TREES: A ROOT CAUSE OF ROCKFALL

Anthony (Tony) Meyers
Principal and Senior Rock Mechanics Engineer, Rocktest Consulting, Adelaide

ABSTRACT

This paper discusses the general processes by which trees cause damage to rock slopes. It discusses the actions of root elongation, which can cause root jacking, and trunk expansion. It discusses research aimed at establishing a relationship between root diameter and the forces applied by roots. The results of this research are inconclusive and at this stage provide little useful information for local geotechnical design purposes. It is concluded that, in general, trees should be removed from bare rock slopes adjacent to public infrastructure where there is greater than a moderate risk associated with rockfalls unless other measures are taken to reduce the risk (e.g. rockfall fence or mesh).

1 INTRODUCTION

Recently, a colleague was about to scale loose rocks from a local rock face that is popular with rock climbers and abseilers. Over the last few years the site had experienced a dozen or so falls of rocks ranging in size from 100 mm to 500 mm. Scaling was required to reduce the risk associated with further rockfalls. As he was about to begin scaling he was told by the Site Manager to ignore the thirty or so large and small eucalypts and casuarinas actively growing within discontinuities on the face on the grounds that “they [were] the only thing holding it together”. Similar recent experiences by the Author suggest that this belief regarding the contribution made by trees to rock slope stability is common among personnel working for local councils and public authorities who are responsible for public safety.

The misguided and potentially dangerous lack of understanding of the influence of trees on rock slope stability is in part due to the scarcity of information available that presents the relevant issues in a manner comprehensible to the lay person and to persons involved in geotechnics. The former group need to understand the issues so they can make appropriate management decisions. The latter group needs to understand the issues so they can advise appropriately and if necessary allow for the affects of trees in stability analyses.

This technical paper is part of an ongoing program that aims to address this lack of information by bringing together some of the relevant issues discussed elsewhere. The information will eventually be condensed into a format suitable for distribution to relevant parties.

2 LOCAL EXPERIENCES

Approximately 40 rockfalls involving greater than 5 m^3 of rock occurred on road, rail and cycle corridors and around public recreational areas in the Adelaide Hills between 2001 and 2006. The majority of these falls occurred on, or soon after, days when rainfall exceeded 25 mm. There is no doubt that the presence of the rain either directly, as overland flow or by its progressive erosive effects, was a major contributor to the majority of the instabilities. However another contributor was trees; their roots were present on the sliding and/or release surfaces at 44% of the sites (Figure 1) and a further 21% of the sites had large trees within 10 m of the instability (Figure 2). This statistic alone does not prove that the roots were a contributor to the instability, however geotechnically similar sites adjacent to those from which rockfalls had occurred and upon which no trees were present were not associated with rockfalls and did not show significant evidence of instability.

Figure 1. Thick tree root which contributed to a 4m^3 wedge failure.

Figure 2: Mature pine trees growing on a 7 m high rock slope, 10 m from the site of a 5 m^3 toppling incident.

This paper is concerned with those rock slopes upon which potentially large, woody trees grow that have roots that extend into the discontinuities. Examples of tree varieties common to the Adelaide Hills that are often associated with this behaviour include *Eucalyptus sp*. (e.g. *camaldulensis*, *leucoxylon, porosa, fasciculosa, viminalis, baxteri, obliqa, odorata*), *Allocasuarina sp*. (e.g. *verticillata, muelleriana*), *Pinus radiata* and olive (i.e. *Olea europae*).

3 FORCES ON AND IMPOSED BY TREES

Consider a single tree growing out of the face of a rock slope a gust of wind blowing through its canopy. The dominant forces applying to the scenario fall into two categories; the horizontal forces and moments caused by the wind and the vertical forces and moments caused by gravity acting on the eccentric trunk and canopy. To assign values to these actions, Eurocode 1 (AENOR, 1998), Niklas (2002) and Horacek (2007) make the following assumptions:

- The wind forces acting on the trunk of the tree are negligible compared to those acting on the canopy and can therefore be ignored.
- The sum of the wind forces acting at each point on the canopy can be replaced with a single point load acting at the centroid of the canopy.
- The tree acts like an elastic cantilever rigidly fixed at one end and free to move at the other. The cantilever is assumed to have a circular cross section of uniform diameter. The point load acts at the distal end.
- All loading is static and hence the affects of dynamic loading are ignored.
- To calculate the self weight of the tree, the weight of the canopy is represented as a point vertical force applied at the centre of gravity of the canopy.

The horizontal force caused by the wind is defined as:

$$F_{wind} = C_{wind} \text{ x } \rho/2 \text{ x } U_{wind}^2 \text{ x } A \quad \textbf{(1)}$$

where F_{wind} is the wind induced horizontal force;

ρ is the density of the air which depends on the pressure and humidity of the air, temperature and height above sea level;

U_{wind} is the wind velocity at a certain height above ground level which is dependent on the geographical setting, topography, season, wind path, gustiness and proximity to large structures;

A is the approximate surface area of the tree exposed to the wind;

C_{wind} is to the dimensionless aerodynamic drag factor or coefficient of wind resistance which describes the ability of the tree to flex in order to diminish the force of the wind. It depends on the genus and species, the shape of the canopy, wind velocity, etc. It is not a constant value but tends to range between 0.1 and 0.4 (Sinn and Wessolly, 1989; Sterken, 2005).

