Modelling of influence of matric suction induced by native vegetation on sub-soil improvement

Behzad Fatahi
University of Wollongong

CHAPTER TWO

2 INFLUENCE OF VEGETATION ON GROUND CONDITIONS - LITERATURE REVIEW

2.1 GENERAL

Emerging public concern since the mid 1990's over slope appearance has encouraged the development of a systematic and integrated approach to using native vegetation to stabilise slopes. Bioengineering applications including the use of vegetation in civil engineering, began with slope stabilisation and erosion control. A railway line is one engineering structure, which is greatly influenced by hydrological and environmental conditions. Given the lengthy rail networks in coastal areas of Australia, numerous rail tracks have been built on clayey soils that are sensitive to moisture, which is why bioengineering methods for improving ground are becoming increasingly popular for stabilising railway corridors.

Based on current research and published literature, South-east Asian countries such as the Philippines, Malaysia, and Hong Kong have used bioengineering ground treatment more than others, so there is greater acceptance of this type of modification, particularly in slope stabilisation. Landscape treatment and the bioengineering technical guideline (GEO 2000) concluded that future development will include a wider use of native vegetation and the potential application of alternative measures. This technique can be cost effective, flexible, applicable in remote areas, and adapts to the environment without loss of life or damage to property.

Tree roots provide three stabilising functions: (a) reinforcement of the soil, (b) dissipation of excess pore pressure and (c) establishing sufficient matric suction to increase the shear strength. Available studies indicate that most attempts to quantify the effects of vegetation have focused on the structural reinforcement provided by the roots, while almost no attempt has been made to relate changes in soil strength and stiffness to the rate of transpiration.

Different aspects of vegetation emphasising root water uptake and transpiration are summarised and described in detail, particularly where they influence some hydrological features and affect the ground water content and condition of the soil. The influence of transpiration, root water uptake, and existing models are presented, followed by a review of some recent work on field observations and measurements, including the predictive models of tree and ground interaction.

2.2 HYDROLOGICAL FEATURES

Using landslide investigation data, Wong and Ho (2000) found that about 70% of recent failures in soil cut slopes were associated with ground saturation that was unlike that assumed in the initial design. It seems that the Hydrogeological effects on soil are not very obvious even today. On the other hand, as Shen (1998) reported, when the steep man-made slopes in Hong Kong were analysed using saturated shear strength parameters, the factor of safety was often found to be less than one. In these cases, the suction generated in unsaturated soils is the main explanation. Although it is well known that high rainfall and infiltration can rapidly reduce suction, Zhang et al. (2004) showed that rainfall does not necessarily eliminate soil suction. Indeed, the slopes will not be fully saturated even during severe storms. Because of this suction, the shear strength of unsaturated soil is more than saturated soil. However, the shear strength of unsaturated soil should only be used if it can be reliably shown that perennial soil suction is sustained.

According to Nelson and Miller (1992), expansion and shrinkage are the result of changes in the soil water system that disturb the internal stress equilibrium. If the soil - water chemistry is altered due to changes in the volume of water or chemical composition, the inter-particle force field will change. If this resulting change in internal forces is not balanced by a corresponding change in the externally applied state of stress, the particle spacing will change to adjust the inter-particle forces until equilibrium is reached. This change in spacing manifests itself as shrinkage or swelling. Reducing evaporation, heavy rainfall, and the growth of trees and shrubs are the most important factors that noticeably alter ground moisture.

Vegetation affects the hydrogeological conditions of the soil profile. Trees, shrubs, and grasses deplete moisture from the soil through transpiration. Furthermore, local field studies by Premchitt et al. (1992) revealed that tree canopies reduce rainfall intensity (I_R) below the vegetation canopy. This means that rainfall intensity below the tree canopy (I_T) is less than I_R (e.g. $I_T = 0.45 I_R$). In most cases, if soil permeability (k) is greater than I_T , the soil in the root zone remains unsaturated.

As mentioned above, plants reduce the moisture content of the soil through transpiration, which generally results in an increase in suction. Furthermore, suction is one of the parameters which control unsaturated soil so it is not surprising that an incorrect estimation of ground moisture content by geotechnical engineers lead to slope failure, distortion, ground settlement, or heave. Therefore, an accurate determination of the features and formulations, which can influence the moisture content of the ground be clarified for geotechnical engineers.

Needless to say, using complicated analysis and imprecise modelling of soil properties leads to unacceptable results, but because measuring all the essential parameters required to estimate the water content of a soil system is cumbersome, expensive, and time consuming, using accurate modelling and analysis to predict geohydrological conditions is an appropriate alternative.

To calculate the water content of a soil system based on the volume balance model, the principle of mass conservation should be used for water in solid, liquid, and vapour states. A soil system means part of the soil with specified boundaries, which are also included in the system. According to Blight (2003), the relevant principle is the Soil Water Balance (SWB), which is used to calculate the water content of a soil system, the initial water content and volume of water entering and leaving the system. Then any changes in the water content of soil system can be estimated. According to Blight (2003), and Panigrahi and Panda (2003), it can be concluded that the following equation represents changes in the amount of water (ΔW) in the soil system, while considering various hydrogeological features.

$$\Delta W = I_T + SI + F_I - T - E - P - D - F_O - SR - \Delta S \pm \Delta L \qquad (2.1)$$

where, T is transpiration, E is evaporation, P is percolation, D is drainage, F_O is outflow of ground water (lateral flow), SR is surface runoff, which is equal to $SR_I - SR_O$, SR_I is input surficial flow to soil system, SR_O is output surficial flow from soil system, ΔS is changes in surface storage (increase is positive), and ΔL is the losses, which stands for imprecision in the measurements, or lack of a definition of the boundary condition in the water balance, or the soil system.

Any variation in the moisture of a soil profile can be estimated by measuring the required parameters, using Equation (2.1), and then identify the parameters incorporated in this equation. According to White et al. (1997) and Blight (2005), transpiration is the key and most uncertain factor in the water balance method, therefore in this study, a review of existing models of transpiration are presented for more clarity. Details of other hydrological features including precipitation, evaporation, drainage, irrigation and surface run off can be found in the references presented in Table 2.1.

2.3 TRANSPIRATION (T)

Transpiration is defined as water vaporised from the plant. This loss of moisture through pores in the leaf is caused by vapour pressure difference between the interior leaf space and ambient air. As Hopkins (1999) summarises, more than 90% of the moisture escapes from leaves with small amounts from other parts such as Lenticles (small openings in the bark) of young twigs and branches. Hence, the transpiration rate relates very strongly to the specification of the leaves. The outer surface of a leaf is covered with a multilayered waxy deposit called Cuticle, which is very hydrophobic and resists diffusion of both water and water vapour from the underlying cells. They also have small pores on the surface called Stomata. Hopkins (1999) showed that their most important role is to provide a route for the exchange of gasses (principally carbon dioxide, oxygen, and water vapour) between the internal air space and the bulk atmosphere surrounding the leaf. About 90 to 95% of water loss induced by transpiration belongs to stomatal transpiration, while the remaining 5% - 10% is caused by cuticular transpiration. Although the cuticle is generally considered to be an impermeable skin, small amounts of moisture can pass through it and when it is thin or dry the stomata close to prevent stomatal, and cuticular transpiration is greater. Because transpiration involves the evaporation of water, it has a significant role in cooling the leaves. The energy budget for a typical mesophyte leaf is as per the following table;

Table 2.1 Description of some hydrological features

Hydrological Features	Comments	Reference
Precipitation	Effective rainfall is the amount of interception which passes through the tree canopy and reaches the ground. Interception can be measured using rain gauges such as a funnel gauge, or radar based on reflected energy. Rainfall intensity can be estimated based on the return period and duration of rain.	Newson (1983), Anderson and Burt (1985), Wilson (1970), Raudkivi (1979) and Nonner (2003)
Evaporation	Water molecules are repetitively swapped between a liquid and atmospheric water vapour. If the number vaporising exceeds the number joining the liquid, the result is evaporation. Evaporation can be estimated using evaporation pans, empirical formulae, the water budget method, mass transfer and energy budget methods.	Sudmeyer (2002), Raudkivi (1979) and Newson (1983)
Drainage	To prevent water logging and salinisation in the crop root zone, drainage is required, the most popular of which are horizontal pipes. The output of these pipes can be measured and is equal to the amount of water drained out of the soil system. Vertical drains used in geotechnical engineering are also a type of drainage system.	LeFluer et al. (1993), Wolski and Mlynarek (2000), Rowe and VanGulck (2004), and Indraratna et al. (2007)
Irrigation	Supplemental irrigation is water artificially added to soil, the volume of which relates to type of vegetation and weather conditions, etc. Usually when the water content is inadequate for plant growth, supplemental water is added, therefore irrigation is considered in planted areas.	Caswell and Zilberman (1985), Smith and Rutherford (1966), Wu et al. (1999) and Shortle and Griffin (2001)
Ground water flow	Geological factors such as grain size, shape, storing, packing, orientation, secondary mineralisation, dissolution and fracturing can affect ground water flow. Based on Darcy’s law, the ground water flow rate is proportional to the hydraulic gradient and hydraulic conductivity.	Anderson and Burt (1985), and Fetter (1988)
Surface run off	When the perception rate exceeds the infiltration rate (which relates to the perception rate, degree of saturation, etc), the water that moves down slope is called surface run-off or overland flow. The most widely applied model to estimate surface run-off was developed by the United States Soil Conservation Service (SCS).	Slack and Welch (1980), Weng (2001) and Sharply and Williams (1990)

