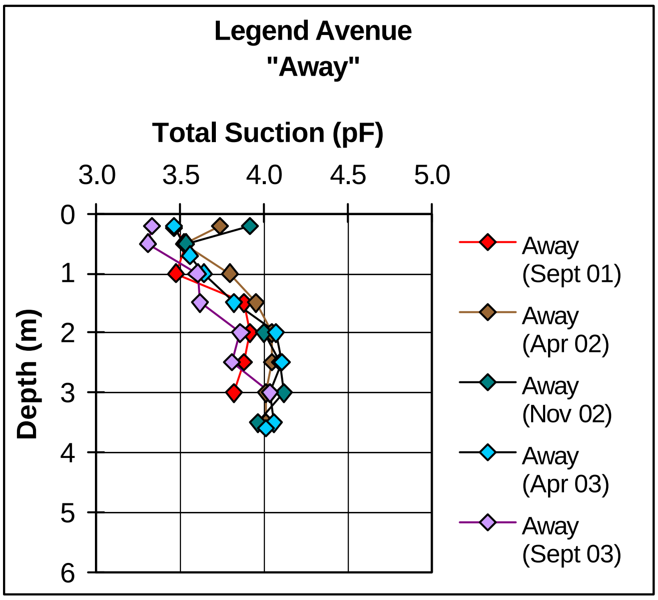

Dene Street
"Near Tree"
Total Suction (pF)
3.0 3.5 4.0 4.5 5.0
Depth (m)
0 1 2 3 4 5 6
Tree (Sept 01)
Tree (Apr 02)
Tree (Nov 02)
Tree (Apr 03)
Tree (Sept 03)


Dene Street
"Away"
Total Suction (pF)
3.0 3.5 4.0 4.5 5.0
Depth (m)
0 1 2 3 4 5 6
Away (Sept 01)
Away (Apr 02)
Away (Nov 02)
Away (Apr 03)
Away (Sept 03)


Station Court
"Near Tree"
Total Suction (pF)
3.0 3.5 4.0 4.5 5.0
Depth (m)
0 1 2 3 4 5 6
Tree (May 02)
Tree (Nov 02)
Tree (Apr 03)
Tree (Sept03)


Station Court
"Away"
Total Suction (pF)
3.0 3.5 4.0 4.5 5.0
Depth (m)
0 1 2 3 4 5 6
Away (May 02)
Away (Nov 02)
Away (Apr 03)
Away (Sept 03)