A variation of Equation 1 introduces a pseudo-dynamic multiplier into the equation that makes some allowance for the increase in the horizontal force due to the swaying motion of the tree. The factor is a function of the natural frequency of the tree which is a function of the type of tree, its height and the mass of its trunk. The value of the multiplier tends to range between 1Hz and 20Hz.

Ennos (1999) found that the thin trunk of a young tree can bend over in strong winds thereby reducing both the wind drag and the height of the centre of pressure of the force. More mature trees in contrast tend to act more like rigid columns. Although they can reduce drag by reconfiguring their canopy they cannot reduce the height of the centre of pressure. The result is that their base tends to experience larger forces and moment than do the bases of younger trees of similar initial height. Young trees are therefore less likely than mature trees to be snapped or uprooted by wind loading, thereby damaging the rock slope, especially during prolonged periods of cyclic loading by strong winds.

As the wind blows on the tree, the canopy usually becomes eccentric (Figure 3). Under these conditions, the vertical force resulting from gravity can be estimated from the following equation (based on Horacek, 2007).

$$F_v = g\left(m_t + m_c \cos\left(\operatorname{atan}\frac{e}{h_z}\right)\right) \quad \textbf{(2)}$$

where F_V is the vertical force;

g is gravity;

m_t and m_c are the masses of the trunk and the canopy respectively;

e is the eccentricity to the centre of gravity of the trunk and the canopy;

h_z is the height to the centre of gravity of the trunk and the canopy.

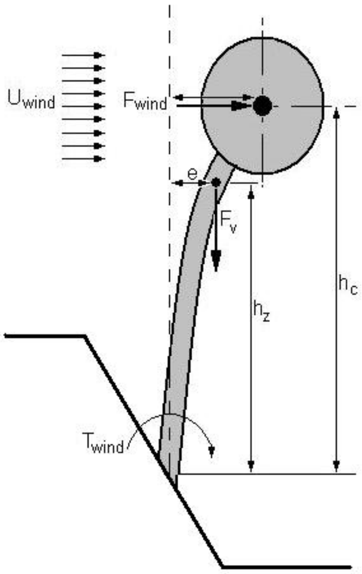

Figure 3: Schematic of a tree on a rock slope subjected to wind loading.

The force of the wind and the eccentricity of the canopy apply bending moments which are a maximum at the base of the trunk. The sum of these moments can be defined as follows (Peltola and Kellomaki, 1993; Horacek, 2007):

$$M_w = F_{wind} \times h_c + F_V \times e \quad \textbf{(3)}$$

where h_c is the approximate height of the centre of gravity of the canopy above the base of the trunk;

There is also moment acting at the base of the trunk caused by the wind acting on the eccentrically shifted canopy which can be defined by the following equation (Horacek, 2007):

$$M_{wind} = F_{wind} \times e \quad \textbf{(4)}$$

The sum of all moments moves the centre of gravity of the tree over the hinge point; a condition required for uprooting to occur (Ray and Nicoll, 1998). Uprooting is resisted by bending of the trunk and the following components of root anchorage:

- weight of the root/soil/rock ball;
- tensile strength of the roots on the downwind side of the tree;
- bending strength of the root hinge;
- frictional resistance of the root system on the downwind side of the tree.

If the total uprooting moment exceeds the resistive bending moment at a particular angle of tree deflection the root system may give way allowing the tree to collapse and bringing with it the rocks surrounding the trunk.

However, Sinn and Wessolly (1989) found that most healthy trees tend to be so well anchored that they are able to withstand all moments applied unless rare conditions occur (e.g. hurricanes). It is only when root elongation is inadequate, allowing the roots themselves to displace in response to the applied loading, that trees tend to overturn. However, it is this latter occurrence that is relevant for many trees that grow on rock faces. Many of them are shallow rooted and hence ongoing resistance to the uprooting moments can only be achieved if their roots can continually elongate as the tree grows. To do so, the roots must either displace the rockmass, a process referred to as "root jacking", or seek out paths in other discontinuities.

4 ROOT JACKING

To ensure a tree can continue to grow, its relatively thick primary roots and finer lateral roots must themselves grow. According to Misra (1997) and FEMA (2005) this process enables the roots to:

- respirate, with a continual flow of oxygen to the root tissue from soil pores;
- take up water via osmosis through the root tissue which requires an ongoing supply of soil pore water;
- take up elements and nutrients through the process of adsorption and absorption, which requires the root system to continuously renew the soil/root interface;
- store nutrients during the dormant period and
- support and anchor the tree to the medium into which it is growing.

For these processes to occur, the roots must continually elongate by following pathways of interconnected voids. If alternative growth paths are inaccessible the root will exert forces on the walls of the discontinuity. Misra (1997) found that the size of the forces will depend on the characteristics of the tree, the root and the external environmental conditions. The characteristics of the root are their osmotic potential, the extensibility of their cell wall and the pressure they can exert on their walls (Dexter, 1987). The external conditions are the moisture content within the discontinuity, localised rockmass strength and temperature (Whalley *et al*. 1994).

