RELATIONSHIP BETWEEN SOIL MOVEMENT, BUILDINGS AND TREES

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1. INTRODUCTION

1.1

Since the late 1970s and during the early 1980s technical papers prepared by the likes of Dr J E Holland and J Richards[1]; D A Cameron and P F Walsh[2]; B G Richards, P Peter and W W Emerson[3] and K C Pile[4] have alerted the engineering profession to the effects of ad hoc planting of shrubs and trees in reactive clay soils where field experience has indicated that the roots of shrubs and trees can, and do, cause distortion and cracking damage in buildings in the near vicinity.

1.2

Over the past twenty years the author has worked in the fields of structural and geotechnical engineering, particularly in relation to diagnosing the causes of structural damage to domestic housing and light commercial structures.

Over this time it has become increasingly apparent that our climate, the environment and our management of same in relation to landscaping techniques has a profound effect upon building performance.

1.3

In spite of the fact that engineers have known for some time that plant roots can have an effect upon the stability of structures, great difficulty has been encountered in attempting to design surface footing systems that will adequately cope with the vagaries of clay soil behaviour over a range of variables which includes

- Aberrations to Adelaide's normally semi-arid climate (e.g. extreme dry periods and extreme wet periods) .
- The root spread and moisture demand of various species of shrubs and/or trees.
- Whether trees exist at a particular building site (or possibly on adjacent sites) and whether some, or all, trees at the site are to be removed to facilitate construction.
- Planting of new trees following construction.
- The removal of existing trees, possibly from neighbouring allotments, in the post construction period.

- Garden watering and storm water disposal patterns.

In current day designs engineers are attempting to make allowance for existing site trees, however, advice is also given to limit new tree planting to specific distances away from buildings depending upon the degree of reactivity of the clay soil and the mature height of the tree or shrub species.

A "reactive" clay soil is one which swells volumetrically upon wetting up and conversely shrinks volumetrically upon drying out.

1.4

Currently, footing design engineers in South Australia are attempting to overcome the many variables in designing for tree root effects by making adjustments to normally expected soil movements caused by seasonal soil moisture content variations so that the footing size is increased to account for the presence of trees.

Alternatively, where practical, many engineers are now reverting back to piered footing systems which have now been "up-dated" to include the newer Tri-Ped™ system developed jointly by the University of South Australia and the South Australian Housing Trust and the piered Waffle Raft system which was developed by Koukourou Urban and Residential Engineers.

These footing systems will be discussed in more detail towards the end of this paper, however, it will suffice to say at this stage that clay soil movement induced by tree root effects is overcome by ensuring that piers or piles are taken completely through any re-active clay layer(s) to found upon a stable stratum such as solid rock, weathered rock, gravel or sand.

This paper will consider in lay person's terms where possible, the relationship between soil movement, building performance and trees. The effects which trees have upon the soil-footing interaction problem will be discussed. The type of damage most usually associated with tree roots will be described. New technologies associated with footing design that will integrate with landscape considerations will be mentioned.

2. THE PHYSIOLOGY OF TREES AND SHRUBS AND SOIL BEHAVIOUR

2.1

During the process of photosynthesis trees absorb carbon dioxide from the atmosphere and oxygen is released via pore openings in the foliage.

At the same time as this gas exchange is occurring the plant also loses water.

The fundamental effect which a tree or shrub has upon soil moisture is dictated by this need to maintain a large water flow to the foliage to replace the ever present moisture loss.

For a tree or shrub to be able to sustain its growth (i.e. not wilt or die) there must be a gradient of water potential from soil-to-roots-to-foliage.

2.2

It has been the author's field experience that Australian native trees and shrubs have a higher propensity to extract significant volumes of soil moisture in comparison with exotic varieties of trees and shrubs most of which do not seem to cause as much structural damage as the native varieties.

2.3

A simplified diagram of the evapo-transpiration process whereby trees remove moisture from the soil and release same to the atmosphere via foliage is shown in figure 1 (attached).

2.4

All clays shrink and swell to some degree with changes in moisture content.

It has been the writer's experience based upon field observations that the root systems of trees and shrubs can have an effect on soil moisture depletion over an approximately circular area of radius equal to the height of the tree in the case of a single tree and otherwise having a radius of one-and-a-half and up to two times the height of the tallest tree in a row or group depending upon the species of tree and watering patterns.

2.5

As the tree roots remove water reactive clay soils (which cover approximately 95% of the Adelaide metropolitan area) shrink volumetrically thereby causing localised and differential settlement in the vicinity of trees and/or shrubs. These settlements are then transmitted to surface footing systems (i.e. strip beams and concrete rafts) to the extent that a gradual and ever-increasing loss of foundation support is imposed upon the footing system.

2.6

As the soil volumetrically shrinks the footing is affected in the following manner

- The soil subsides from immediately beneath the founding surface of concrete footing beams and/or slabs.
- There is a shear "down drag" caused when soil adhering to the sides of the footing beams exerts its downwards component of shrinkage.

The loss of footing support caused by a shrinking foundation then causes the footing system to carry its superstructure loads in cantilever action until such time as the footing no longer possesses sufficient strength or stiffness to remain level and a curvature, either concave or convex, forms and manifests in the superstructure construction as cracking in walls and ceilings.

2.7

In diagnosing building problems for householders the author is often asked why concrete paving slabs have "pulled away" from house footings.

The simple answer is that the soil surrounding such a dwelling has suffered from the horizontal component of volumetric soil shrinkage and the friction between the base of pavement slab and soil induces a lateral force pulling the slab away from the buildings. This minor form of damage is almost always observed on building sites where tree root moisture demand exacerbates soil drying occurring through normal solar evaporation.

2.8

In current day footing design analysis engineers calculate the potential for soil movement in the form of swelling and shrinking. Where trees are present either on the subject site or on neighbouring sites the anticipated increased soil movement likely to be caused by the presence of trees is also calculated and then added to the soil movement for the site without any trees present.