Table 2.2 The energy budget for a typical mesophyte leaf (from Hopkins, 1999)

Please see print copy for Table 2.2

2.3.1 Measuring Transpiration`

According to Alarcon et al. (2000) and Hopkins (1999), there are three principal methods commonly used to measure the rate of transpiration. The first is weight loss, the second is gas exchange, and the third is sap flow. Sealing a well-watered potted plant to prevent evaporation through the pot or the surface can illustrate the weight loss method because the plant may be weighed at intervals and any weight loss attributed to loss of water transpiring through the shoot. As Kramer (1983) reports, the weight loss method, also known as the lysimeter method, has been scaled up for agricultural field studies by constructing large containers filled with soil (perhaps several cubic metres), mounted on weighing devices buried in the ground. In these cases records of water input (rainfall, irrigation) and evaporation must be kept. The lysimeter method is generally considered to be the most reliable and accurate for field studies but lysimeters are expensive to construct and are not considered to be portable. The gas exchange method is often used in conjunction with experiments on photosynthesis, which involves sealing a leaf or branch in a transparent chamber with a flowing air system. Transpiration can be estimated as the difference in water content of the air entering and leaving the chamber. The temperature, content of carbon dioxide, and other parameters can also be measured. This method has also been scaled up for field studies by enclosing entire trees or other large plants with a sealed plastic canopy. Gas exchange methods, whether on a small scale in the laboratory or in large-scale field measurements, are usually limited to short-term studies. The act of enclosing the plant may, over the long term, significantly alter the microclimate surrounding the leaves, therefore the temperature, humidity of the incoming air stream, and air velocity must be carefully monitored and controlled. Alternatively, chambers and measuring systems can be made quite portable and a number of commercial instruments are now available for field studies.

As Smith and Allen (1996) mentioned, the sap flow method provides direct and continuous measurement of whole plant water use with a long time resolution. With this method the heat pulse velocity is measured by temperature sensors inserted upstream and downstream of a line heater. Then the heat pulse velocity is related to the rate of sap flow using theoretical calibration factors. The theoretical calibration factors commonly used can be found in Swanson and Whitfield (1981) and Fernandez et al. (2001). As Alacon et al. (2000) reported, the compensation heat pulse technique developed by Swanson and Whitefield (1981), is one of the popular sap flow methods used to measure transpiration. In this method, one set of heat pulse probes is installed per tree and each set consists of a 1.8mm diameter heather needle and two thermocouple probes with the same diameter. Heather and thermocouples are inserted into parallel holes drilled radially into the trunk 300mm above the surface and then the heat pulse velocity is measured. The method recommended by Green and Clothier (1988) and Swanson and Whitfield (1981) considers the effects of wounding caused by a probe, but after that the heat pulse velocity is related to the actual sap flow, using developed equations such as Edwards and Warrick's (1984). The sapwood area of the tree stems is determined from an analysis of trunk cores taken by cutting the trunk down at the end of the experiment.

2.3.2 The Influence of Humidity, Temperature, and Wind Speed on Transpiration Rate

The rate of transpiration is affected by the humidity, temperature, and wind speed which influence the rate of water vapour diffusion between the sub-stomatal air chamber and the ambient atmosphere. Based on Fick's law of diffusion, it can be concluded that the rate of transpiration is proportional to the difference in vapour pressure between the leaf and the atmosphere, divided by the sum of resistances encountered in the air and the leaf.

Humidity is the actual water content of air that may be expressed either as vapour density or vapour pressure. In practice it is more useful to express the water content as relative humidity (RH). Relative humidity is the ratio of actual water content of air to the maximum amount of water that can be held by air at that temperature. The effects of humidity and temperature on the vapour pressure of air are illustrated in Table 2.3.

Table 2.3 Water vapour pressure (kPa) in air is a function of temperature and varying degrees of saturation. (after Hopkins, 1999)

Please see print copy for Table 2.3

Temperature modulates the transpiration rate through its effect on vapour pressure, which in turn affects the vapour pressure gradient. A leaf exposed to full sunlight may actually reach temperatures 5^{o}C to 10^{o}C higher than the ambient air. As long as the stomata remain open and a vapour pressure gradient exists between the leaf and the atmosphere, water vapour will diffuse out of the leaf. This means transpiration may occur even when the relative humidity of the atmosphere is 100 %. This is often the case in tropical jungles, where the leaf temperature and consequent saturation vapour pressure is higher than the surrounding atmosphere. According to Hopkins (1999), the water vapour condenses once it touches the leaf because the atmosphere is already saturated, thereby giving substance to the popular image of a steaming jungle.

As Nobel (1991) reports, wind speed has a significant effect on transpiration because it modifies the effective length of the diffusion path for existing water molecules due to a boundary layer of undisturbed air on the surface of the leaf. The thickness of the boundary layer increases the length of the diffusion path, which according to Fick's law decreases the rate of diffusion and rate of transpiration. As the wind speed increases the boundary layer becomes thinner and the diffusion path decreases. In accordance with Fick's law, the vapour pressure gradient steepens and, all other factors being equal, the rate of transpiration increases. According to Hopkins (1999), this relationship holds at lower wind speeds but as wind speed increases, it tends to cool the leaf and may cause sufficient desiccation to close the stomata.

2.3.3 Influence of Leaf Area on Transpiration Rate

The main function of the leaf is to absorb the energy of sunlight and produce sugar through photosynthesis, which is the essential basis for all plant growth. The energy of the sun is absorbed by the green chlorophyll pigment within the leaf and is used to convert carbon dioxide and water into sugar.

$$6CO_2 \quad + \quad 6H_2O \quad \xrightarrow{\text{energy from sun}} \quad C_6H_{12}O_6 \quad + \quad 6O_2$$

As Biddle (1998) concluded, although this process uses water, less than 1% of the water required by a plant is incorporated into sugar or forms part of the cell content. The remainder of more than 99% is lost via transpiration from the leaves. Obviously, the transpiration rate of a plant is found by summing the transpiration rate of whole leaves on the plant, which means the total transpiration rate of a tree increases with the leaf area. Based on Green (1993), the transpiration rate of a whole plant can be calculated using:

$$T_p = \sum_i f_i \left[\frac{sR_{n,i} + 0.93\rho_a c_p D_a / r_{a,i}}{s + 0.93\gamma(2 + r_{s,i} / r_{a,i}} \right] \tag{2.2}$$

where, f_i is the fractional area of each leaf expressed in terms of the total leaf area of the canopy, $R_{n,i}$ is the net radiation flux density absorbed by each leaf, D_a is the vapour pressure deficit of air, $r_{a,i}$ is the boundary layer resistance of each leaf, $r_{s,i}$ is the stomatal resistance of each leaf, s is the slope of saturation vapour pressure curve at the ambient air temperature, γ is the psychrometric constant, ρ_a is the air density and c_p is the specific heat capacity of air at constant pressure.

Generally speaking, the size and leaf area of a tree, including the planting arrangement, weather, and soil conditions affect the transpiration rate. Under particular atmospheric conditions, the transpiration rate depends on the surface area of leaves exposed to the atmosphere and the extent of the root system, which absorbs water from the soil. According to Vertessy et al. (1995) studies on Eucalyptus, the surface area of leaves can be estimated from,

$$L = c_f d_b^{\ n} \tag{2.3}$$

where, L is the surface area, c_f is a constant, d_b is stem diameter, and n is a coefficient. According to Landsberg (1999), the best way to extract c_f and n is to use the destructive sampling and non-destructive tests. Non-destructive equipment can be calibrated by destructive sampling. One of the key factor influencing the tree surface area and the rate of transpiration is the size of the tree. According to Warbington et al. (1998), tree size can be classified according to the stem diameter (d_b) as shown in Table 2.4.

Table 2.4 Tree size classification (Warbington et al.,1998)

Please see print copy for Table 2.4

2.4 TREE PHYSIOLOGY

For many years, a problem of some interest to plant physiologists has been how the integrity of the xylem water column is maintained and how it moves to the top of the tallest trees. Hopkins (1999) showed that several mechanisms have been proposed but the only one to have stood the test of time combines transpiration with the strong cohesive forces of water. In Australia, there have been reports of Eucalyptus trees measuring more than 130m in height. A force of the order of 2.0 to 3.0 MPa would be required to move water from the ground to the top. Based on Hopkins (1999) investigation, the three most prominent features are root pressure, capillarity, and the cohesion theory, as explained later.