Roots exert pressure in both the axial and the radial directions as they elongate. FEMA (2005) noted that as the root elongates only root tissue within about six root diameters behind the tip is involved with force generation. The tissue further back behind the tip acts as an anchor to support the base of the root against the soil. If the radial pressure is greater than the rockmass strength, root jacking can occur. FEMA reported that long, smaller diameter roots are more likely to cause damage than are short, thick roots which generate significant force but cause minimal radial movement. The researchers noted that a root will tend to minimise the length over which the elongation force is expressed, thereby reducing its potentially destructive nature. When water supply is short, up to one third of the root's diameter may be sacrificed to facilitate elongation thereby increasing the likelihood for jacking to occur.

If the rockmass strength is less than the root pressure, the rate at which the root elongates will decrease proportionally to the increase in the pressure that the root must exert to grow. Root growth will just about cease where the rockmass strength is similar to the maximum pressure the root can exert. If the rockmass strength is such that a primary root can "squeeze" no further into a small rigid discontinuity, the number and/or length of the lateral roots may increase to satisfy some of the demands of the tree. The result may be the development of a dense root mass within the discontinuity that takes maximum benefit from the limited space available. It is common for such a mass to be seen on slip surfaces after a rock has fallen. However, as noted by Misra (1997), a restriction in the growth of a primary root may eventually restrict all growth in its lateral roots and the root system may eventually die.

Roots do not keep on elongating for the life of the tree. Niklas (2002) found that the rate of elongation decreases with the age of the tree. Hence, the susceptibility of a tree, and hence the rockmass around it, to fail as a result of wind loading will often increase as the tree matures and grows in mass and height. Some tree varieties are less susceptible than others to the maturity/instability relationship.

5 ROOT PRESSURE MEASUREMENT

In 1893, Pfefffer was the first researcher to successfully measure the forces applied by roots. However, since then there have been few significant advances in the tedious techniques required to measure these forces either in the field or the laboratory (e.g. Bengough and MacKenzie, 1994). There has therefore been a relative scarcity of research carried out in this area considering the vast amount of research that gets carried out on other aspects of tree growth.

One study of relevance was that by Misra (1997) who measured the maximum axial root growth force imposed by the primary roots of eucalypt seedlings. The results indicated that that the force, F_{max} (N), could be expressed in terms of the root diameter, d (mm), by the equation:

$$F_{max} = 0.19d^{2.94} \tag{5}$$

A typical 2 mm primary root tip could therefore generate approximately 1.5 N of force which is equivalent to lifting 150 g of mass. FEMA (2005) reported that pressures at the tip of an axial root can be significantly higher than that reported by Misra with values ranging up to 15 MPa, although they noted that 1 MPa is most cited. Even at the lower range, a 2 mm diameter root tip could therefore generate approximately 3 N of force which is equivalent to lifting 320 g of mass.

The cited works are invaluable for highlighting the growth characteristics of roots and the relationships between their diameter and the forces they impose on the growing medium. However, the results are not directly relevant for geotechnical design purposes for the following reasons.

- Research carried out under controlled conditions in a laboratory (e.g. Misra *et al*., 1986; Walley and Dexter, 1993) has generally been based around fast-growing, soft-rooted plants (e.g. peas, *Pisum sativum* and lupins) which are not generally associated with instabilities in rock, rather than on slower growing woody trees.
- Results from research on woody trees (e.g. *Eucalyptus sativum* and *grandis, Quercus robur, Pinus radiata, Conifer sp., Prunus serotina etc.*) tend to be of more relevance to geotechnical design. However, for practical reasons it has still been carried out on seedlings. There is insufficient evidence that the non-linear force/diameter relationships (e.g. Equation 5) determined in this research are relevant at the larger diameters associated with instabilities in rock.
- Field based research on mature trees has tended to be aimed at assessing the potential for specific trees or varieties of trees to collapse. This research often has involved the application of staged loads to the canopy of the tree, through a system of pulleys, wire ropes and load cells and subsequent measurements of trunk deformation. While the results of this type of research have indicated the stiffness and collapse potential of the particular tree being tested, it generally has not applied sufficient force to test the response of the root system to excessive loading; the characteristic of most relevance to the current study. Nor have the results necessarily been relevant to different individual trees or trees of different genus and/or species that are growing in different environments. In particular they have not tended to consider the load/deformation responses of trees growing on the faces of rock slopes.

In lieu of suitable relationships being available that are relevant for local geotechnical design purposes, it was considered worthwhile to collect data on mature local trees that are causing root jacking on rock slopes. However, it soon became obvious that there was a significant problem locating suitable sites. There is no shortage of sites where root jacking has caused rocks to fall or slide from the faces. However, these sites were of no use for this study as the volumes of the rocks involved could not be definitively assessed, nor could their mode of failure or their spatial relationships to the roots involved. Because a root's elongation occurs behind an exposed face, it was difficult to locate sites where jacking is currently occurring; a rock needs to have been jacked a significant distance for its displacement to become obvious. It was therefore possible to collect data from only 35 sites which is an insufficient number to be a statistically representative sample set.

Field Data Collection

The following data were collected at each of the 35 sites:

- GPS location and a description and sketch of the root jacking scenario.
- Tree type, whether it is dead or alive, an estimate of its height and the diameter of its trunk at a height 1m above the surface.
- The location of the tree relative to the block and the slope face (e.g. whether the tree is growing in the discontinuity at the rear of the block, in another discontinuity, behind the crest etc.)
- Characteristics of the discontinuity containing the root (i.e. angle of dip, width, roughness, moisture and infill).
- Mean and maximum diameter and length of the root.
- Location of the root relative to the block (i.e. whether the root is under a particular edge or surface or behind the block.)
- Width, height, length, type and weathering characteristics of the rock being jacked. These characteristics were used to estimate the mass of the block.
- Mode of displacement of the block (i.e. planar sliding or tilting)

Table 1 summarise some of the characteristics of the sites.