The cumulative effect of the soil movement for no trees present and the soil movement for trees present is then factored to arrive at a design soil movement which most usually leads to a considerable increase in dimensions of surface footings.

3. TYPICAL DAMAGE CAUSED BY TREE ROOT SOIL DRYING

3.1

It has been the author's experience that cracking in 80% of cases involving domestic dwellings and light commercial structures has been either wholly caused, or at least contributed to, by the effects of tree root drying shrinkage of foundation soils.

3.2

With respect to the predominant species of trees and shrubs causing building damage, Australian native varieties which tend to have rapid early growth rates and a high affinity for moisture head the list.

Exotic tree varieties which tend to be slower growing and which do not seem to have such a large demand for soil moisture tend to be at the lower end of the scale.

3.3

Typical building damage which has been encountered where trees are in close proximity to buildings is as follows

- Stepped diagonal and horizontal crack patterns in external walls, jamming of internal doors and windows and cracking across ceiling linings and in ceiling cornices where it is common to find gap formation between ceiling cornices and wall faces to which they are attached. (Refer Figs. 3, 4.)

- If a large tree is too close to a building then in some cases, albeit rather rare, tree roots can have an uplifting effect on building footings due to the volumetric displacement of foundation soil as major roots progressively grow and spread beneath the building. This type of damage tends to be characterised by V-shaped vertical cracking in the position of the offending root intrusion with the top of the crack wider than the base.

- The spread of tree roots can cause retaining walls to lean where the pressure exerted by the spread of roots applies an additional lateral force behind the wall.

- Branches of trees which overhang structures and which are severed during periods of high winds often cause impact damage to roofs and walls.

- Debris from trees such as leaves and twigs can cause roof downpipes to block up thereby causing an overflow of roof gutter water into eaves linings or possibly allow gutter overflow to cause ponding of water adjacent the footings thereby inducing soil heave in a localised sense which tends to cause vertical V-shaped cracking in walls wider at the top than at the bottom.

- Tree roots often enter sewer pipe installations at joints or splits in the pipes leading to eventual leakage and pipe blockage. This often causes cracking damage from soil heave.

3.4

There is another interesting aspect of the effects of trees on buildings which relates to the cutting down or removal of an existing tree or shrub.

After tree removal foundation soil is immediately left in a highly desiccated state with a high demand for moisture absorption (i.e. suction) of water. If water is then made available via rainfall or by garden watering then the soil will swell causing upwards heave of nearby structures. Engineers refer to this phenomenon as "rebound", or recovery, of soil. (Refer Fig. 5.)

Others have postulated that the tendency for rebound and recovery of structures can go beyond restoring structures to pre-tree affected levels to the extent that a secondary heave crack pattern would be likely to occur.

It has been the author's field experience that this is not what usually happens. In point of fact, the author has often recommended tree removal (or cutting down and poisoning) to arrest settlement cracking in structures caused by the tree drying effect. To this time, excellent results have been achieved in either stabilising or restoring structures so that eventual repairs remain permanent.

3.5

In cases where trees exist on a building site and are removed immediately prior to construction, the author has found it necessary to recommend excavation of a depression at the position where the tree root has been grubbed out and to then fill the depression with water at regular intervals each day for a period of approximately 10 days to induce soil rebound prior to the laying of concrete footings.

In cases where this has not been done, the writer has observed localised edge heaving of footings following the first winter period and/or lawn and garden establishment after the building is occupied.

Often the localised edge heaving will manifest as cracking in walls and/or ceilings.

3.6

There is one further case which requires consideration. On some building sites fully matured trees or shrubs are specified by owners, architects, or possibly landscape designers, to remain.

Engineers currently prepare designs attempting to take into account the effects of trees although owners are warned that state-of-the-art technology has not yet reached anything like the point where engineers can predict with confidence the actual effects of trees on a building in any given environment. The Australian Standard for the Design and Construction of Residential Slabs and Footings provides design advice for "*normal garden conditions and site conditions*". It specifically precludes the planting of trees too close to a footing although the Code is not specific with respect to safe planting distances in this regard.

The CSIRO, however, has produced a supplementary information sheet no. 10-91[6] titled "*Guide to Home Owners on Foundation Maintenance and Footing Performance*" which, under item 3 sets out the following recommended limits for the planting of trees near a structure.

- Class E sites d = 1.5 x mature height of tree.
- Class H sites d = 1 x mature height of tree.
- Class M sites d = 0.75 x mature height of tree.

4. FOOTING DESIGN AND TREES - THE FUTURE

4.1

As mentioned previously in this paper, engineers can thus far make only a "reasonable" prediction of how much the foundation soil is likely to shrink volumetrically beneath a structure due to the combined effects of climate, garden neglect and tree root moisture suction. It is only reactive clay foundation soils which change in volume with changes in moisture content causing structural deformation and cracking.

In many areas of Adelaide containing soils at the "extreme" end of the range of reactivity, there is an underlying stratum of stable weathered or solid rock.

The most recent thinking with respect to overcoming the effects of volumetrically shrinking soils is to revert to a piered type footing system ensuring that piers are founded onto the weathered or solid rock horizon and underreamed at the base (i.e. opened out to a locally larger diameter) to prevent the pier from uplifting so that it is effectively "anchored" beneath the clay layer(s).

4.2

When timber floored structures were popular a pier-and-beam footing system with piers bearing upon the underlying stable soil strata provided adequate protection against the effects of soil drying induced by tree root effects.

Today pier-and-slab type footing systems have been developed along the lines of suspended slab technology whereby a grid of piers with underreamed bases is founded on a stable soil stratum and then a stiffened slab is seated upon the piers with allowance for a "clear space" to accommodate soil swell which can occur if existing trees are removed.