If the stem of a well-watered herbaceous plant is cut off above the soil line, xylem sap will exude from it (Figure 2.1) and its magnitude can be measured by attaching a manometer to the cut surface. This is known as root pressure because the forces, which give rise to this exudation, originate in the root. The question to be answered at this point is whether root pressure can account for the rise of sap in a tree. The answer is probably ‘no’ for several reasons. Root pressure values in the range of 0.1 to 0.5MPa are common, which are no more than 16% of that required to move water to the top of the tallest trees. In addition, root pressure has not been detected in all species and is not always detectable even in those species, which do exhibit it. Finally, it has been clearly established that during periods of active transpiration, when water movement through the xylem is expected to be most rapid root pressure, is under tension (i.e. negative pressure). According to Nobel (1991), root pressure cannot serve as the mechanism for the ascent of sap in all cases but could serve to fill vessels in small, herbaceous plants and some woody species in the spring, when sap moves up to the developing buds.

Please see print copy for Figure 2.1

Figure 2.1 A demonstration of xylem sap exudation due to root pressure in tomato. Photograph was taken 10minutes after excising the stem of a well-watered plant (Hopkins, 1999)

If a glass capillary tube (that is a tube of small diameter) is inserted into a volume of water, it will rise inside to some level above the surface of the surrounding water. This is called capillary rise or capillarity. The calculated rise of water in a capillary tube is inversely proportional to the radius of the tube. In a large tracheid or small vessel of 50µm diameter the water will rise about 600mm but with a large vessel (r=200µm), capillarity would account for a rise of only 800mm. On the basis of these numbers, capillarity in tracheids and small vessels might account for the rise of xylem sap in small plants less than 75mm high but to reach a 100metre high tree by capillarity, the diameter of the capillary would have to be about 0.15µm – much smaller than the smallest tracheids. Therefore as discussed by Hopkins (1999), capillary is inadequate as a general mechanism for the ascent of xylem sap.

The most widely accepted theory for the movement of water through plants is cohesion theory. As explained by Hopkins (1999), this theory depends on the existence of a continuous column of water from the tips of the roots, through the stem and into the mesophyll cells of the leaf. The theory is generally credited to Dixon (1914). According to cohesion-tension theory, the driving force for water movement in the xylem is evaporation of water from the leaf, which generates tension, or negative pressure. Because the water column is continuous, this negative pressure, or tension, is transmitted through the column all the way to the soil. The ability to resist breakage is a function of the tensile strength of the water column. The tensile strength of water will depend on the diameter of the conduit, the properties of the conduit wall, and the presence of any dissolved gasses or solute. It is now generally accepted that pure water, free of dissolved gas, is able to withstand tension as low as –25 to –30MPa at 20^{o}C. This is approximately 10 times greater than the –2.5 to –3.0 MPa required to pull an uninterrupted water column to the top of the tallest tree.

2.5 ADVANTAGES OF BIOENGINEERING

Engineers usually assume that it takes 5 - 10 year before the roots of plants established by bioengineering methods have strengthened the soil sufficiently. Because native vegetation takes time to become activated these methods were previously considered unacceptable for use in densely populated urban areas, where fast ground improvement measures are required.

Nonetheless, bioengineering techniques have advantages for Australia, South east Asia, and other tropical regions, where deforested upland sites with high landslide risk and soft soil formations are very sensitive to moisture. Here these methods are reasonable and can be used in quantity to tone the scale of sites and projects. If trees are normally used to reduce the moisture content of soil and increase its suction and strength, deciduous trees, which shed all their leaves seasonally, should not be used because their water uptake capacity (transpiration rate) is proportional to the area of their leaves. Bioengineering is usually recommended as a complementary technique and can be combined with inert systems such as gabions, geosynthetic reinforced soil retaining walls, timber crib, concrete crib walling, retention and drainage (Barker, 2001; Martin, 2001; Martin et al., 2001). This means that bioengineering systems have been considered as only contributing a superfluous margin of safety to previously stable soil structures like slopes, or hybrid slope retention structures. For example, in slopes of over-consolidated clay, tree planting is useful because it can compensate time dependent decrease in the strength of the clay. Martin et al. (2001) drew the conclusion that hard surface covers will continue to be needed, especially on steep, urban cut slopes. With greater confidence in the use of vegetated surfaces, particularly in conjunction with soil nailing, it is estimated that the percentage of soil slopes with permeable covers can increase to more than 70% over the next ten years.

Native vegetation is generally a more cost effective technique for ground stabilisation than other conventional methods. Noraini and Ghani (2001) have provided a cost comparison between geo-structure (vegetation) and conventional civil structures elements. They concluded that a bioengineering slope stabilisation method is at least 80% cheaper than conventional methods of slope stabilisation (e.g. rock gabion). As According to Potter (2006), although trees and large shrubs may not be desirable on steep grades due to lack of stability of the vegetation upon maturity, low growing species of shrubs and groundcovers such as sedges, rushes and grasses can provide an increase in slope stability through both soil desiccation and tensile reinforcement from the root structure.

Tree roots usually develop in surficial layers, so planting vegetation is useful for surficial or shallow soil stabilisation. For example, Perry (1989) reported that 95% of all slope failures in over-consolidated clays in South East England were less than 1.5m deep. Likewise, according to manual of slope protection (JHA, 1984) published by Japan Road Association, 67% of all failures in all types of natural and formed slopes and soils are less than 2m deep. In addition, Martin (2001) and Dobson and Moffat (1995) concluded that significant root enhancement of soil strength appears to be generally limited to the upper 1 – 2m of its profile.

2.6 ROOT REINFORCEMENT EFFECT

Besides establishing sufficient matric suction to increase their shear strength, tree roots can stabilise the soil through reinforcement. From studies of Docker and Hubble (2001), Dobson and Moffat (1995) and Norris and Greenwood (2000), it can be concluded that tiny tree roots less than 20mm diameter are commonly considered to increase soil strength through an increase in apparent cohesion of the soil matrix, while larger roots tend to act as individual anchors. Indeed, if roots distribute superior reinforcement vertically and horizontally, the potential for increased cohesion increase is greater. Based on experimental tests conducted by Operstein and Frydman (2000) and Docker and Hubble (2001), changes in soil friction angle induced by reinforcing tree roots are negligible. They have not considered the influence of active roots or the drainage condition of the soil. In fact, active tree roots act similar to prefabricated vertical drains and discharge the water from the soil medium and prepare drained conditions. Root density is the most important factor for estimating the increased shear strength of the ground induced by reinforcing roots. Docker and Hubble (2001) applied some in-situ direct shear test on ground covered by Casuarina glauca species growing on the banks of the Nepean River within the Camden valley, (NSW, Australia) in clayey sand. Based on their field tests, at 10% shear strain (residual stress) and root area ratio (R_a), around 20% - 40% of shearing resistance was provided by the roots. Operstein and Frydman (2000) obtained an equation for the apparent cohesion induced by tree roots:

$$\Delta C(r,z,t) = k_r T_r(r,z,t) \tag{2.4}$$

where, ΔC is the apparent cohesion due to tree roots, T_r is the relative root tensile strength contribution and k_r is an experimental constant. The value of T_r is influenced by the root area ratio and the tensile strength of roots and their diameter. Studies by Operstein and Frydman (2000) showed that the value of relative root tensile strength can be described by:

$$T_r(r,z,t) = T_i(r,z,t) R_a(r,z,t) \tag{2.5}$$

where, T_i is the tensile strength of root and R_a is the root area ratio, which is the root cross section for the unit area of soil . Docker and Hubble (2001) proposed that the root area ratio, including the depth and distance from the trunk, can be determined as an exponential relationship. Therefore:

$$R_a(r,z,t) = R_{a0}(t)e^{-b_1(t)z - b_2 r(t)} \tag{2.6}$$

where, R_{a0} is the root area ratio exactly underneath the trunk and b_1 and b_2 are experimental coefficients. Operstein and Frydman (2000) indicated that the tensile strength decreases exponentially with the root diameter. Thus:

$$T_i(r,z,t) = Ae^{-m_1 d(r,z,t)} \tag{2.7}$$

where, A and m_1 are experimental coefficients and $d(r,z,t)$ is the average root diameter at point (r,z) at time t. In this study it is assumed that the average root diameter decreases with the same exponential function as the root area ratio. Hence:

$$d(r,z,t) = d_0(t).e^{-b_1(t)z - b_2(t)r} \tag{2.8}$$

where, $d_0(t)$ is the average root diameter directly beneath the trunk. As a result, according to Equation (2.4), the apparent cohesion due to tree roots, $\Delta C(t)$, can be estimated by multiplying a constant value and relative root tensile strength factor $T_r(r,z,t)$. In order to determine $T_r(r,z,t)$, Equation (2.5) incorporating Equations (2.6)-(2.8) are used.