Table 1: General characteristics of field sites.

	Number			**Tree height (m)**			**Root diameter (mm)**			**Block Mass**		
	Sliding	Lifting	Total	Min.	Mean	Max	Min.	Mean	Max	Min. (kg)	Mean (t)	Max (t)
Eucalypt sp.	17	2	19	2	6	13	8	67	200	26	3.6	13.3
Other sp.	15	1	16	2	5	12	10	56	120	56	2.1	13.5

Other varieties include predominantly *Casuarina sp*. and *Pinus sp*.

Figure 4 shows the heights of all tree types plotted in terms of the diameters of their trunks. Lines of best fit were added to various forms of the plot and their regression coefficients are listed in Table 2. The results suggest that there are strong correlations between variability in the heights and variability in the diameters. This result is not unexpected as the higher the tree, the greater the forces and moments expected and hence the thicker the trunk required.

In general, the more mature the tree, the greater the number of roots and the greater the mean diameter of all roots. Any one of the roots could be involved in jacking. The diameter of a particular root involved in jacking would not be expected to be equivalent to the mean diameter of all roots; it could be much smaller or much greater or anywhere in between. In addition, the diameter of the root will vary along its length. Hence, its diameter at the point of jacking would not be expected to be the same as either the mean diameter of the root or the mean diameter of all roots. For these reasons, a low correlation between the height of a tree and the width of its root at the point of jacking would be expected.

To test the above hypothesis, lines of best fit were added to various forms of Figure 5 and their regression coefficients are listed in Table 2. The results indicate that there is a moderate correlation between the variability in the parameters. This unexpected result may be explained by the conclusions of Misra (1997) who, citing the work of several researchers (e.g. Bengough and MacKenzie, 1994), found that a root under high mechanical stress (e.g. within a discontinuity) will increase in diameter in order to keep on elongating. The increase in diameter applies a force to the walls of the discontinuity which can eventually cause jacking. FEMA (2005) noted that the increase in diameter may be restricted to just the section that is experiencing the stress. As noted in Section 4, the maximum pressure that a root can exert is a function of the characteristics of the tree. A large healthy tree with a mature root system would be expected to have roots that are capable of exerting a greater pressure than could the roots of a smaller tree. Hence, as suggested by Figure 5, there may be some tenuous relationship between the height of a tree and the diameter of the root that causes the jacking.

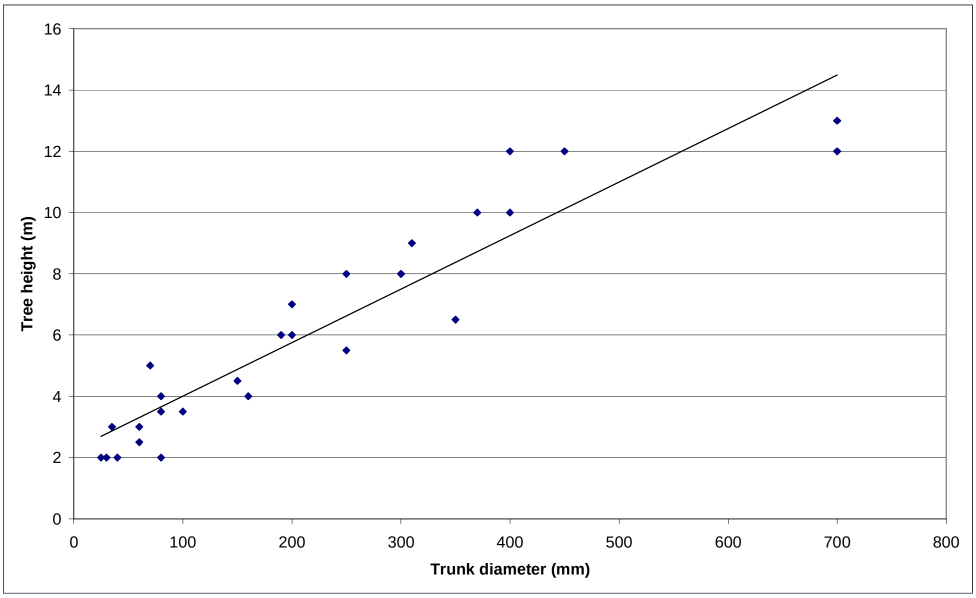

Figure 4: Height of all trees in study plotted against the diameter of their trunk 1m above the ground surface.