The pier-and-slab footing systems currently developed as suspended slab systems easily accommodate soil shrinkage induced by tree root effects and because of the clear space left beneath these slab systems no superstructure damage occurs.

4.3

Two new and innovative pier-and-slab footing systems are the Tri-ped™ developed by the University of South Australia and SA Housing Trust and the piered Waffle Raft system developed by Koukourou Urban and Residential Engineers.

4.4

The Tri-ped™ footing resembles a three legged stool consisting of three piers (for small house shapes), a suspended floor slab and an air space between the slab and the underlying foundation soil.

The slab relies only upon support from the three piers and not upon the underlying foundation soil so that this type of footing is suitable for tree planting as volumetrically shrinking soils will not have any effect upon structural performance.

4.5

The piered Waffle Raft footing consists of a series of cast in-situ bored piers, underreamed at the base and founded upon a stable soil stratum featuring a suspended waffle slab set out with stiffening ribs at 1.2 metre centre-to-centre spacing with piers supporting each third rib intersection in both directions (i.e. piers at 3.6 metre centre-to-centre spacing in two directions at right angles in a regular grid framework).

4.6

There is also a newly developed screw-in foundation system (SIF) which involves the sinking by "self tapping" means of specially developed, corrosion resistant, circular hollow steel piers to a prescribed depth to provide support to a shallow stiffened raft footing above.

Although a clear space between bottom of footing and foundation soil does not form part of the normal design technique using this system, in the author's opinion it could be easily adapted to the construction of a clear space.

4.7

Another development which warrants consideration regarding the tree-footing interaction problem is the potential for using large collection trenches (i.e. soakage wells) on individual building allotments to collect surface and roof stormwater rather than conveying same to Council drains.

It is possible that the growth of trees and their demand for moisture could be satisfied by feeding from the soakage well area so that the accumulation of water on the site would not cause the reactive clay soil to swell.

While the author would not be prepared to recommend such an approach at this point in time future research may provide sufficient answers that will not increase the cost of surface concrete footings and yet be compatible with the growth of trees by adopting the soakage pit-tree growth approach.

5. SUMMARY

5.1

The Adelaide Metropolitan area extending north to Gawler and south to Willunga is predominantly underlain by reactive clay soil profiles of varying degrees of "reactivity".

The term "reactive" refers to the clay soil's propensity to change in volume with changes in moisture content.

Trees, especially Australian native species can, and do, extract significant volumes of moisture from clay soils leading to a net moisture deficit within the soil mass surrounding trees over a circular area of radius approximately equal to the height of the tree for a single tree. For a row or group of trees the zone of influence can extend to a circular area of radius approximately equal to 1½ to 2 times the height of tallest tree in the row or group.

5.2

The Australian Standard AS2870.1-1988 covering the construction of residential Slabs and footings does not give any specific guidance to designers with respect to taking account of tree root drying effects in foundation soil.

5.3

A specialist group called the "Footings Group" has been formed within the South Australian Chapter of the Institution of Engineers Australia.

This group has established a set of empirical design guidelines for a "best approximation" to the design of footings on sites where nearby trees would be likely to have an effect upon the structure.

5.4

The technology is available for engineers to be able to design footing systems that are suspended clear of the foundation soil by piering through clay layers to a stable (i.e. non-reactive) soil stratum so that a clear space exists beneath the base of the footing and the existing ground surface.

The current cost extra charged by builders to home buyers for the necessary additional work of piering and setting up void forms to create the clear space and also for the provision of flexible couplings to waste plumbing is in the vicinity of $9,000-12,000.

This is a significant extra for the home buyer to contemplate, however, if we are to design aesthetically pleasing and comfortable urban environments that will be tolerant of ad hoc tree planting then the community must be prepared for the attendant increase in construction costs to provide "tree tolerant" footing systems.

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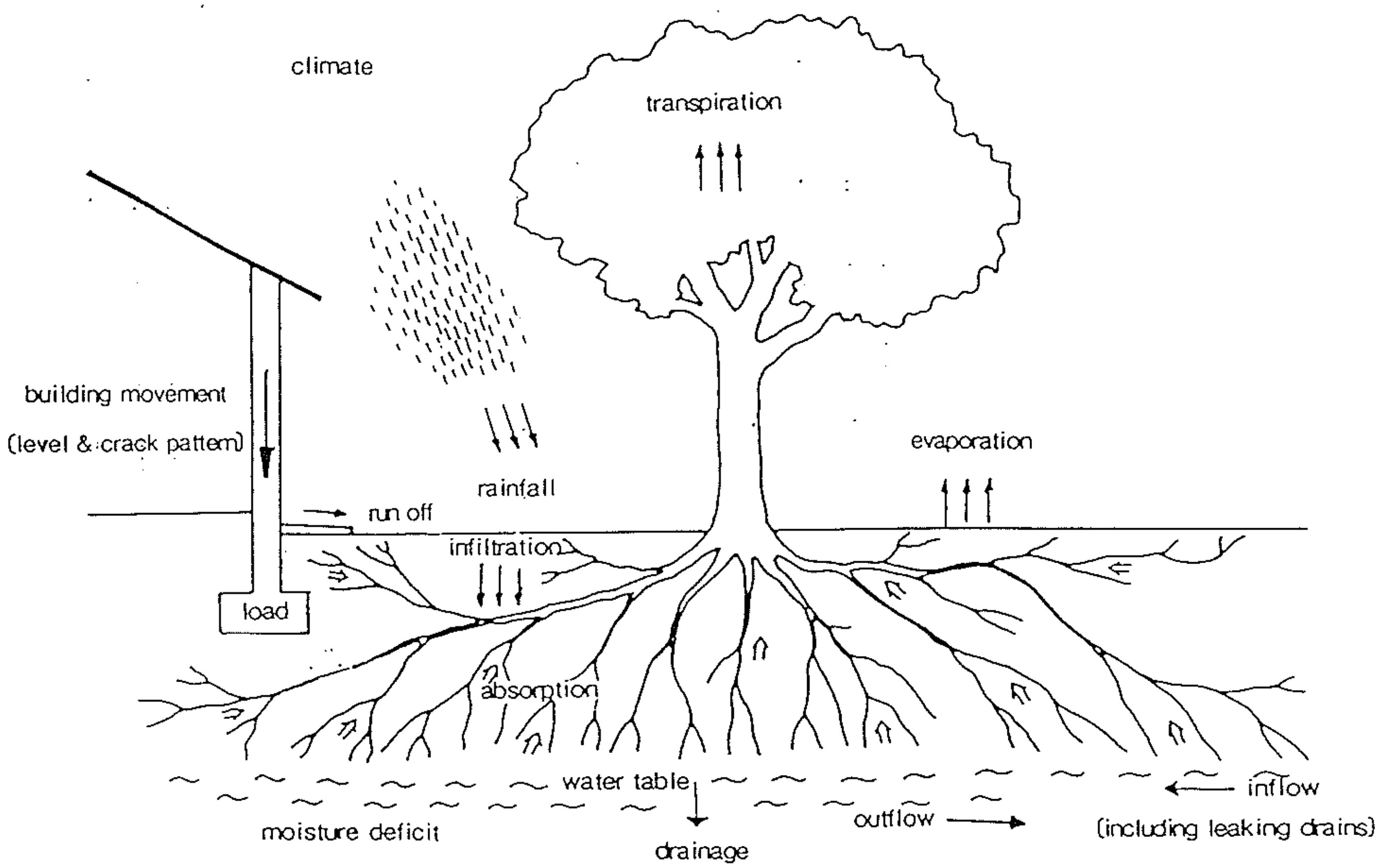