2.7 ROOT LENGTH DENSITY MEASUREMENTS

According to Bohm (1979), the root system can be measured in different ways. The most well known methods of field measurements are excavation, monolith, auger, profile wall, glass wall, and radio-active tracers. A brief description of each is given below.

2.7.1 **Excavation:** A trench with an almost vertical wall is dug some distance from the plant and then the soil is carefully removed from the wall to expose the roots. The soil should be removed using compressed air, from the base of the plant to the tips of the roots. The soil particles should be removed in a direction parallel to the roots, as roots resist more against pulling force parallel to the direction of their growth. The roots should be drawn on a piece of paper showing their distribution and length. Photographs of the roots during the excavation help to interpret the data and drawings. This was often the only effective method to use in stiff or dry, sandy soils. Also, according to Bohm (1979), excavation is a more suitable method to use for trees and shrubs than grasses or annual crops.

2.7.2 **Monolith:** A trench about 1m long by the maximum root depth is dug and then monoliths are taken away from the side wall, layer by layer. Sharp metal sheets are beaten into the soil with a hammer to extract monoliths and then the soil is separated from the roots by washing. As Bohm (1979) describes, for sandy or loamy soil, the monolith is submerged directly into a tank of water until it is saturated and then followed by washing. Because washing out soil monoliths with high clay content is extremely difficult, Schuurman and Goedewaagen (1971) recommended washing after drying and then soaking in a solution of sodium pyrophosphate. Photographs of the root system can be taken after washing is finished.

2.7.3 **Auger:** Samples of soil are taken using a hand auger or any other mechanical sampling tool. The samples vary from 70mm to 100mm in diameter, which causes least root disturbance from tube friction. The root distribution can be evaluated by breaking the sample horizontally and exposing both sides of the breakage, or separating the roots from the soil by washing and cleaning. In their field investigations, Nimah and Hanks (1973) obtained replicate samples at 150mm deep intervals within the active root zone. They were washed to remove the soil, dried at 105^{oc} to remove excess water, weighed and then ashed at 625^{oc} for 4 hours and then weighed again. The amount of root per depth of increment is assumed to be the difference in weight.

2.7.4 **Profile wall:** A trench is dug to the required length and depth by hand or trench digging machine and then the final working face of the profile is smoothed into an almost vertical wall. The roots are exposed using mechanical tools, water, or air pressure, and then immediately mapped and counted. Mapping can be done on cross section paper and a counting frame placed onto the wall. The roots are shown on the map by dots; the larger the diameter, the larger the dot. With this method the roots are not collected afterward, therefore if the dry weight of the root is required other methods should also be included.

2.7.5 **Glass wall:** A trench must be dug, the wall next to the roots must be smoothed and a sheet of glass must be placed against it with maximum contact because any free space between them alters the environmental conditions of the roots. To assist contact between glass and wall a thin layer of soil is carefully removed carefully to enable observation and recording of growth. Thermocouples and moisture tensiometers are fitted through the glass at various depths and distances to monitor the environmental conditions.

2.7.6 **Radioactive tracers:** A radioactive tracer is injected into the plant stem and the pattern of root activity is determined by taking soil-root samples and recording their radioactivity. The level of radioactivity in the samples enables the distribution of roots as a means of carrying to be predicted. To minimise hazards under field conditions, rapid decaying radioactive elements with strong gamma emitter such as 32P and 86Rb are used. This indirect method of measuring the root density and distribution can also be used by injecting tracer into the soil and tracing it within the plant.

2.8 ROOT DEVELOPMENT

Some traditional beliefs suggest that trees may be as large below ground as above. Researchers such as Docker and Hubble (2001), Dobson and Moffat (1995), Sudmeyer (2002), and Landsberg (1999), found that the total cross-sectional area with depth and distance from trunk yielded the following exponential relationship:

$$\beta = \beta_0 \exp(-k_1 z) \exp(-k_2 r) \tag{2.9}$$

where, β is the root length density at point (r, z), β_0 is the root length density at ground surface just under the tree trunk, k_1 is a coefficient to determine the rate of change of β with depth, and k_2 is a coefficient to determine the rate of change of β with lateral distance. According to Equation (2.9), the root density will decrease by distance from the tree trunk but Sudmeyer (2002) reported that this decrease would be relatively gradual in deep sand and decrease abruptly in clay sub-soil.

Tree roots are highly sensitive to environmental conditions and soil factors such as compaction, stony soil layer, poor soil aeration, water logging or high water table, dryness and infertility. Dobson and Moffat (1995) reported that almost 90% of tree roots might be found in the upper 600mm of soil.

2.8.1 Maximum Root Depth

The maximum depth of tree roots is variable. For example the roots of a Lucerne (Medicago sativa) have been found growing as deep as 39m (Meinzer, 1927), Perennial grasses to 7m, and even winter wheat (Triticum aestivum) can penetrate to 2m in one growing season (Russell, 1973), while reports of very shallow rooting of trees (i.e. less than 300mm) are quite common (Laing, 1932; Yeatman, 1955). These variations cannot be adequately explained by the ability of different species to root, in fact according to Sutton (1969), the soil environment is extremely important. Laitakari (1935) found that birch root (Betula pendula) has the potential to grow at least 4m deep in loose, well-drained soils, but in waterlogged moor soils the entire root system may be restricted to the upper 400mm of more aerobic soil.

Another example is where a 1-2 year old C.glauca tree has a maximum root depth of 41% (linear relationship) of its height (Docker and Hubble, 2001). Dobson and Moffat (1995) mentioned that in special circumstances such as a compacted clay blanket, the maximum depth of the root depth is limited to the depth of the clay.

2.8.2 Horizontal Root Spread

Contrary to popular belief a tree root system is primarily horizontal, not vertical. Maximum lateral root development can be related to either the size of the canopy or height of the tree. Dobson and Moffat (1995) believe that the horizontal spread of roots can be of the order of 1-3 times of the height i.e, 20m or more for mature trees. Sudmeyer (2002) also stated that for the three Australian native trees, including Eucalyptus globules (*Tasmanian Blue Gum)*, Pinus radiate (Monterey pine), and Pinaster (maritime pine) the maximum horizontal root spread is about 1 - 2 times the height.

As an example of the lateral spread of roots, in some codes growing trees on cap layers of land fills was prevented because it was believed that the roots would grow vertically into the rubbish part of the land fill and release deadly gases. However as Dobson and Moffat (1995) concluded, roots usually grow horizontally and can therefore be used in cap layers of land fill.

2.9 TREE ROOT WATER UPTAKE

The loss of moisture from the soil may be categorised as (a) water used for metabolism in plant tissues and (b) water transpired to the atmosphere. However, as suggested by Radcliffe et al. (1980), the volume of water required for photosynthesis or metabolism in plant tissues compared to the total water uptake by roots is negligible. Total transpiration can then be assumed to be the same as the water uptake through the root zone.

One of the first hypotheses launched to demonstrate the mathematical form of root water uptake (or sink term) was Van den Honert's hypothesis (1948):

$$S(z,t) = \frac{\Phi_S - \Phi_L}{R_{SL}} .S_{act}(z,t) \tag{2.10}$$

where, S is the rate of root water uptake, Φ_S is the total soil water potential, Φ_L is the total leaf water potential, R_{SL} is the effective hydraulic resistance to water flow from the soil to the leaves depending on the depth, and S_{act}, which is the specific surface of the active part of the roots depending on the depth below the surface. Measuring R_{SL} is very difficult and consequently the above formula can only be used to understand the concept of root water uptake (Gardner, 1964; Feddes et al. 1974; Novak 1987). Obviously soil conditions, type of vegetation, and atmospheric conditions affect transpiration or the rate of root water uptake.

2.9.1 Soil Conditions

2.9.1.1 Effect of Soil Suction

Soil suction is the force resisting the movement of water which also affects the transpiration rate. The greater the soil suction the more difficult it will be for soil water to be discharged by the roots. Soil suction relates to the soil moisture content through the soil water characteristic curve.

Therefore soil suction can be a reduction factor for the potential transpiration rate; if the soil moisture content increases so too will root water uptake. The soil suction reduction factor can also be a function of moisture content, which is why some of the recommended formulae for the reduction factor are based on soil matric suction and others are based on soil volumetric moisture content. A general trend suggested by Feddes et al. (1976) for the root water uptake rate that includes the wilting and anaerobiosis points is presented in Figure 2.2.