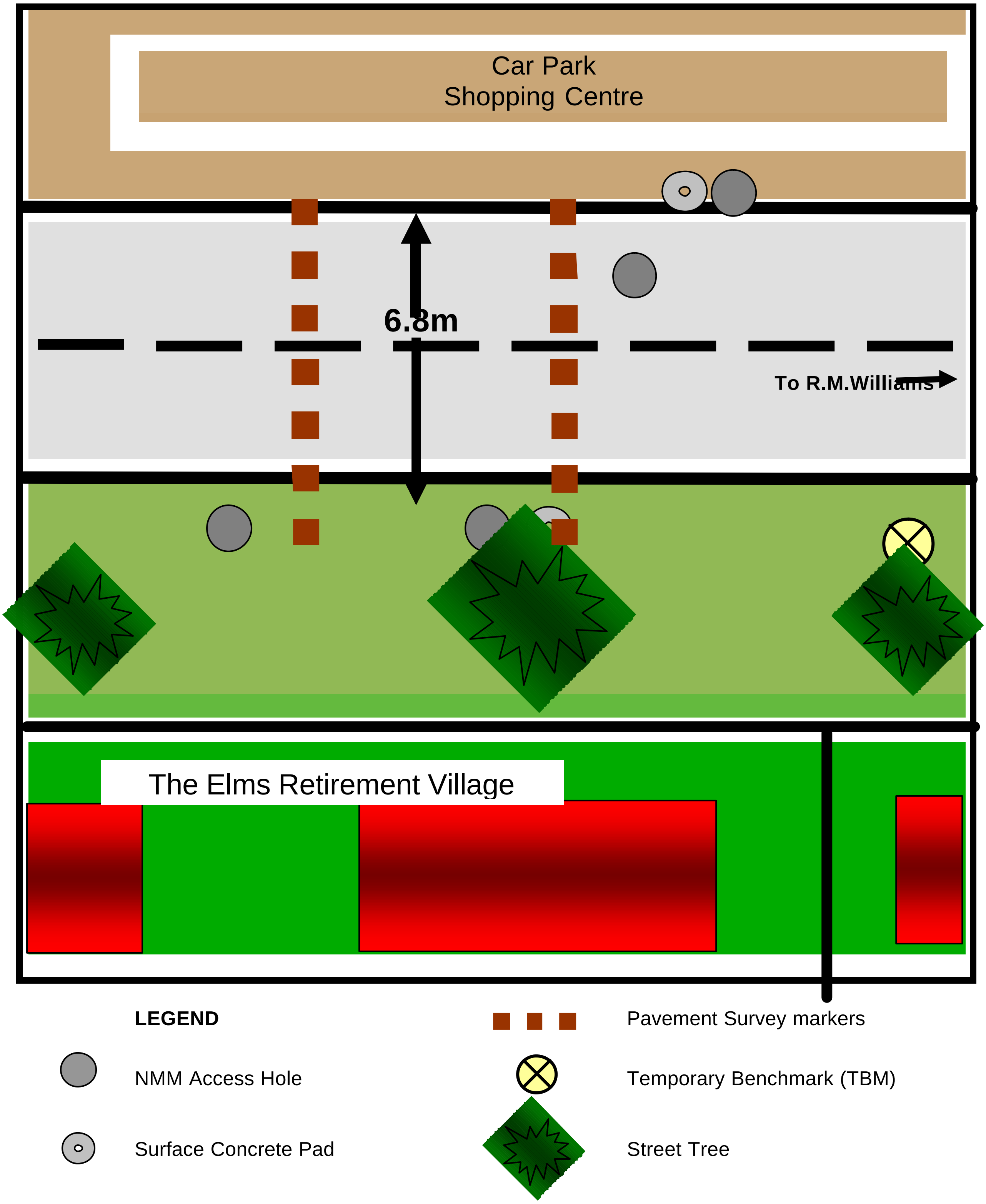

Legend Avenue
"Near Tree"
Total Suction (pF)
3.0
3.5
4.0
4.5
5.0
Depth (m)
0
1
2
3
4
5
6
Tree (Sept01)
Tree (Apr 02)
Tree (Nov 02)
Tree (Apr 03)
Tree (Sept03)


Legend Avenue
"Away"
Total Suction (pF)
3.0
3.5
4.0
4.5
5.0
Depth (m)
0
1
2
3
4
5
6
Away (Sept 01)
Away (Apr 02)
Away (Nov 02)
Away (Apr 03)
Away (Sept 03)