FIG. 1 : SHOWS EVAPO-TRANSPIRATION MOISTURE LOSS FROM SOIL (5)

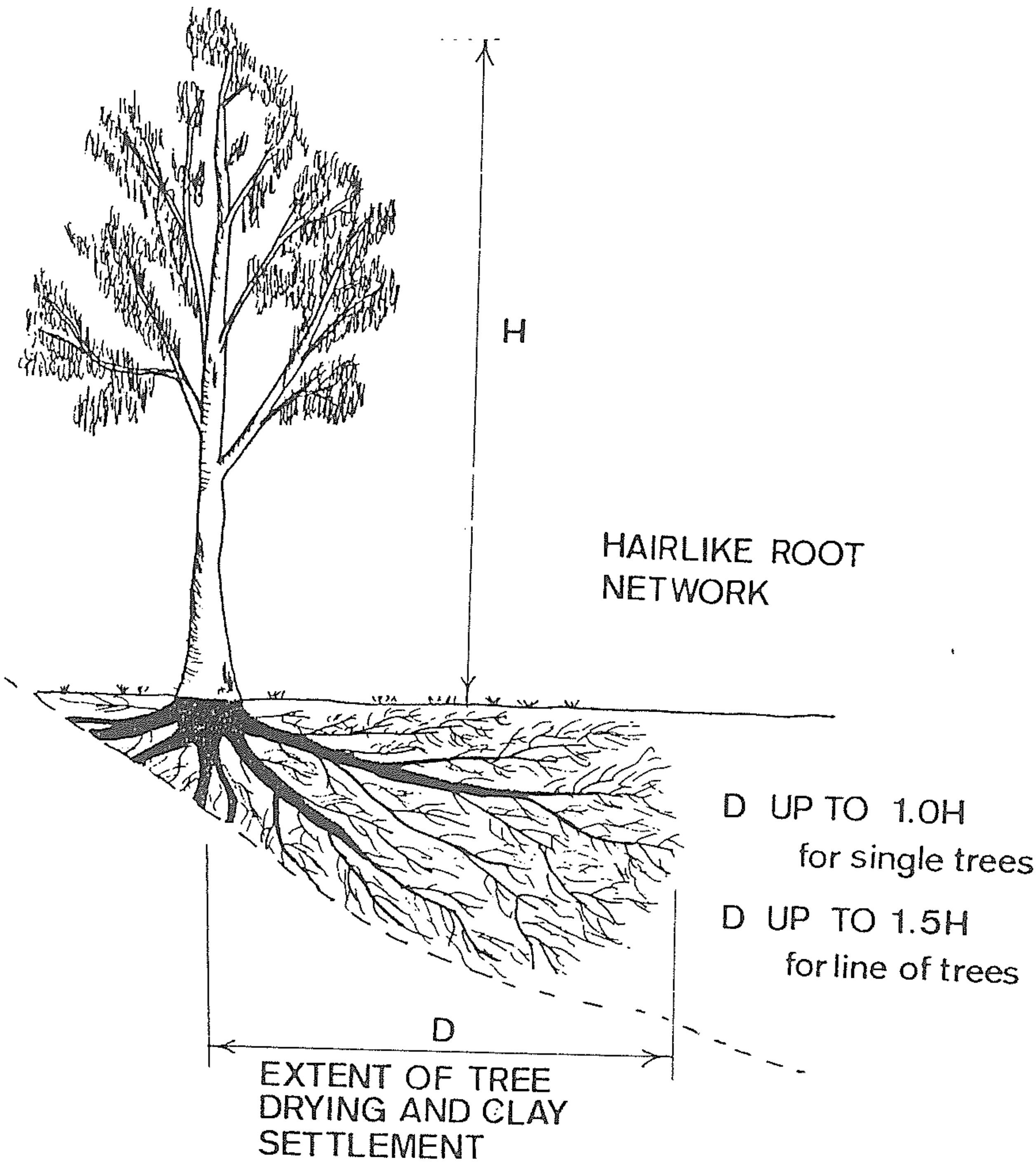
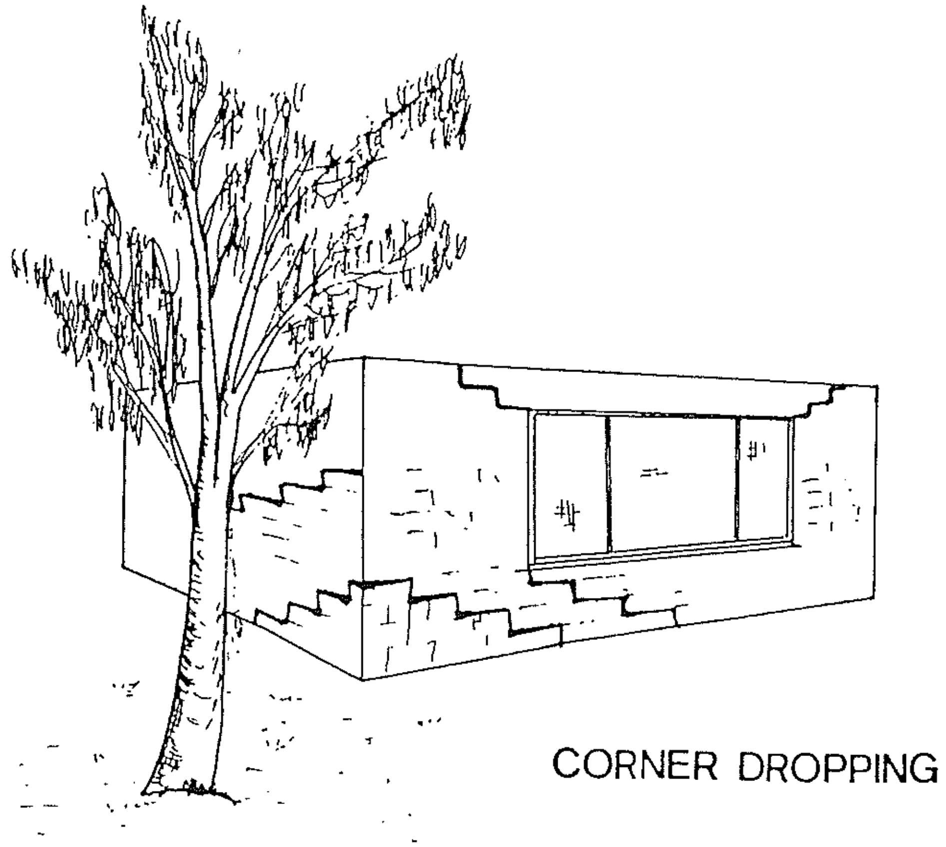