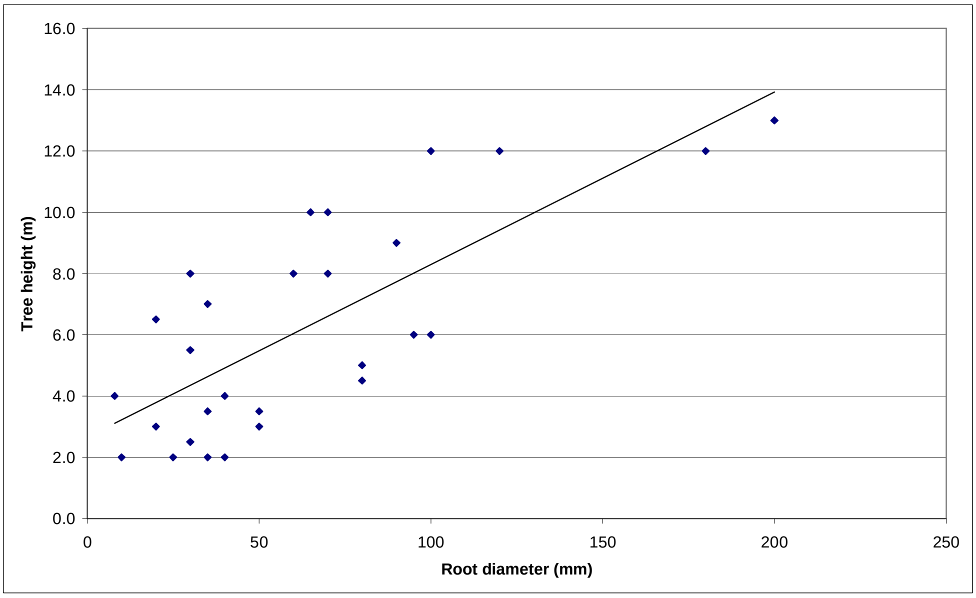

Figure 5: Height of all trees in study plotted against the diameter of the root causing block displacement.

Table 2: Regression coefficients applicable to each data set and relationship.

	Coefficient of determination, R^2		
	Eucalypt sp.	**Other sp.**	**All sp.**
Tree height vs trunk diameter	0.91	0.95	0.87
Tree height vs root diameter	0.55	0.81	0.57

The aim of the project was not to obtain a relationship between root diameter and root force, for it is not possible to do so using this approach. Just because a specific root has exerted a particular pressure does not mean that it could not have exerted a higher pressure if it had been required to do so. The aim of the project was just to obtain an indication of the upper bound of forces that had been applied by the particular trees studied.

Referring to Figure 6, the force required by the root for it to overcome the shear strength of the plane and cause the block to slide was estimated using the equation:

$$F_{r(s)} = \frac{W\,(\cos\theta \tan\phi_r - \sin\theta)}{\cos\alpha \tan\phi_r + \sin\alpha} \qquad \textbf{(6)}$$

where $F_{r(s)}$ is the force applied by the root to cause sliding;

W is the vertical force resulting from the mass of the block and gravity;

ϕ_r is the residual friction angle of the discontinuity. In this study ϕ_r was defined in terms of Barton and Choubey's (1977) non-linear relationship which is a function of discontinuity roughness, intact rock strength, normal stress and basic friction angle. Cohesion was assumed to be zero.

$\alpha = 0.5\,(\beta - \theta)$ where θ is the dip angle of the sliding surface and β is the dip angle of the plane behind the block.

In the study the term "tilt" rather than the term "topple" is used. The latter term is used generally to define the scenario where block displacement is associated with the weight vector falling outside the base of the block. In the cases considered in this study, displacement occurs as a result of the root lifting an edge of the block, usually the rear edge. This action can cause a state of toppling but does not necessarily do so. Referring to Figure 4, the root force required to cause tilting was estimated using the equation:

$$F_{r(t)} = \frac{0.5\,W\cos\theta\,(D - H\tan\theta)}{D} \qquad \textbf{(7)}$$

where $F_{r(t)}$ is the force applied by the root to cause tilting;

W is the vertical force resulting from the mass of the block and gravity;

D is the depth of the block;

H is the height of the block.

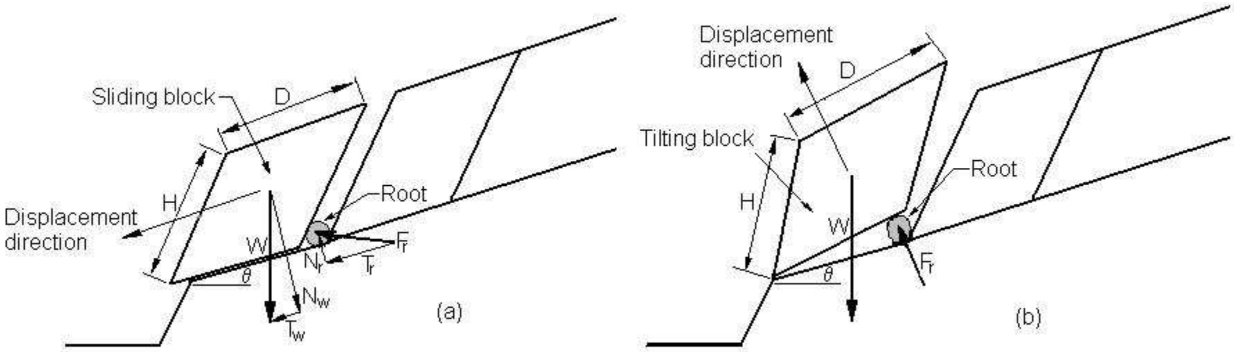

Figure 6: Schematic of root causing a block to (a) slide and (b) topple.

The following discussion considers the data from all sites as a single set. It is not however necessarily valid to do so as the data comes from a range of genera, albeit predominantly *Eucalyptus*, and species. However, when considered according to genus, there is minimal difference in the results due to their highly scattered nature. Therefore, for the purpose of highlighting general trends, the following discussion considers all data together.