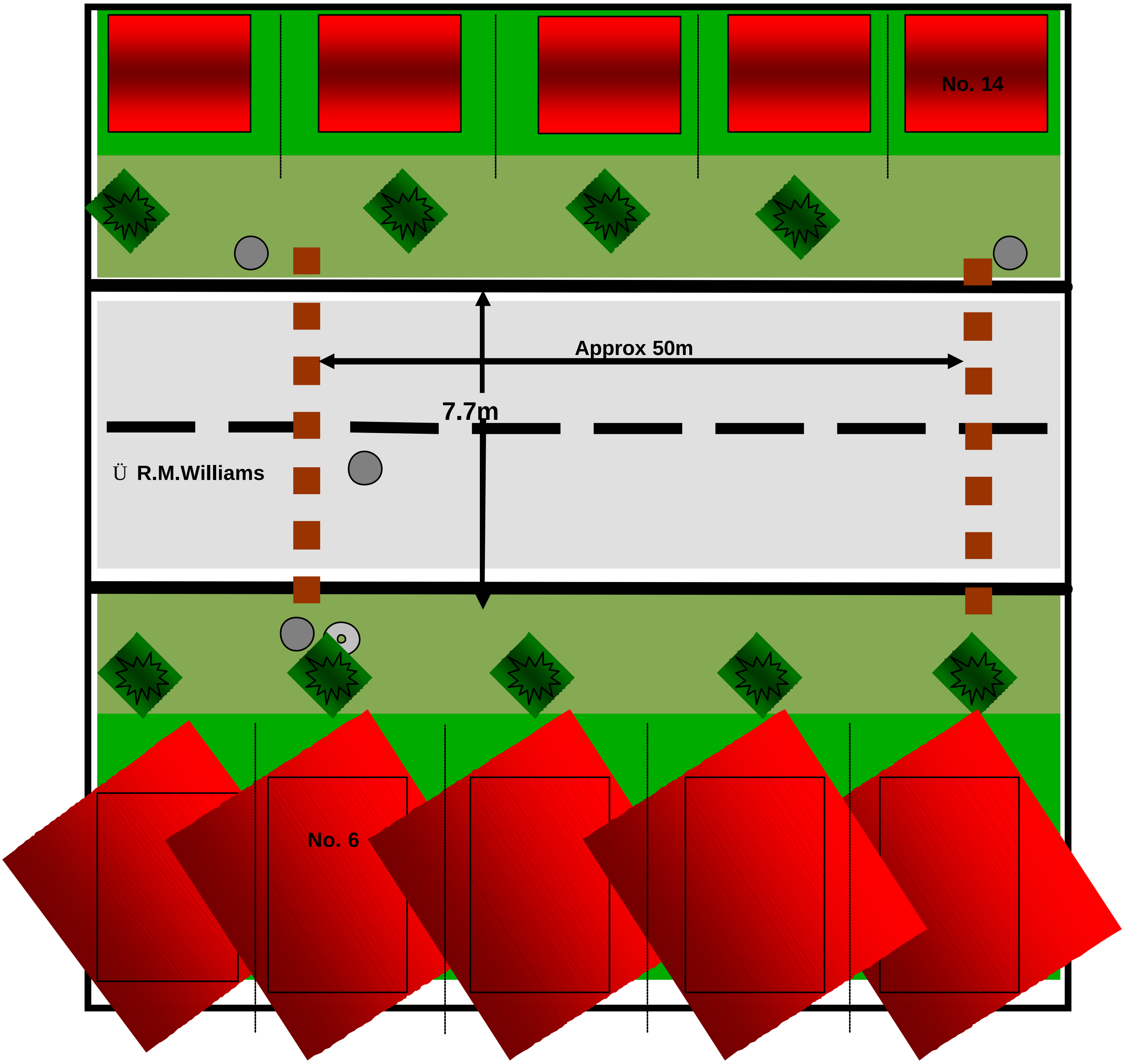
APPENDIX F

Site Overviews

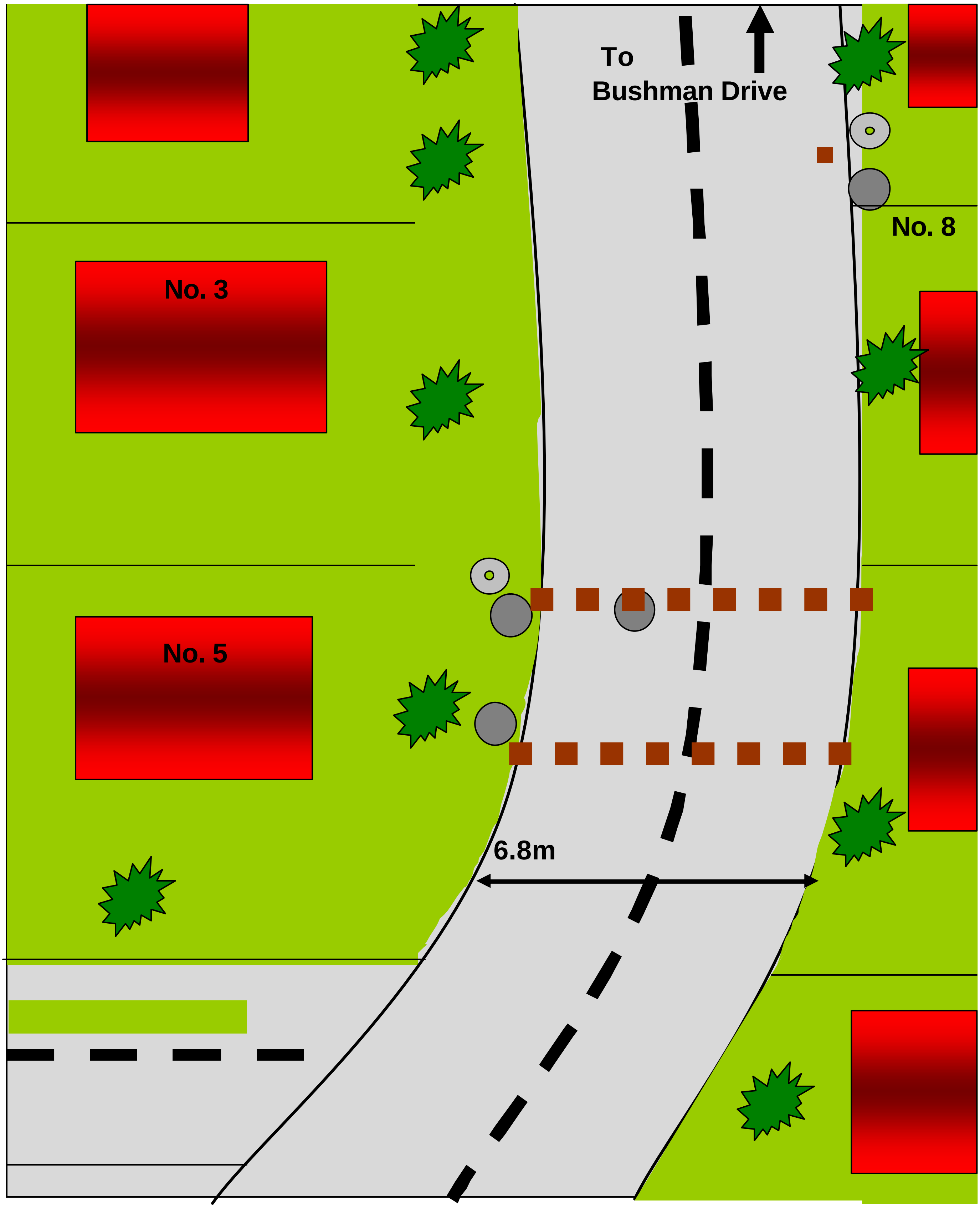
Homestead Avenue, *Chinese Elms*