FIGURE 2: GENERAL TREE ROOT SYSTEM[1]



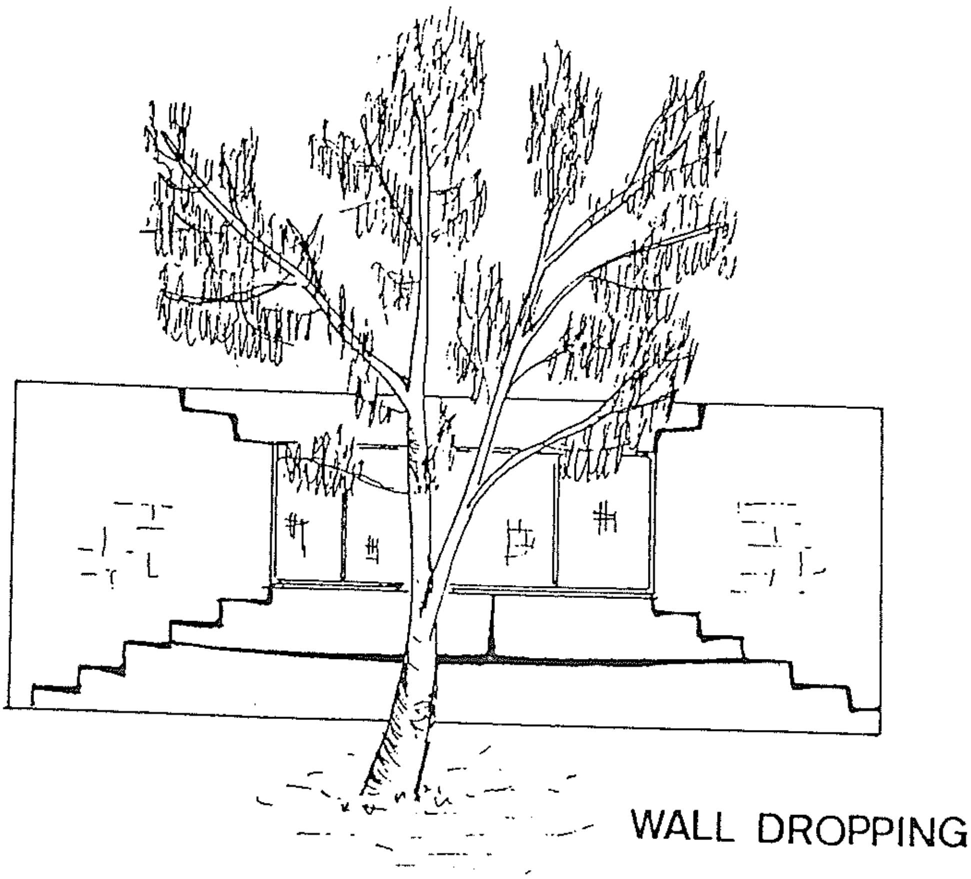


FIGURE 3: TWO MOST COMMON FORMS OF DISTRESS CAUSED BY TREE DRYING SETTLEMENT.[1]