Figure 7 shows the force applied by the roots to displace the blocks plotted in terms of the diameter of the roots. As expected, there is no significant correlation between the parameters. In addition, no envelope is obvious that defines the maximum root force in terms of root diameter. Plotted on the figure is the line obtained by the application of Equation 5. No forces were determined having values even near those suggested by the line. It appears therefore that, at the diameters, for the tree types and for the harsh environment being considered, the relationship may overestimate the forces. Also plotted on the figure is a region within which an alternative envelope may lie. There are however far too little data to make any claim as to its location and therefore, until significantly more data become available, the figure must be considered to show no more than a set of random data points.

The most useful relationship for geotechnical design purposes would be one that shows an envelope defining the maximum possible root force in terms of tree height. The relevant parameters from this study are plotted in Figure 8. As expected, there is no significant correlation between the values. Also plotted on the figure is a region within which an envelope may lie. Once again, until more data become available, no claim can be made as to its location.

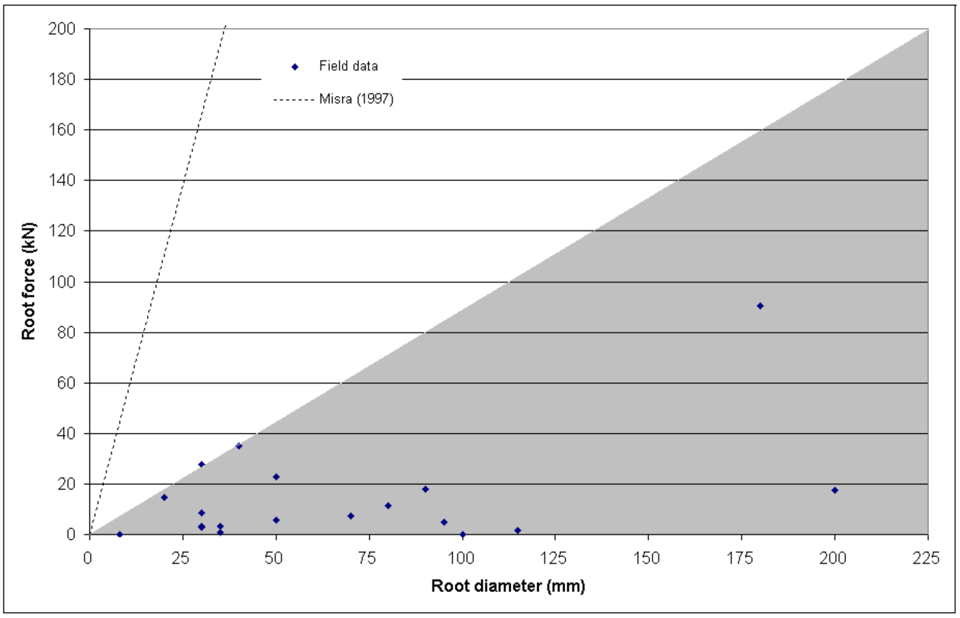

Figure 7: Force applied by roots to cause jacking plotted in terms of the diameter of the root. An envelope based on Equation 5 and a region within which an alternative envelope may lie are indicated.

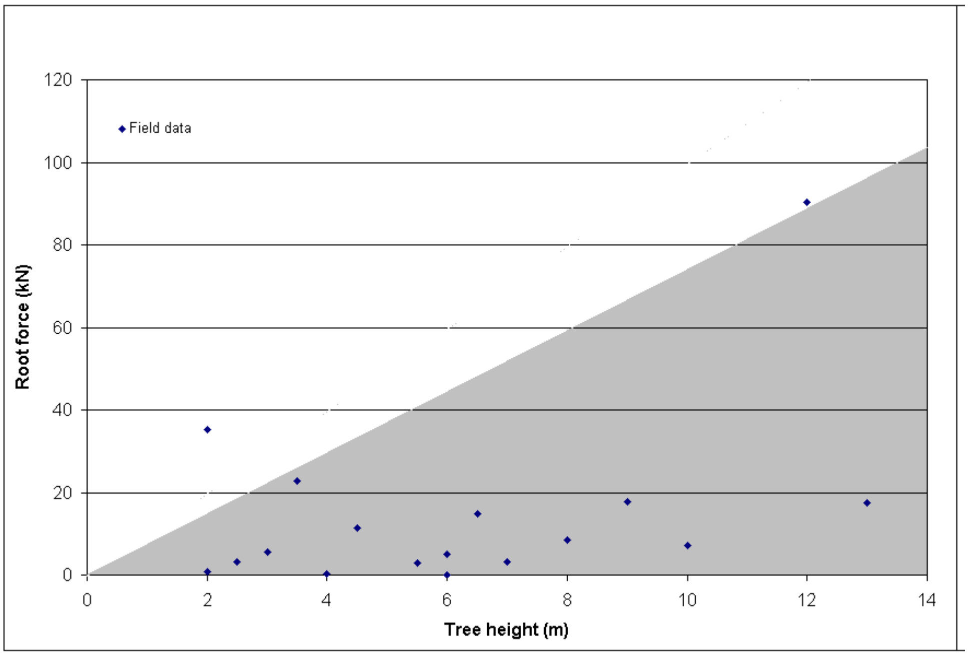

Figure 8: Force applied by roots to cause jacking plotted in terms of the height of a tree. A region within which an envelope may lie is indicated.