Please see print copy for Figure 2.2

Figure 2.2 water uptake – moisture content relationship (After Feddes et al., 1976)

In Figure 2.2, θ_W is the wilting point moisture content, θ_d is the minimum moisture content when $S = S_{\max}$, θ_{an} is the lowest value of moisture content at the maximum root water uptake rate and θ_{sat} is the saturate moisture content. A number of equations proposed for $f(\psi)$ are given in Table 2.5.

2.9.1.2 Effect of Soil Hydraulic Conductivity

Gardner (1960) conducted a quantitative study on root water uptake determination. Gardner's water extract function was based on a steady flow of water to the root, which was assumed to be an infinitely long cylinder. Gardner (1960) launched the following root water uptake rate based on Darcy's law:

$$S(x, y, z) = b.(\delta - \psi - z).k.\beta(x, y, z) \tag{2.11}$$

where, S is the rate of root water uptake, b is a constant, δ is the water potential of plant roots, ψ is soil suction, z is the depth below soil surface, k is the unsaturated hydraulic conductivity, $\beta(x, y, z)$ is the root density as length of roots per unit soil volume.

Table 2.5 Different root water uptake reduction factors suggested by different researchers

Reference	Model	Comments
Feddes et al. (1978)	$\begin{cases} f(\psi)=0 & \psi<\psi_{an} \\ f(\psi)= & \psi_{an}\le\psi<\psi_d \\ f(\psi)=\dfrac{\psi_w-\psi}{\psi_w-\psi_d} & \psi_d\le\psi<\psi_w \\ f(\psi)=0 & \psi_w\le\psi \end{cases}$	where, ψ_W = the soil suction at wilting point, ψ_d = the highest value of ψ and ψ_{an} = the lowest value of ψ at $S=S_{\max}$, where $S_{\max}$ is the maximum rate of root water uptake.
Radcliffe et al. (1980)	$f(\psi)=\dfrac{0.0001}{0.0001+0.9999e^{-1.45\theta}}$	θ = volumetric soil moisture content
Molz (1981)	$f(\psi)=\dfrac{\theta(z,t)L(z,t)[\psi(z,t)-\phi_x(t)]\alpha_T}{S_{\max}\int_0^{v(t)}\theta(z,t)L(z,t)[\psi(z,t)-\phi_x(t)]dz}$	$\theta(z,t)$ = volumetric soil water content, $L(z,t)$ = length of roots per unit soil volume, $v(t)$ = depth of root zone and $\phi_x(t)$ = water potential of the root xylem, $G(\beta)$= Root density distribution function, α_T = a coefficient depending on the transpiration rate and $S_{\max}$ is the maximum rate of root water uptake
Perrochet (1987)	$f(\psi)=\dfrac{k(\psi)(\psi_r-\psi)}{k(\psi_0)(\psi_r-\psi_0)} \quad \lvert\psi\rvert>\lvert\psi_0\rvert$ $f(\psi)=1 \quad \lvert\psi\rvert\le\lvert\psi_0\rvert$	$k(\psi)$ = hydraulic conductivity of the soil , ψ = soil suction around the roots, ψ_r = root suction generated by the plant, ψ_0= soil suction around the roots from which the transpiration rate starts to diminish and $S_{\max}$ is the maximum root water uptake rate
Novak (1987)	$f(\psi)=1 \quad \psi_{an}<\psi\le\psi_d$ $f(\psi)=\dfrac{\overline{\psi}}{\psi(z)} \quad \psi_d<\psi<\psi_w$ $f(\psi)=0 \quad \psi_w\le\psi$	ψ_w = soil suction at wilting point, ψ_d = highest value of ψ at which $S=S_{\max}$, ψ_{an} = soil suction at anaerobiosis point and $\overline{\psi}$ = average value of ψ in the depth interval where $\psi_d<\psi<\psi_w$ and $S_{\max}$ is the maximum root water uptake rate

Whisler et al. (1968), using one dimensional flow equation, suggested a linear relationship between the root water uptake and hydraulic conductivity similar to Gardner (1960):

$$S(z) = f(\beta).k.(h_p - h_s) \tag{2.12}$$

where, $f(\beta)$ is root density function, h_p is water potential of roots, and h_s is water potential of soil

Molz and Remson (1970) suggested that root water uptake can be presented based on diffusivity instead of matric suction. Thus

$$S(x, y, z) \propto f(D(\theta)) \tag{2.13}$$

where, $D(\theta) = k.\frac{d\psi_m}{d\theta}$, $D(\theta)$ is the diffusivity, θ is the volumetric water content, and k is the soil hydraulic conductivity, which is considered in the diffusivity function.

Feddes et al. (1974) introduced the following equation,

$$S = \frac{-k.[h_r(z) - h(z)]}{b(z)} \tag{2.14}$$

where, $h_r(z)$ is the pressure head at the soil-root interface, $h(z)$ is the pressure head in the soil, $b(z)$ is an empirical function representing the geometry of flow.

Hillel et al. (1976) proposed the following equation to predict the root water uptake based on the hydraulic head of soil and plant and their resistance to flow:

$$S = \frac{(\phi_{soil} - \phi_{plant})}{(R_{soil} + R_{roots})} \tag{2.15}$$

where, ϕ_{soil} is the total hydraulic head of the soil as a function of depth, ϕ_{plant} is the hydraulic head in the plant at the base of the stem, R_{soil} is resistance to water flow in the soil, equal to $1/Bkl$, where B is an empirical constant, l is the length of active roots per unit soil volume, R_{roots} is the hydraulic resistance of the roots taken to be the sum of a resistance to absorption and a resistance to conduction which depends on depth.

Selim and Iskandar (1978) suggested that:

$$S = \frac{T.L(z).k}{\int_0^{z_{\max}} L(z).k.dz} \tag{2.16}$$

where, T is transpiration rate per unit soil surface area, $L(z)$ is length of roots per unit soil volume, z is depth below soil surface, $z_{\max}$ is depth of root zone

In this study, it is assumed that the root water uptake as a function of potential transpiration should be related to the soil moisture content or suction where it touches the roots, and the permeability coefficient should be included in the flow equation. Consequently, the suggested equations for root water uptake, which include functions of hydraulic conductivity, cannot be used in a time dependent flow equation in conjunction with potential transpiration. In this study, potential transpiration will be used, not differences in the hydraulic head, neither will approaches, which include permeability in the root water uptake model.

2.9.1.3 Effect of Soil shear strength

Every root must overcome local resistance to penetration to expand. As suggested by Clausnitzer and Hopmans (1994), the results of penetrometer tests are appropriate to estimate the root system morphology and shape of the root zone. Hence, the less resistant soil is to penetration, the larger the root zone will be. Therefore, when amount of water available in root zone of stiff soil is less, so too will be the rate of evapo-transpiration. Figure 2.3 shows that the root was expanded on the left hand side of the soil 250mm below the surface because on the other side, the soil is more compacted due to traffic load. Consequently, the compaction level and strength will be considered in root distribution.

Please see print copy for Figure 2.3

Figure 2.3 Root development within the sandy soil, compacted below 25 cm and to the right of the plant axis (after Clausnitzer and Hopmans, 1994)

2.9.2 Tree Specifications

2.9.2.1 Effect of Root Length Density

Depending on its type, soil conditions and atmospheric circumstances, every plant has a certain rate of transpiration. Distribution of potential/maximum root water uptake depends on the root density and potential rate of transpiration. Distribution of transpiration within the root zone when water is unrestricted depends mainly on the length and distribution of roots within the root zone. Various equations proposed to include the effect of root density in the water uptake model are given in Table 2.6.