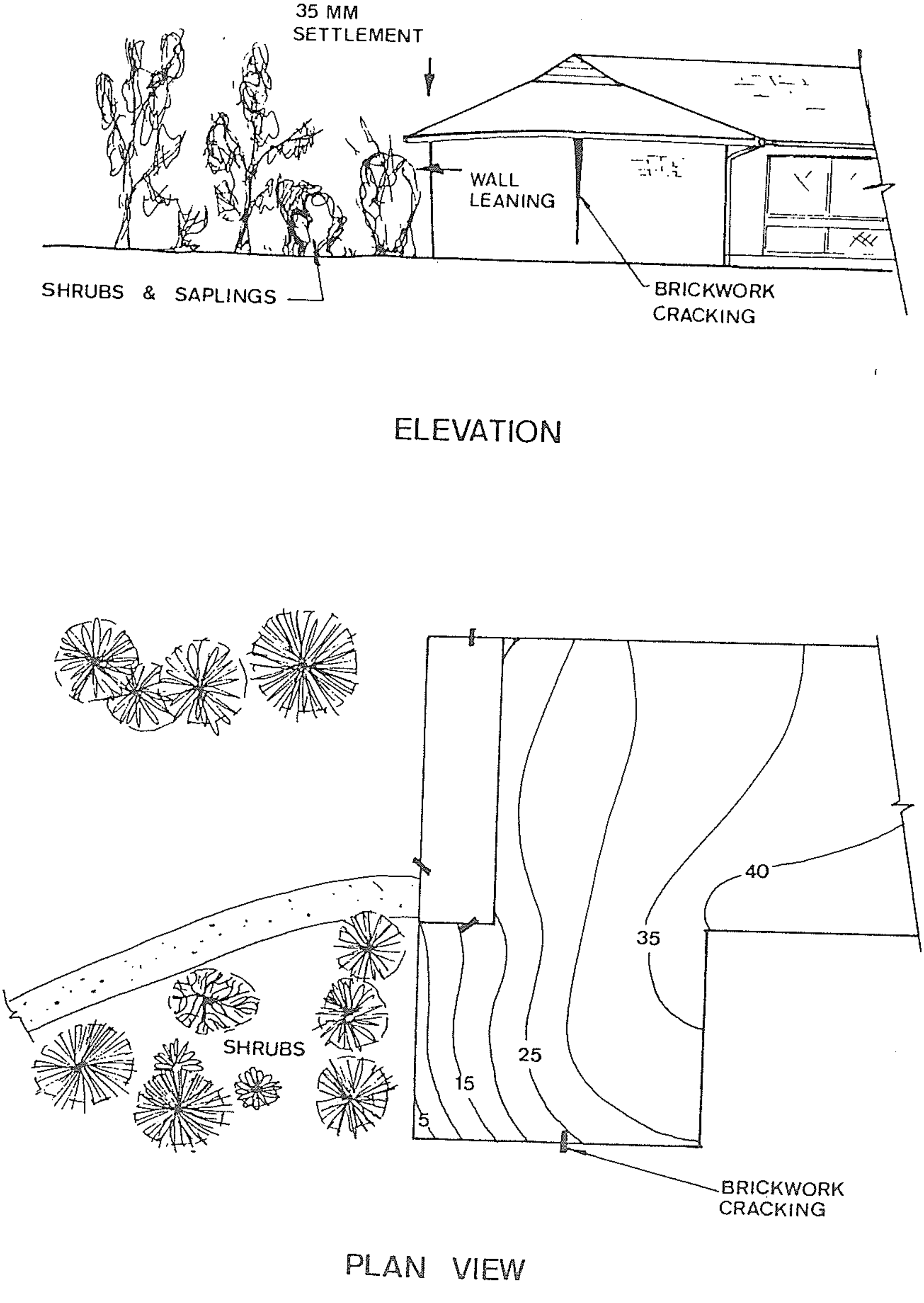


FIGURE 4: SHRUB DRYING SETTLEMENT [1]