6 SOME OTHER EFFECTS OF TREES

Although jacking of rocks and the application of forces and moments to the rocks are obvious scourges of tree growth, there are other undesirable actions caused directly or indirectly by trees.

- Root jacking relatively rapidly increases the aperture width of previously tight discontinuities. The discontinuities can subsequently act as a, previously non-existent, path for water. Any resulting water pressure can cause the shear strength of a discontinuity, having the kinematic potential to act as a sliding surface, to reduce to a value sufficient to allow an overlying block to begin sliding. The water pressure can also increase the shear force acting on a previously stable block to a value sufficient for the block to begin sliding.
- The rate at which a previously tight discontinuity weathers can significantly increase once the discontinuity has been jacked open by a root allowing for a rapid reduction in the shear strength of its surface. This action may be caused by deposition of the products of physical or chemical weathering of the intact rock material (e.g. hydrolysis of feldspar, biotite, amphibole etc. to form clay). Materials may also be transported in solution from elsewhere. Other common occurrences are the, previously mentioned, build up of a dense mass of fine root hairs and the growth of micro-organisms (e.g. lichen, fungi etc.).
- *Eucalyptus sp*. and *Allocasuarina sp*., typical to the Adelaide Hills growing on rock slopes, generally have trunk diameters to 0.3m although diameters up to a metre do occur. An area of rock, extending approximately 0.25m to 1.0m beyond the trunk, is disturbed by its presence. As the diameter of the trunk increases, its area of influence must also increase. For example, by geometry, a 10% increase in the trunk diameter could cause between 0.5% and 7% increase in the area of rock affected. This rock cannot generally displace horizontally as it is confined by adjacent rock. It must therefore rotate, causing some of it to displace vertically. It is common for these rocks to be involved in rockfalls.
- Draped or pinned mesh is commonly used for reducing the risk of rockfalls and it is not uncommon for trees to grow under the mesh. A tree may either grow within an aperture of the mesh or grow directly under a wire. When growing, the centre of the trunk is in compression and the outer layers are in tension (Doitpoms, 2007). The tensile forces can be significant and the wire can react to them. If the trunk grows through an aperture of the mesh the forces can cause low tensile strength wires to fail or ringbark the tree (Figure 9). In most cases, the tree will eventually force the mesh off the face thereby placing the wires in it under tension. Draped mesh generally deforms significantly more than pinned mesh; deformations of more than a metre are common with the former installation. The ability for pinned mesh to deform will depend on the anchor spacing and the elasticity of the wire and the mesh. Agostini *et al.* (1988) found that a 1m square panel of low tensile strength (450 N/mm^2) mesh, fixed securely around its edge, deformed by approximately 150 mm before failing. Morton *et al.* (2007) found that a 1.3 m panel of high strength (1770 N/mm^2) mesh, fixed securely around its edge, deformed by approximately 150 mm before

failing. In practice, pinned mesh is anchored at corners of a grid rather than along the edges of a grid. Stress concentrations will develop at the anchors potentially allowing failure to occur at deformations less than those indicated. However, the performance of either installation type will not generally be compromised by a tree if it is cut back before deformations become excessive.

Figure 9: Young eucalypt growing on a rockface through the aperture in draped mesh.

7 TREE MANAGEMENT

No tree or large woody bush should be allowed to grow on the face of any bare rock slope for which there is a moderate or greater risk (AGS 2000) associated with rockfall. Trees should also be removed from an area within 2m behind the crest. If there are any indications that roots of trees growing further back behind the crest have the potential to damage the slope, they too should be removed. All trees to be removed should be cut off at the base of the trunk.

To prevent regrowth, holes (e.g. 20 mm) can be drilled into the into the sap layer (i.e. 30 mm depth) of the stump at a steep angle. Slits can also be cut into the top of the stump with a chainsaw. These features are then filled with a recommended residual poison following all appropriate safety procedures. Spraying is not recommended as it can poison the surrounding area. Regrowth will however often still occur, and the site should be routinely (e.g. every two years) inspected and new vegetation and regrowth cleared.

A face can be accessed from cherry pickers, boom lifts etc. However many slopes, and in particular those over 12 m in height, are often better accessed by persons using abseiling techniques. Persons must however be certified to carry out such work according to Standards Australia (1997a, 1997b) for Industrial Twin Rope Access.

There is often discussion as to whether the stump and roots of the tree should be removed due to the potential for the roots to rot. In the Author’s experience, the potential damage resulting from root rot is significantly less than the damage caused to a slope by attempting to remove stumps and roots.

In the case of significant or protected species, it may be necessary to leave them in place. However, if there is a significant likelihood that their roots may cause jacking and increase the risk associated with rockfall, it is prudent to cover an area, radiating at least 10 m out from the canopy, using draped or pinned rockfall netting. The netting can be shaped around the trunk so it is not damaged by trunk growth. Alternatively, an appropriately dimensioned rockfall fence can be installed along the toe of the slope below the tree.

Finally, for every tree removed, at least two of an appropriate local species should be grown and nurtured elsewhere to compensate for the many trees removed from the paths of “progress”.

