The Role of Roots in Slope Stability

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Abstract

The presence of roots is highly influential on slope stability. The strength properties of the roots and the extensiveness of the root network dictate the degree of mechanical stabilization. Research surrounding this topic has expanded significantly in the last thirty years due to the attention gathered from deforestation in mountainous areas leading to landslides and slope failures (Nilaweera & Nutalaya, 1999). Roots provide mechanical stabilization of slopes through its tensile strength, frictional properties and bending stiffness. An ideal slope contains both fine and coarse roots, as both offer different advantages. Fine roots have higher tensile strengths and are effective at stabilizing the upper soil layers while coarse roots extend into greater depths of the soil and aid in anchoring large volumes of soil. The growth of roots among other factors can create continuous macropores known as soil pipes. Soil pipes improve drainage, which help to dissipate pore water pressure and is especially important in slopes experiencing large volumes of rainfall. However, when soil pipes become eroded and the cavities become blocked, water can build up and cause a slope failure.

Keywords: slope stability, vegetation, root strength, landslide, soil

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Introduction

Plants' roots uptake nutrients and water as well as provide mechanical support against wind, snow and gravitational forces exerted by the plant itself. Roots also aid in binding the soil it is contained within, improving the stability of the slope and reducing soil erosion.

The study of root systems and slope stability is challenging and comprehensive; therefore empirical data on this topic is difficult to obtain. Research is limited due to many methodological issues (Reubens, 2007). Firstly, roots are difficult to sample. They can grow to great depths below the ground and occupy large amounts of area. This makes sampling tedious and highly difficult to gather solid and accurate data. Secondly, trees and shrubs occupy a wide range of root dimensions and are elaborately and extensively intertwined. Thirdly, the complex nature of the interactions between abiotic and biotic features, such as rocks and other debris further complicate the problem.

An exploration of basic soil mechanics is necessary to understand the forces and causes behind slope failures. The principle of effective stress, pore water pressure, seepage and slope stability analysis of soils will be explained in order to better appreciate and understand slope stability. Moreover, human and natural induced activities will be briefly investigated to discover the general processes that cause slopes to fail.

Building on soil mechanics, the effects of roots on the mechanical stabilization of slopes as well as their hydrological implications will then be presented. These are the two main mechanisms by which roots interact with soil when dealing with slope stability (Nilaweera & Nutalaya, 1999). The paper will be divided between these two areas, with a greater emphasis on the mechanical nature. Both the mechanical and hydrological implications will be analyzed and discussed with a qualitative approach. The temporal and spatial factor of roots, specifically root density and stand structure, will be analyzed to understand their role in slope stability. A comparison between hardwoods and softwoods will be made to discover the effectiveness of their roots. Lastly, an examination of the role of vegetation on slope stability will be conducted.

Basic Soil Mechanics

The Principle of Effective Stress

Consider a soil mass that is subjected to a normal stress, σ. This is the stress being applied to a soil plane. Newton's third law states that in order to achieve equilibrium, the stresses in the soil must be equal and opposite to σ. The reactive forces in the soil can be denoted by σ' and *u*, for effective stress and pore water pressure, respectively. Effective stress is defined as the stress acting on the soil particles while pore water pressure is the pressure of the water present in a soil mass.

The principle of effective stress is the single most important principle in soil mechanics (Budhu 2007). Karl Von Terzaghi, whom is considered to be a pioneer of soil mechanics, discovered it in the mid-1920s.

The equilibrium equation is:

$$\sigma' = \sigma - u$$

This principle explains that the deformation of soils is a function of effective stresses and not total stresses (Budhu 2007). Moreover, the principle of effective stress only applies to normal stress and not shear stresses (Budhu 2007). Shear stresses can be defined as the stress applied parallel to the soil plane and is calculated by dividing the applied force over a cross sectional area. Effective stress cannot be a negative value due to the fact that soils cannot sustain tension. However, pore water pressures can be positive or negative. When pore water pressure is negative, suction is present, which results in an increase in effectives stress. Pore water pressure can easily be calculated by the depth of water multiplied by the unit weight of water and is commonly measured using either pore water pressure transducers or by piezometers.