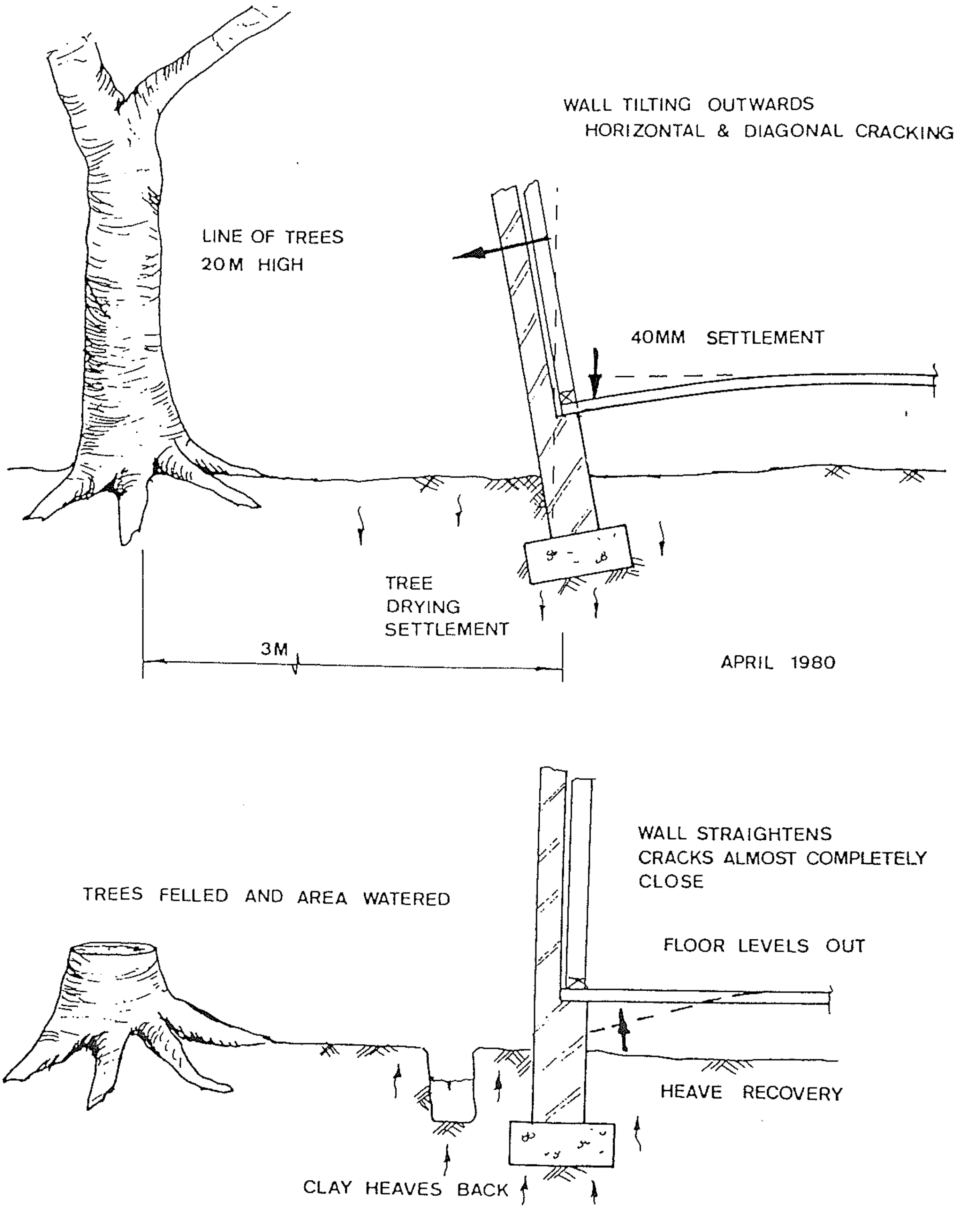


FIG. 5 : TREE DRYING SETTLEMENT AND 'REBOUND' RECOVERY.[1]

Informative Literature

Garden Layout – Trees to Avoid

An attractive garden layout is an essential aspect of the development of your new home

As well as beautifying the surroundings and adding value to the property, it introduces an element of climate control and provides as much privacy as you want – you set the levels through landscape planning.

But there are pitfalls, especially with regard to trees. The right tree, planted in the right place on the block, can be a valuable and growing asset. But the wrong tree in the wrong place – for instance, a tree with a massive root structure planted alongside the house – can cause heartbreaking structural damage and other problems which are difficult and costly to remedy.

It makes good sense in this important area, as with so many others to do with housing, to get professional advice. You'll probably get it for free and it will save you a lot of money in the long run

Nurserymen will give you information about any particular tree's root structure and growing patterns, before you buy.

The Board of Works will tell you where your sewerage and drain pipes are so you can avoid planting trees over or close to them.

Homeowners are responsible for maintaining house connection sewers up to the point of connection to the MMBW's sewerage network. So you will have to foot the bill if a licensed plumber or drainer has to be called in to clear the sewer of tree roots – and it can be an expensive job!

The CSIRO's Building Research Division will give you advice on trees and foundations: where to plant, what to plant, what trees to avoid and the problems you're likely to strike if you plant particular trees in certain types of soil.

The accompanying table of tree species which should not be planted near a building was prepared by staff at the division who have seen many examples of the damage trees can do.

Damage to houses by trees generally develops after long dry and hot periods (typically for Melbourne, in the months from February to May). Because the soil is so dry, the trees expand their root systems, at ever-greater distances from their trunks, in their search for moisture for survival.

When trees remove moisture from clay soils, the soils shrink, causing buildings on them to settle. That movement causes structural damage, usually in the form of ugly cracks in external and internal walls. Most of Melbourne has clay soils so most areas are susceptible to the problem. Tree roots may also damage building footings by direct physical contact

Among other things, clearing trees from a site eliminates nature's moisture-removing mechanism. During the wet months, rainfall on clay can cause significant soil expansion known as 'soil heave' which can damage a building as much as the trees might have!

If you are planning a garden layout, the MBAV's Technical Department recommends that except in extremely sandy conditions you observe these precautions:

- If possible, lay concrete paths hard against the wall, with a fall away from the house to a stormwater discharge point;
- If you decide to put garden beds against the walls, make sure water cannot pool anywhere – and install adequate agricultural drainage,
- If your layout includes lawns right up to the house, make sure that filling is built up against the walls but not above the damp course or over ventilators because this can cause rising dampness and lack of ventilation. Ensure that pooling cannot occur and again, it is best to put in agricultural drains

Species Of Trees To Avoid

Common Name	Mature Height (m)
Yellow gum	4.5 to 7.5
Athel	to 6
Pepper	6 to 15
False acacia, Black Locust	9 to 15
Weeping willow	9 to 15
Claret Ash	9 to 15
Desert Ash	9 to 15
Yate	9 to 18
Candlebark	9 to 30
Manna gum	9 to 60
Swamp sheoak	12 to 15
River sheoak	12 to 30
Lemon-scented gum	to 15
Smooth-barked apple	15 to 24
Sugar gum	15 to 30
Southern silky oak	15 to 30
Plane	15 to 36
Spotted gum	18 to 30
English oak	to 20
Black poplar	to 24
English elm	to 30
Fig	to 30
Pine	to 30
River red gum	24 to 30
Norfolk Island pine	30 to 60
Tasmanian blue gum	30 to 60
Karri	to 60
Cedar	variable
Date palm	variable
Cypress	variable

UNIVERSITY OF SOUTH AUSTRALIA

SOUTH AUSTRALIAN HOUSING TRUST

TRI-PED™

TRI-PED™ FOOTING

Revolutionary Design

Introduction

The University of South Australia, in collaboration with the South Australian Housing Trust, has developed a revolutionary new footing which dramatically reduces cracking caused by the action of expansive clay soils.