8 CONCLUSIONS

In general, trees growing on bare rock slopes adjacent to public infrastructure can increase the risk associated with rockfalls due to the need for roots to elongate if the tree is to remain healthy. Limited research into the forces applied by these roots has meant that they cannot easily be incorporated into rock slope stability analyses. However, no matter what the forces may be, if no other surface treatment is to be applied to a rock slope (e.g. rockfall fences or mesh), in most cases the trees should be removed from the face and appropriate varieties established elsewhere.

9 POSTSCRIPT

The Author acknowledges that may of the concepts discussed in this paper are generalised, a necessity due to the complex nature of tree science and the difficulty of extracting from the rigorous and humbling scientific research carried out in this area, information of most relevance to the discipline of Rock Mechanics.

There is still a great deal of work that can be done in this area. With this thought in mind, the Author would welcome direct communication with others with useful contributions, thoughts, amendments or corrections. Especially welcome would be any data that can be added to those already collected. With time, genus or even species-specific envelopes relating tree height to maximum root jacking force may be developed – what an exciting concept!

10 ACKNOWLEDGEMENTS

The Author wishes to gratefully acknowledge Dr. Mark Jaksa, The University of Adelaide, for proof reading this paper and for making valuable suggestions.

11 REFERENCES

Aenor (1998) Eurocodigo 1. Bases de proyecto y acciones en estructuras. Parte 2-4. *Acciones en estructuras. Acciones del viento*. Asociacion Espanola de Normalizacion y Certificacion. Madrid. Espana.

Agostini, R., Mazzalai, P. and Papetti, (1988) A. *Hexagonal Wire Mesh for Rock-Slope Stabilization.* Officine Maccaferri S.P.A. Bologna, Italy.

AGS (2000) Landslide Risk Management. Australian Geomechanics Society Sub-Committee on Landslide Risk Management, *Australian Geomechanics*, Vol. 35, No. 1, March, p.87.

Barton and Choubey (1977) The shear strength of rock joints in theory and practice. *Rock Mechanics*, Vol. 6, pp. 183-236.

Bengough, A.G. and MacKenzie, C.J. (1994) Simultaneous measurement of root force and elongation for seedling pea roots. *Jnl. Experimental Biology*. Vol 45, January, pp. 95-102.

Dexter, A.R. (1987) Mechanics of root growth. *Plant and Soil*, Vol. 98, pp.303-312.

Doitpoms (2007) The Structure and Mechanical Behaviour of Wood: Part III The Structure of Wood. Downloaded 28/01/2007 from University of Cambridge, Dept. of Materials Science and Metallurgy website www.doitpoms.ac.uk/tlplib/wood/index.php

Ennos, A.R. (1999) The aerodynamics and hydrodynamics of plants. *Jnl. Exp. Biology* Vol. 203, pp.3281-3284.

FEMA (2005) *Federal Emergency Management Agency Technical Manual for Dam Owners – Impacts of Plants on Earthen Dams* FEMA 534 September, Chapter 5 Page .2.

Horacek, P. (2006) Tree Statics and Static Assessment Part II. Downloaded 29/01/2007 from www.treeworks.co.uk/past_seminars.php

Misra, R.K. (1997) Maximum axial growth pressures of the lateral roots of pea and eucalypt. *Plant and Soil*. Vol 188, pp.161-170.

Misra, R.K., Dexte, A.R. and Alston, A.M. (1986) maximum axial and radial growth pressure of plant roots. *Plant and Soil*, Vol. 95, pp. 315-326.

Morton, E.C., Thompson, A.G., Villaescusa, E. and Roth, A. (2007) Testing and analysis of steel wire mesh for mining applications of rock surface support. Submitted for Proc. *11th Congress of the ISRM – 2nd half Century of Rock Mechanics*, Lisbon, July 9-13, 2007.

Niklas, K.J. (2002) Wind, size and tree safety. *Jnl. Arboriculture*, Vol. 28 No. 2 March, pp 84-93.

Peltola, H. and Kellomaki, S., (1993) A mechanistic model for calculating windthrow and stem breakage of Scots pines at stand edge. *Sylva Fennica*, Vol. 27, pp.99-111.

Pfeffer, W, (1893) Druck und Arbeitsleistung durch Wachsende Pflanzen. *Abh. Konig Sach. Ges. Wissensch*, Vol. 33, pp.235-474.

Ray, D. and Nicoll, B.C. (1998) The effect of soil water table depth on root plate development and stability of Sika spruce. *Forestry*, Vol.71, pp.169-182.

Sinn, G. and Wessolly, L. (1989) A contribution to the proper assessment of the strength and stability of trees. *Arboricultural Journal*, Vol. 13, pp.45-65.

Standards Australia (1997a) Australian/New Zealand Standard: Industrial Rope Access Systems: Part 1: Specifications. (AS/NZS 4488.1:1997). Strathfield, NSW: Standards Australia International

Standards Australia (1997b) Australian/New Zealand Standard: Industrial Rope Access Systems: Part 2: Selection, Use and Maintenance. (AS/NZS 4488.2:1997). Strathfield, NSW: Standards Australia International

Whalley, W.R.; Clark, L.J. and Dexter, A.R. (1994) The temperature dependence of the maximum axial growth pressure of roots of pea. *Plant and Soil*. Vol. 163, pp.211-215.

Whalley, W.R. and Dexter, A.R. (1993) The maximum axial growth pressure of roots of spring and autumn cultivars of lupin. *Plant and Soil,* Vol. 157, pp. 313-318.