Table 2.6 Influence of Root density on root water uptake rate

Reference	Model	Comments
Molz and Remson (1970)	$S=(-\frac{1.6}{z_{\max}}.z+\frac{1.8}{z_{\max}}).\alpha_1$	$z_{\max}$ is the maximum root depth (m) and z is depth from soil surface(m) and α_1 is a coefficient relating to the rate of root water uptake.
Perrochet (1987)	$S=\alpha\frac{c(2z-L(t))+L(t)}{[L(t)]^2}$	c is constant depending on the plant and its vegetative stage; $L(t)$ is confining distance of roots below the soil surface and α is a coefficient relating to the transpiration rate
Hoogland et al. (1981)	$S=f(\psi)(a-bz)$	$f(\psi)$ is the soil suction reduction factor, a and b are constants, in principle to be determined from measured root water uptake data.
Prasad (1988)	$S=\frac{2T_{pj}f(\psi)}{z_{rj}}(1-\frac{z}{z_{rj}})$	$f(\psi)$ is the soil suction reduction factor, T_j is potential transpiration rate on the j th day, and z_{rj} is the rooting depth at j th day.
Nimah and Hanks (1973)	$S=\frac{[-H_{root}-(PRES.z)+h(z,t)+s(z,t)].RDF(z).k}{\Delta x.\Delta z}$	H_{root} is an effective water potential in the root at the soil surface where z is considered zero and $PRES$ is a root resistance term equal to $1+R_c$ where R_c is a flow coefficient in the plant root system assumed to be 0.05. $h(z,t)$ is soil pressure head, $S(z,t)$ is the salt (osmotic) potential soil osmotic head, $RDF(z)$ is the proportion of total active roots in depth increment Δz, k is hydraulic conductivity at depth z, and Δx is the distance between the plant roots at point in the soil where $h(z,t)$ and $s(z,t)$ are measured.
Raats (1976)	$S=\alpha\frac{e^{-\frac{z}{\delta}}}{\delta}$	δ is the parameter chosen to satisfy the mass balance equation; z is depth and α is a coefficient relating to the transpiration rate
Vrugt et al. (2001)	$S=\frac{f(\psi)X_mY_m\beta(x,y,z)T_p}{\int_0^{X_m}\int_0^{Y_m}\int_0^{Z_m}\beta(x,y,z)dxdydz}$	X_m, Y_m, Z_m are the maximum rooting length in the x, y, z directions respectively, $\beta(x,y,z)$ is the shape factor describing the spatial distribution of potential root water uptake and T_p is the potential transpiration
Molz (1981)	$S=\frac{\theta(z,t).L(z,t).[\psi(z,t)-\phi_x(t)]\alpha}{\int_0^{v(t)}\theta(z,t).L(z,t).[\psi(z,t)-\phi_x(t)].dz}$	$\theta(z,t)$ is volumetric soil water content, $L(z,t)$ is length of roots per unit soil volume, $v(t)$ is depth of root zone, $\phi_x(t)$ is water potential of the root xylem and α is a coefficient relating to the transpiration rate

2.9.2.2 Effect of Relative Proportion of Active Roots

Root water uptake occurs through active parts of roots and as Radcliffe et al. (1980) mentioned, water primarily enters the plant through the most active part of young roots and root hairs. When estimating the root water uptake, only the active distribution density is important. If the reinforcement effect must be considered, so too should the reinforcing root distribution. It is important to notice the difference between the distribution of active roots and reinforcing roots. Therefore, in this study β refers to the active root density.

2.9.2.3 Effect of Leaf Area

Most transpiration of water occurs through leaves, whereas through tissues of the stem it is comparatively negligible. For example, when a plant has large leaves, transpiration will increase causing momentary wilting. Usually the leaf area effect is considered as the leaf area index (LAI). LAI and its effects on potential transpiration were described in greater detail in Section 2.3.3.

2.9.3 Effects of Atmospheric Conditions

2.9.3.1 Potential Transpiration Rate

Potential transpiration is defined as evaporation of water from plant tissues to the atmosphere, when the moisture content of the soil is unrestricted. Therefore, the maximum possible root water uptake is called the potential transpiration that relates to meteorological characteristics, as well as the condition and age of the plant. Direct measurement of potential transpiration is very difficult, so in practice an indirect estimation is usually carried as follows:

$$T_P = ET_P - E_P \tag{2.17}$$

where, T_P is the potential transpiration, ET_P is the potential evapotranspiration (from both plant and soil), and E_P is the potential evaporation (only from the soil surface). To estimate ET_P and E_P, a combination of energy balance and mass balance methods can be used. Penman (1948), Monteith (1965) and Rijtema (1965) developed appropriate methods for determining the potential transpiration through potential evapotranspiration and evaporation. For example, potential transpiration based on Penman-Brutsaert's model as further described by Lai and Katual (2000), is given by:

$$T_P = W(R_n - G) + (1 - W)E_A \tag{2.18}$$

where, T_P is the potential latent heat flux, R_n is the net radiation, G is the soil heat flux, W is a dimensionless weighted function that depends on the slope of the saturation vapour pressure-temperature curve and psychometric constant, and E_A is the atmospheric drying power function.

2.10 SOIL SUCTION MEASUREMENT

Pomper et al. (1990) defined soil suction as "the tensile pressure that must be applied to a unit area of water to prevent it from entering the soil". According to Edleefsen and Anderson (1943) soil suction can be described as the free energy state of the soil. This free energy is part of the potential energy that soil water can have. In fact, water energy consists of elevation energy, velocity energy, and suction energy. Suction energy is called free energy. As described by Richards (1965), the free energy of soil water can be calculated based on the partial vapour pressure of the soil water. The relationship between free energy of the soil water of suction (ψ) in thermodynamic physics can be written as follows:

$$\psi = -\frac{RT}{u_{w0}.\omega_v}.\ln\left(\frac{\bar{u}_v}{\bar{u}_{v0}}\right) \tag{2.19}$$

where, ψ is soil suction or total suction (kPa), R is universal (molar) gas constant (8.31432 J/(mol.K)), T is absolute temperature (K), u_{w0} is specific volume of water or the inverse of density of water (m^3/kg), ω_v is molecular mass of water vapour (18.016 kg/kmol), $\bar{u}_v$ is partial pressure of pore-water vapour (kPa), $\bar{u}_{v0}$ is saturation pressure of water vapour over a flat surface of pure water at the same temperature (kPa). Actually, the term $\overline{u}_v / \overline{u}_{v0}$ is equal to relative humidity (RH). Hence, Equation (2.19) in $20^{o}C$ and $25^{o}C$ can be simplified:

$$\psi = -135022 \ln(RH) \qquad \text{(at } 20^{o}C\text{)} \tag{2.20}$$

and

$$\psi = -137182 \ln(RH) \qquad \text{(at } 25^{o}C\text{)} \tag{2.21}$$

It means that by measuring the relative humidity (RH) the soil suction can be predicted. RH is relative humidity just above the soil water. As variations in temperature significantly affect soil suction it is imperative to have a clear understanding about how they affect the soil. Using conventional methods of geotechnical site investigation in a specific season in a year, a snapshot of temperature of the soil can be measured. The temperature of the soil is a periodic function. Fluker (1958) recommended the general equation:

$$\theta_{d,t} = \theta_{ave} + A_d \sin(\omega(t - t_d)) \tag{2.22}$$

where, θ_{ave} is the annual average soil temperature, A_d is the amplitude of the sine wave expressed as a function of depth, t_d is the time lag between the peak yearly air temperature and the peak yearly soil temperature expressed as a function of depth $\omega = \pi / 6$, t is the number of months since the first of the year. Pomper et al. (1990) field measurements confirm Fluker's equation (Figure 2.4).

Please see print copy for Figure 2.4

Figure 2.4 Comparison between measured and predicted soil temperature in 4 years duration (after Pomper et al., 1990)

Relative humidity in a constant temperature can be affected by the curvature of the water surface and its salt content. That part of the suction, which relates to curvature is called matric suction (ψ_m) and the part, which relates to salt content is called osmotic suction (ψ_π). Thus, total suction can be written as follows:

$$\psi = \psi_m + \psi_\pi \tag{2.23}$$

The curvature of soil water relates to the capillary action of water, which is associated with the matric suction component of total suction. The radius of the meniscus (R_S) can be calculated from (Kay and Laby, 1973):

$$R_S = \frac{2T_S}{u_a - u_w} \tag{2.24}$$

where, T_S is water surface tension equal to 72.75 dyne/m, u_a is air pressure, u_w is water pressure, $\psi_m = u_a - u_w$ is matric suction, which is a component of total suction. In other words, the matric suction is the value of relative water pressure,

$$\psi_m = |u_w - u_a| = u_a - u_w \tag{2.25}$$

If it is assumed that radius of the meniscus (R_s) is equal to the pore radius (r), the matric suction can be read from Figure 2.5.

Please see print copy for Figure 2.5

Figure 2.5 Relationship between pore radius, and matric suction (after Fredlund and Raharadjo, 1993)

Osmotic suction is part of the soil water free energy which causes water movement based on the conventional osmotic effect or potential energy. As described by Bulut et al. (2001), osmotic suction can be estimated by:

$$\psi_\pi = -\nu.R.T.m.\phi \tag{2.26}$$

where, ψ_π is osmotic suction, ν is number of ions from one molecule of salt (i.e. ν =2 for NaCl, KCl, NH_4Cl and ν = 3 for Na_2SO_4, $CaCl_2$, $Na_2S_2O_3$, etc.), ϕ is osmotic coefficients, which relates to molality, molecular mass of water and water density. Bulut et al. (2001) and Lang (1967) reported the osmotic coefficients of several salt solutions in different temperatures. Therefore, clay minerals, cation exchange capacity, temperature, dielectric constant of the pore fluid and the soil salt content can influence the osmotic suction.

Several devices have been developed for measuring total, matric, and osmotic suction. These devices, with their methods range, and limitation, are shown in Table 2.7. Because most measure the soil suction indirectly, the output of these instruments has no meaning in terms of soil suction until they are calibrated in an environment with known soil suction.