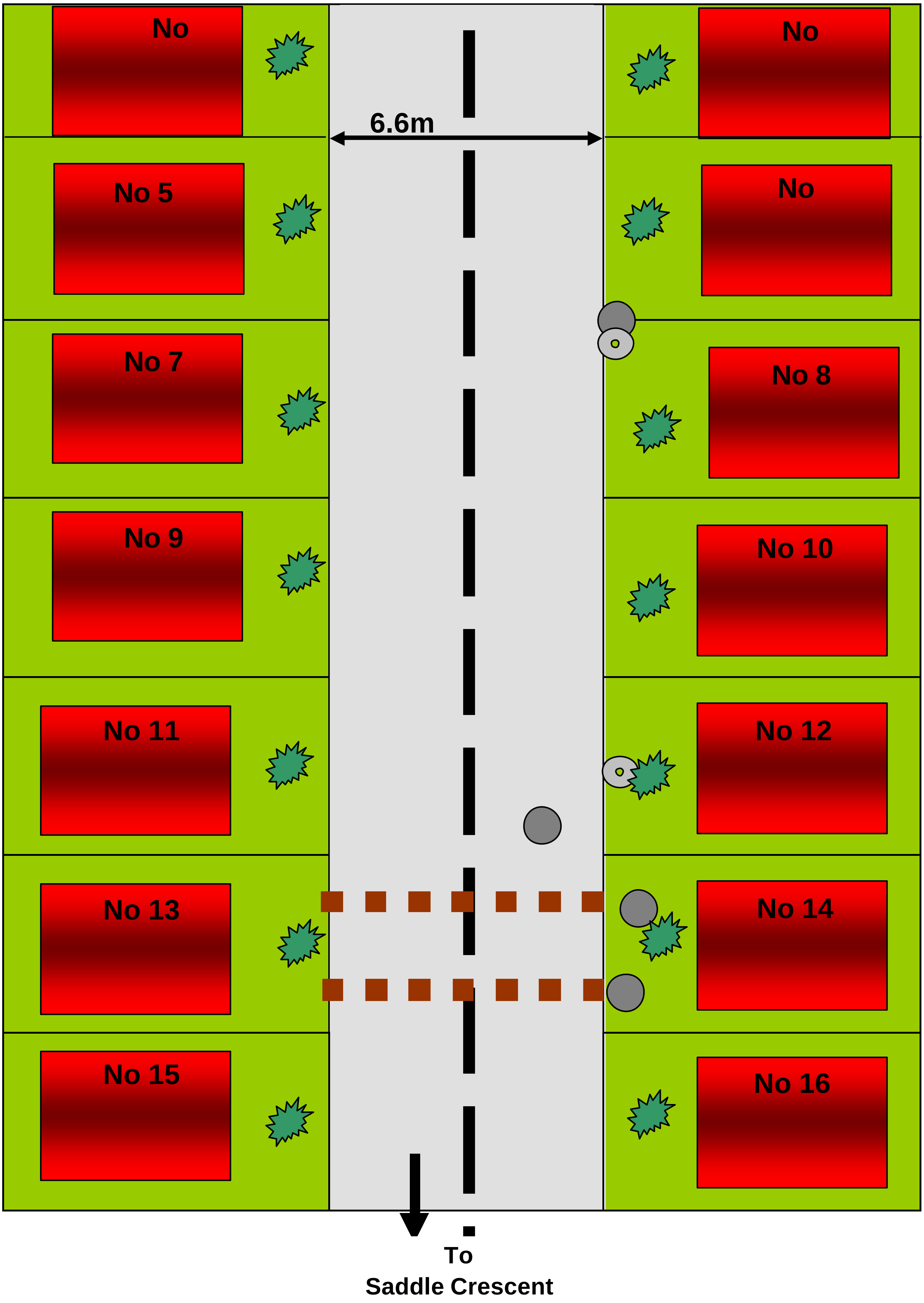
Legend Avenue, *Pyrus Species*



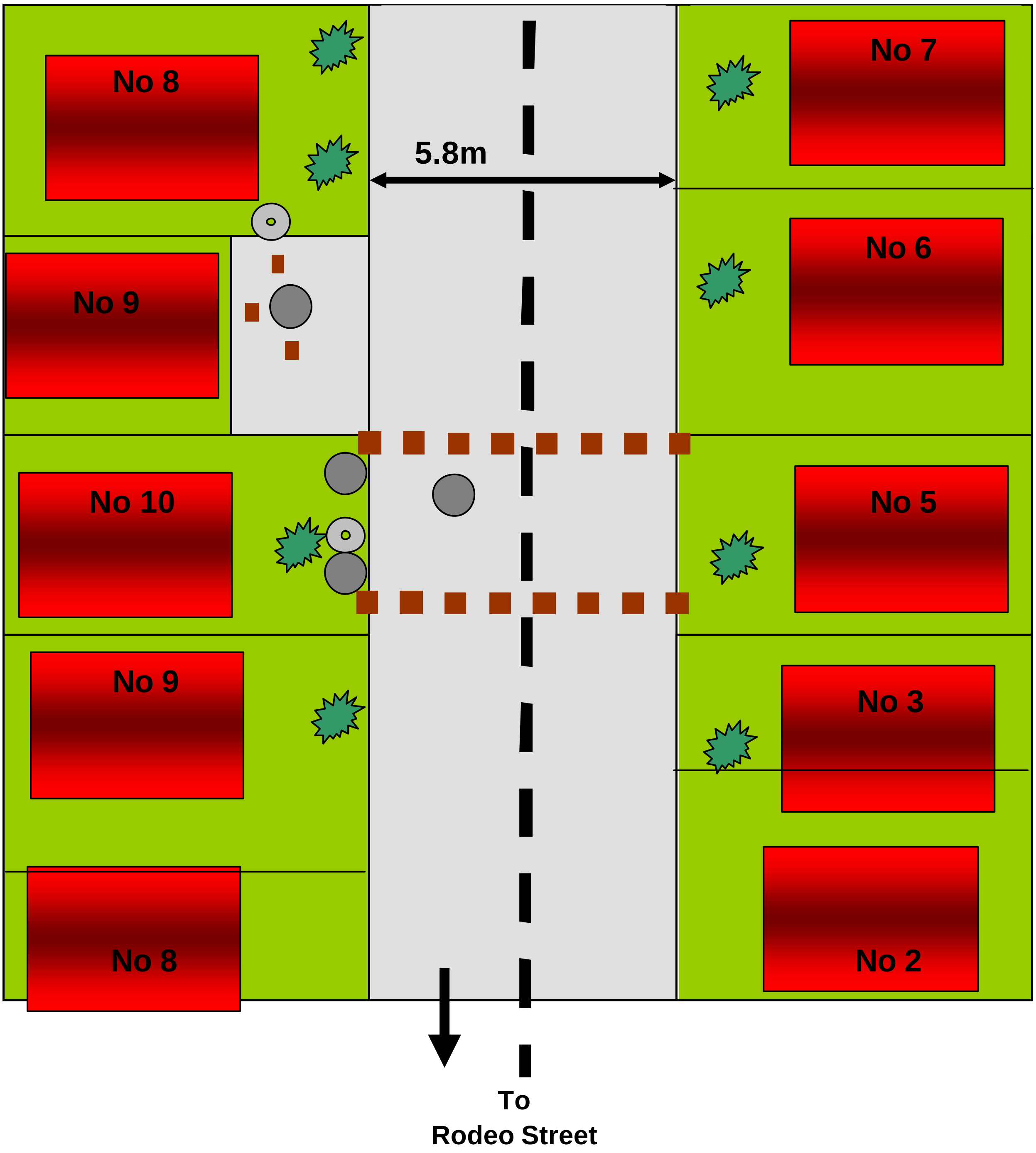
Saddle Crescent, *Golden Raintree*



Dene Street, *Pyrus Species*



Drover Court, *Golden Raintree*



Station Court, *Coral Gum*