Named TRI-PED™, the footing resembles a three legged stool and consists of the following simple components:
- three piles;
- a suspended floor slab; and
- a small air space between the slab and the underlying soil.

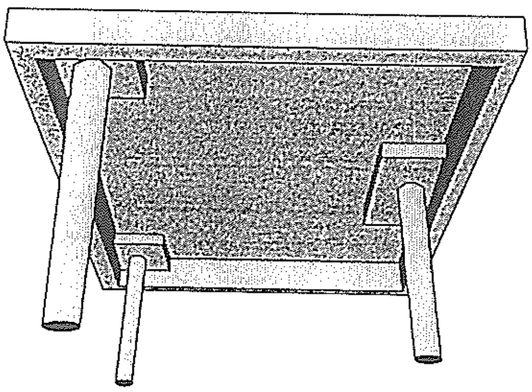


Figure 1 - Perspective view of underside of TRI-PED™ footing

Whenever cracking due to ground movement is a problem, TRI-PED™ offers an unbeatable, structurally determinate solution by combining the power of modern computer aided structural analysis with the simplicity of the tripod.

The TRI-PED™ was invented by A/Prof Mark Symons from the University of South Australia's Structural Materials and Assemblies Group (SMAG). It offers a new and unique answer to many of the difficulties experienced by residential homes and other small structures which are built on highly expansive soils or problem sites. TRI-PED™ represents the most momentous advancement in footing design and construction for many years.

Benefits

The TRI-PED™ footing provides structural, environmental, social and strategic benefits.

Structural
The TRI-PED™ footing is
- independent from the main causes of severe cracking and distortion of houses
- versatile and adaptable, and
- suitable for use on sloping sites, reclaimed land and in areas of poor soils, including loose sands, uncontrolled fill, silts and muds

The TRI-PED™ is appropriate for masonry, light weight or tilt-up construction, for single and two storey dwellings and for new forms of housing construction

Environmental
The significant environmental benefits are:
- unrestricted planting of trees and shrubs and general landscaping adjacent to houses
- planning and development of sites previously considered uneconomical or not feasible
- elimination of chemicals for termite protection, and
- easy integration with innovative methods of on-site water conservation.

Social
TRI-PED™ has the following benefits:
- it is suitable for courtyard style developments and urban infill projects allowing trees and gardens to be placed closer to houses, and
- home owners and potential home buyers can be more secure in the knowledge that their house will not crack due to soil movements.

Strategic
Strategic and financial advantages include:
- reduction of long term maintenance costs
- extended life of building
- cost reductions compared with other footing systems design to the same requirements, and
- maximisation of assets.

Principles of Design

The TRI-PED™ footing achieves its superior performance and utility through the application of a few simple principles of design. The result is a cost effective, radical new design which eliminates problems experienced with conventional footings. The design principles are:

- the slab is always clear of the underlying soil
- the slab is sufficiently stiff to limit deflection
- the three-point support results in integrity if there is differential movement, and
- all loads are transferred through the piles to an acceptable depth

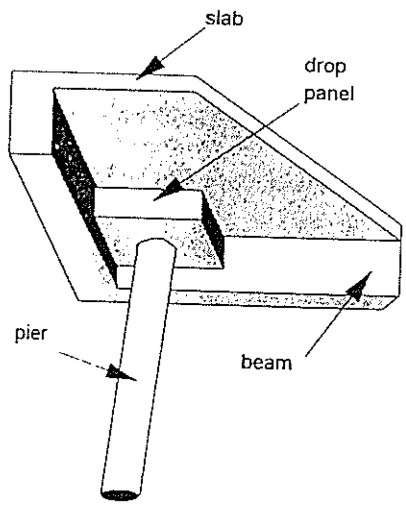
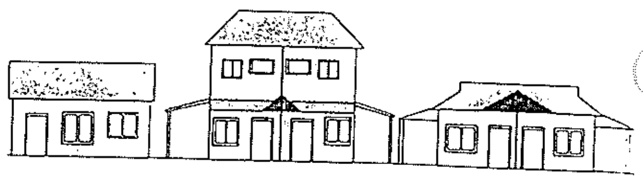


Figure 2 - TRI-PED™ Components

Proven Track Record

A full scale, 90 square metre, rectangular, brick veneer house was built on extremely reactive soil at Gilles Plains, South Australia, to demonstrate the application of the TRI-PED™ footing.

The prototype footing was test loaded and the results confirmed both the structural adequacy and the design techniques. The house was completed and occupied in early 1993. It is being monitored regularly and, as predicted, minimum movement and no cracking of the house has been detected.



Following the complete success of the prototype, the second phase of development was undertaken. A group of various house types was constructed for the purpose of monitoring and comparing the long term behaviour of the TRI-PED™ footing with stiffened raft footings. The houses are located in the rapidly developing Adelaide suburb of Northfield, which is notorious for its extremely reactive clay soils and excessive ground movement.

The village, made up of single-storey detached, single-story attached and two-storey attached dwellings, was completed in 1994. Ongoing monitoring of the buildings indicates that the TRI-PED™ footing delivers all the expected benefits.

Collaboration between the University of SA, as designer, and the SA Housing Trust, as an experienced construction authority, has resulted in the footing's practical implementation and ongoing development. The partnership has been assisted by an Australian Research Council Collaborative Grant.

The TRI-PED™ is subject to an international patent application under the name 'Three Point Support Footing Means and Method'.

Future Development

Further development of the TRI-PED™ will focus on its application to other innovative building technology. For example, subsequent research has commenced in the areas of:

- new and more radical building designs
- modular arrangements for larger buildings; and
- extension of the system for use with integrated building construction and design.

International Significance

The international demand for improved housing has brought with it the demand for an efficient footing system for buildings on reactive soils. Reactive clay soils exist in most countries in the world. The TRI-PED™ footing represents a simple, elegant solution to this world-wide housing industry problem

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