Table 2.7 Soil suction measurement devices and their details

Component measured	Device Name	Suction range (kPa)	Available standard	Test location	Comments	Available types	Reference
Total suction only	Thermocouple psychrometer	100 - 8000	AS 1289.2.2.1	Lab/ Field	Indirect, Electronic recording is possible, but constant temperature is required, and its precision is limited in the wet range, one sample per test	Wescor Dew Point Microvoltmeter with C-51 sample chamber and Peltier Type Psychrometer	Krahn and Fredlund (1972), Fredlund and Raharadjo (1993), Woodburn et al. (1993)
	Isopiestic humidity control	4000-400000	N/A	Lab	Indirect, temperature sensitive, sensitive to salt solution properties, conductible for either wetting or drying paths, equilibrium time depends on sample size, chamber size and moisture content.	Salt bath or osmotic desiccator	Young (1967)
	Polymer resistance/Capacitance sensor	Entire	N/A	Lab	Indirect, inexpensive, fast response time, long term stability, ability to be connected to data logger for continuous monitoring	Thin film capacitance and polymer probe	Wiederhold (1997), Albrecht et al. (2003)
	Transistor psychrometer	100 - 70000	AS 1289.2.2.1	Lab	Indirect, manually applied water drop, accuracy depends on the degree of ambient temperature control, more than one sample in each run	8 and 12 probe SMI transistor psychrometer	Woodburn et al. (1993)
	Two pressure humidity	10000-600000	N/A	Lab	Indirect, computer automated, temperature sensitive, one sample per test, incremental suction measurement	N2 gas system with Vaisala HMI38 humidity/temperature probe	Likos and Lu (2001)
	Chilled mirror hygrometer	100-450000	ASTM D6836	Lab	Indirect, simple and very quick, scatter for high suction values	metallic mirror, Dewpoint Potential Meter (WP4)	Gee et al. (1992), Leong et al. (2003)

Component measured	Device Name	Suction range (kPa)	Available standard	Test location	Comments	Available types	Reference
Matric suction only	Standard tensiometer	0-100	N/A	Lab/ Field	Accurate, good contact is required between the sensor tip and the soil, easily installed, but has difficulties with cavitation and air diffusion through ceramic cup. Should be saturated before the test.	Mechanical Bourdon type pressure sensor Electronic diaphragm type transducer	Cassel and Klute (1986), Stannard (1992)
	High capacity tensiometer	0-1500	*N/A*	Lab/ Field	Small, quick, reliable, high air entry pressure ceramics	Cyclic prepressurisation	Ridley and Burland (1993), Guan and Fredlund (1997)
	Tempe Pressure Cell	0-100	ASTM D2325	Lab	One sample per test, high equilibrium time, not suitable for wetting procedure	1400/1405 Tempe Pressure Cell with 3cm and 6cm cylinders	Soil Moisture Equipment Corp. (1995)
	Hanging column	0-80	ASTM D6836	Lab	Applicable for large samples, can be connected to data logger, capable to be combined with tensiometer-coiled TDR probe	SWC-HCA, 1502C Tektronic cable tester	Or and Wraith (1999)
	Porous block	30-3000	NT Build 420 and ASTM D 2325	Lab/ Field	Indirect, accurate calibration curve is very important	Gypsum block	Bouyoucos (1965)
	Pressure plate	0-1500	ASTM D 2325, ASTM 6836, and ASTM D 3152	Lab	Accurate, simultaneous measurement of several samples is possible, but equilibrium on dry samples is slow	5 bar, 10 bar and 15 bar,	Hilf (1956)

Component measured	Device Name	Suction range (kPa)	Available standard	Test location	Comments	Available types	Reference
Matric suction	Imperial College instrument	0-1500	N/A	Lab/ Field	Accurate and very quick, good contact between porous stone and pressure transducer is required and it can have a wide application in the field	Miniature pressure transducer with Entran Ltd EPX series	Ridley and Burland (1993)
	Centrifuge method	0-120	ASTM D6836	Lab	Indirect measurements, different matric suction are applied by varying the angular velocities,	Temperature control centrifuge	Singh et al. (2001)
	Thermal conductivity sensor	0-1500	N/A	Lab/ Field	Indirect measurement using a variable pore size ceramic sensor, fairly precise, easily installed, but relatively expensive and complex electronics required	AGWA-II, and FTC-100	Phene et al. (1971); Wong et al. (1989)
	Fredlund SWCC Device	0-1500	N/A	Lab	Applying overburden pressure and applying various stress paths, used for both drying and wetting paths, ability to measure diffused air, used for remoulded or undisturbed samples	SWC-150 and SWCC-100	Padilla et al. (2005)
Osmotic suction only	Electric resistance sensor	Entire range	N/A	Lab	Used in conjunction with a psychrometer or electrical conductivity measurement, convenient in situ measurement, but sensitive to change in soil solute concentration	Pore fluid squeezer	Krahn and Fredlund (1972), Campbell and Mulla (1990)
Total and matric suctions	Filter paper	30-30000	ASTM D5298	Lab/ Field	Indirect, Inexpensive, simple, and fast, but continuous monitoring of soil moisture is not possible	Whatman No. 42, Schleicher and Scuell No. 589 White Ribbon, Fisher 9-790A	Gardner (1937), Al-Khafaf and Hanks (1974)

2.11 TREE – GROUND INTERACTION

Previous studies reported that civil engineers have been aware that trees and shrubs help deform foundations placed on expansive and collapsible soils. The effect will be more severe in regions with wet seasons and very dry seasons. As Biddle (1998) and McInnes (1986) reported, engineers have mainly focused on the detrimental effect of vegetation on buildings and pavements. New field observations show that, where there are trees beside railway tracks, their localised, undrained failure is minimised. Using native vegetation beside remote railway lines in Australia to stabilise existing railway corridors built over expansive clays and compressive soft soils has become increasingly popular. Properly selected and used vegetation, including native trees and shrubs, can reduce soil moisture by root water uptake. Moreover, vegetation can increase the shear strength and stiffness of soil by increasing the matric suction and control erosion (Figure 2.6).

Figure 2.6 Trees planted along Railway lines, Coalcliff, NSW, Australia

Potter (2006) conducted extensive tests to investigate the feasibility of using native vegetation to improve rail infrastructure. He concluded that planting vegetation beside the tracks reduces the moisture for a considerable depth and distance away from the trunk. As Figure 2.7 illustrates, his investigations showed that the soil suction under the centre of the track was higher, which resulted in a stiffer and stronger sub-grade.

Please see print copy for Figure 2.7

Figure 2.7 Field measurements of total suction at Miram site in July 2004, (a) non-vegetated, and (b) vegetated (Potter, 2006)

Potter (2006) took samples and tested them in the laboratory to measure the resilient modulus of the sub-grade in vegetated and non-vegetated sites. Potter (2006) found that resilient modulus of the samples obtained from the non-vegetated sites were much lower than from the vegetated sites. He concluded that although vegetation can have undesirable effects, introducing native vegetation can be a method to decrease the soil moisture and increase the performance of the sub-grade. Planting native trees in a way that is likely to reduce soil water content and uniformly increase soil suction is desirable.

When modelling the vadose zone that contains vegetation, details of the root water uptake is required to develop a realistic model. Although current design standards such as the Uniform Building Code (1997) and Standard Australia (1996) provides guidelines for design and construction of footings and structures on expansive clays, none of them provide any guidelines on how ground desiccation caused by native vegetation should be included. Blight (2005) concluded that most investigations of vegetation on the ground were opportunistic and unplanned and that existing models are very simple or are not validated by field data. Existing models only consider the effect of root reinforcement or a very simplified model for root water uptake. Another problem with existing models in geotechnical engineering is that they do no consider the growth rate of roots. The extent and shape of the root system, including changes over time, also play a major role in determining water uptake patterns. Biddle (1998) has conducted the most comprehensive field observations to predict pattern of soil drying in the proximity of trees on clay soils for 60 different cases. These investigation included Horse chestnut, Lime, Norway maple, Oak, Plane, Poplar, Silver birch, White beam and Leyland cypress trees in London, Gault, Oxford, and Boulder clays, and clay silt. Although the root density influences the redistribution of moisture near a tree, Biddle (1998) did not report on root distribution. Gardner (1961) mentioned that the moisture content near a plant was largely influenced by the distribution of its roots. He concluded that according to existing studies the interaction of tree, soil, and atmosphere was variable and unpredictable. Unless this interaction is fully comprehended, an accurate prediction of how vegetation affects structures is impossible. Cameron (2000) records that in Australia the suction under rows of Eucalypt trees may exceed that further away from the trees, down to 6 metres or more. Although the nature of tree species and root systems are important, Cameron (2000) did not considered them in his study. Cameron (2001) and Jaksa et al. (2002) recommended suction boundaries for the top 6metres of soil strata according to the field measurements (Figure 2.8).

Their studies have attempted to cover the lack of guidelines for footing design influenced by trees. The existing guidelines do not distinguish any increase or decrease in suction by depth, lateral distance, and consequently soil shrinkage or swell under the specified tree species, soil, and weather conditions. They conclude that more data was needed to formulate reliable design guidelines. Blight (2005) conducted series measurements of the soil moisture content adjacent to a line of poplar trees and evergreen bushes. Despite the planned and sustained field moisture content recordings, Blight (2005) concluded that the moisture distribution pattern near the native vegetation was very complex, difficult to understand, and that the water content was greatly influenced by hydrological features such as rainfall, evaporation, and transpiration.

Please see print copy for Figure 2.8

Figure 2.8 Recommended total suction profile for (a) single large spotted gums (Depth/Height<0.5) and (b) a group of large spotted gums (Depth/Height <0.8) (Jaksa et al. 2002)

2.12 PREDICTIVE MODELS

Although field measurements of moisture and suction close to vegetation has drawn the attention of soil scientists and engineers, analytical and numerical solutions of moisture flow equations have not interested them because there are no two or three dimensional root water uptake models, which could capture key factors such as root water uptake, soil suction, root distribution, and atmospheric conditions. Furthermore, by introducing such a model into the unsaturated flow equation, a highly non-linear partial differential equation results, which is difficult to solve analytically. The proper initial and boundary conditions of the model also introduce extra complexities. Moreover, coupled flow and deformation modelling is required to determine the real behaviour of ground under transpiration, when the water flows through a porous media.

Two common numerical methods used to predict ground water are the finite element (FE) and finite difference (FD) methods. Some of the main differences according to Stone (1999) are as follows:

i) The grids for the FD model are square or rectangular, whereas grids for the FE models are a mesh of squares, rectangles, triangles, or polygons.

ii) Equations are solved by differentiation using the FD method but by integration using the FE method.

iii) In the FD method, output applies to the node but is assumed to be constant throughout the cell with which it is associated. In the FE method, output may be determined (interpolated) for any individual point between nodes, within the area covered by the grid.

Although predicting the moisture content and suction around a tree or row of trees needs two or three dimensional modelling, different methods for one dimensional flow equations including root water uptake have been presented over the past two decades. Because of the complexity and non-linearity of a flow equation incorporating the root water uptake, researchers were able to solve the problem using a one dimension flow equation. One dimensional analysis is suitable for finding out the distribution and depth of moisture of large, grassed farms. In one dimensional analysis, coupling the flow and deformation equations close to trees is impossible because soil has multi-dimensional stress states. Molz and Remson (1970) considered a very simple root water uptake model, which did not consider soil suction as a limiting factor and assumed a linear distribution for root water uptake rate with depth. They solved a one dimensional flow equation including a root water uptake sink term using the numerical Douglas-Jones (Douglas and Jones, 1963) predictor-corrector method and changing the flow equation to linear finite difference equations with a tri-diagonal coefficient matrix. The predictions of the profile of moisture content compared reasonably with experiments. They concluded that further understanding of the distribution of moisture close to vegetation results from a better physical understanding of the effective distribution of the roots.

Chang and Corapcioglu (1997) developed a one dimensional numerical model for simulating vertical unsaturated soil water flow in cropped soil. They used Borg and Grimes' (1986) model in the analysis, incorporating the vertical growth rate of the roots. Their numerical predictions agreed with the field data for cotton. Mathur and Rao (1999) solved the one dimensional Richard's equation, incorporating rainfall and evaporation terms and validated the model using published experimental and simulation results. After this validation exercise, they included the root water uptake extraction term in the flow equation and obtained the moisture content profile. They showed that the water content and root water uptake decreases over time but did not compare the results of the water content with field measurements or consider the root extraction term. .

Fredlund and Hung (2001) conducted a numerical flow and deformation analysis using a one dimensional root water uptake, which changes linearly from maximum value on surface under the tree to zero at depth $z_{\max}$. The solution of the moisture flow equation as well as the stress and displacement analysis has been obtained using PDEase2D differential equation solver. The stress state variable method has been used in their analysis to consider changes in volume of an unsaturated soil. Although they conducted a coupled flow and deformation analysis, which is the first in this area, a realistic root water uptake and root zone shape have not been considered. In fact, soil suction is a limiting factor for root water uptake and a horizontal and vertical distribution of roots determines the distribution of root water uptake, which must be included in the analysis. They assumed that the root water uptake rate is time independent, which is unrealistic. Also, Fredlund and Hung (2001) have not validated their model with field measurements, they just reported that the displacement predictions have the same pattern as Bozozuk and Burn (1960) monitoring.

More recently Vrugt et al. (2001) developed a three dimensional root water uptake model based on the one dimensional model by Raats (1974). They extended this model by including a radial component and thickness term to the three dimensional model. Then they solved the three dimensional flow equation considering the root water uptake sink term using Van Geunchten (1980) and Mualem's (1976) unsaturated permeability model. Vrugt et al. (2001) used the HYDRUS-3D code to simulate the water flow near an almond tree irrigate for a 16 day period (Figure 2.9).

Please see print copy for Figure 2.9

Figure 2.9 Simulated versus measured soil volumetric water contents around the almond tree employing HYDRUS-3D (Vrugt et al., 2001)

They concluded that after optimising the parameter of the selected root water uptake model and soil hydraulic parameters, the agreement between simulated and measured water content was good, with an overall time-average root mean squared error value of 0.018. However, they have not included the mechanical parameters of the soil in their analysis and only water flow (without the coupling effect of stress and deformation) has been simulated. In addition, rather than accurate field and laboratory measurements of the required parameters, they used genetic algorithms and simplex algorithms to optimise parameter values for HYDRUS-3D model.

Buyuktas and Wallender (2002) developed a three dimensional model for the unsaturated flow equation subjected to root water uptake using a modified SWMS_3D model. This model can incorporate other hydrological features, including evaporation and irrigation. They provided some examples to verify their model against analytical solutions or experimental data. Although they concluded that the model gives satisfactory results and mentioned that the model can predict the ground water table elevation very well, the soil moisture content and suction profiles have not been presented and discussed. Furthermore, as they have not included stress and deformation equations in their analysis, the ground settlement cannot be calculated with their model. Rees and Ali (2006) conducted a finite element analysis to solve Richard's unsaturated moisture flow by incorporating a sink term. The sink term is the rate of root water uptake as a function of depth and lateral distance. Although they mentioned that soil suction is a limiting parameter for root water uptake, suction reduction, which is one of the key factors and is not distributed uniformly within the root zone, has not been considered in their model. Furthermore, the direct effect of distribution of roots has not been considered in their modelling, although they assumed that the root water uptake changes linearly with depth and lateral distance. Although to capture a more realistic behaviour of ground near trees, coupled flow and displacement equations need to be solved simultaneously, they have only solved the flow equation without considering the coupling effect of the solid body. They also concluded that a good overall correlation between field data and numerical predictions existed.

2.13 SUMMARY

Apart from providing natural soil reinforcement, tree roots dissipate excess pore water pressure and produce sufficient matric suction to increase the shear strength of the surrounding soil through transpiration. Transpiration is a continuous process of discharging water from the soil matrix via the tree canopy. Using various forms of native vegetation is becoming increasingly popular in Australia for stabilising soft soils. It is well recognised that vegetation has a number of favourable mechanical and hydrological effects on ground stability.

Most attempts to quantify the effects of vegetation have focused on the mechanical strengthening provided by the roots but ignored the implications of transpiration on the soil pore water pressure. When modelling the vadose zone influenced by vegetation, a detailed consideration of root water uptake is required. Existing models only consider a very simplified model for tree root water uptake implemented mainly in the flow equation. In order to quantify the dissipation of pore pressure and induced matric suction the complex inter-relationship between the soil, plant, and atmosphere should be analysed.

Given the importance of the vadose zone in most geoenvironmental projects, there is a strong need to develop a better understanding of how trees, including root based suction, influence behaviour within this zone. Trees can provide suction up to the wilting point of a soil-root system (approximately 3 MPa) and therefore ground consolidation associated with transpiration increases the strength and stiffness of the soil. This process may be compared with improving soft soil via prefabricated vertical drains and vacuum preloading. The suction induced by transpiration increases the effective stresses, which in turn increases the settlement and stiffness of unsaturated soil.

For a better understanding of the variation of moisture content close to native vegetation, there is a strong need to develop a root water uptake model that includes soil properties, vegetation specifications, and atmospheric conditions. Soil suction, root distribution, and the potential transpiration rate are key parameters that need to be directly included in the model. Subsequently, to accurately analyse the effect of vegetation on ground, the rate of root water uptake must be included in the flow equation and the coupled flow and deformation equations must be solved simultaneously. Furthermore, a realistic shaped root zone must be considered in the modelling because it influences the shape of moisture content, suction, and settlement profiles considerably.