Seepage

As water flows through the soil particles in a soil mass it exerts a frictional drag on the soil particles. The frictional force that acts on the soil particles is known as seepage (Budhu 2007). When seepage occurs downward it acts in the same direction as the gravitational effective stresses, which causes a decrease in effective stress within the soil. Conversely, when seepage occurs upwards, the opposite occurs and there is an increase in effective stress. When the pore water pressure is equal to the normal stress at that point, the effective stress will be zero causing the soil to have no frictional resistance to deformation. Moreover, the soil will have very little strength and slope failures at this point are common. Zero effective stress and upward seepage is also associated with liquefaction and quicksand.

Slope Stability and Factor of Safety

One method of calculating the factor of safety of a slope is by using the assumption of an infinite slope to simplify calculations. As the name implies, an infinite slope assumes dimensions that extend over an infinite distance and deal with planar slip surfaces. Each vertical block is assumed to have the same forces acting on it (Budhu 2007). The factor of safety is calculated by the driving forces, or shear strength of the soil, divided by the resisting forces. The shear strength of soil is based on the Mohr-Coulomb failure criterion, where $\tau_f = \sigma'_n tan\varphi'$ for an effective stress analysis (Budhu 2007).

$$FS=\frac{\tau_f}{\tau_m} \qquad FS=\frac{\sigma'_n \tan\varphi'}{\tau_m}$$

τ_f is the available shear strength of the soil

τ_m is the minimum shear strength required to maintain stability

σ'_n is the normal effective stress

φ' is effective angle of internal friction

A two-dimensional method of calculating slope stability is Bishop's method. It is used for circular slip surfaces and results in only roughly 1% error (Budhu 2007). Simplifying assumptions are made to reduce a two-dimensional analysis into a solvable statically determine problem. The method divides a slope into an arbitrary number of slices where the forces and moments of each slice are then summed up. Increasing the number of slices will result in a more accurate answer but also creates more calculations. The following is Bishop's factor of safety equation for an effective stress analysis (Budhu 2007).

$$FS=\frac{\sum[W_j(1-r_u)+(X_j-X_{j+1})]\tan(\varphi')_j m_j}{\sum W_j sin\theta_j}$$

φ' is effective angle of internal friction
W_j is the total weight of a slice including any external load
r_u is the pore water pressure at the base of each slice
X_j is the interslice shear force
m_j is the moment force of each slice
$\theta_j$is the inclination of the slip surface within the slice to the horizontal plane

Factor of safety can be defined as the resisting forces divided by the driving forces. A factor of safety of less than 1 means the slope has failed while a factor of safety greater than 1 means the slope is intact. Generally, a higher factor of safety costs more financially. Moreover, when human lives are at stake, the factor of safety is well over 1.

Bishop's method and the infinite slopes method of calculating slope stability make many assumptions in order to simplify calculations. It is important to understand that a real life slope stability analysis is a three-dimensional problem and therefore the calculations mentioned above have degrees of error. There are many abiotic and biotic features of a slope that are not taken into account and are very difficult to measure so it is important to always be conservative with the results.

Causes of Slope Failures

Figure 1 - Landslide at Stafford Lake, BC. (Photo: J. Ip)

Figure 2: Closer view of the same landslide (Photo: J. Ip)

Slope failures are initiated by a variety of causes including: natural forces, human misjudgement and activities, and burrowing animals (Budhu 2007). A slope failure in steep, mountainous landscapes can result in shallow landsliding (Roering,J.J. 2003). This is the common erosional process in these environments and is often comprised of colluvial sediments (Roering,J.J. 2003). As the debris flow accumulates along its long path downwards, it deposits sediment and scours the slope along the way. Shallow landslides can have large implications when it occurs near human values. Water quality and fish habitat are at risk, and in areas where unstable slopes border human activity, infrastructure and human welfare are at stake as well. The following are some of the common human and natural induced activities that compromise the stability of a slope.

Erosion

The weathering and transportation of solids on natural slopes is a continuous process. Erosion alters a slope's geometry where it may lead to slope failure. In a forestry example, erosion is commonly seen when the soil is heavily compacted after harvesting. Forest harvesting exacerbates erosion by exposing mineral soil and removing the forest floor. The forest floor protects the underlying soil from the impact of rain drops and helps absorb water. Roads also lead to increased rates of erosion by changing the natural drainage pattern.

Earthquakes

Earthquakes apply seismic loading that reduces the shear strength in soils. These shear forces cause the grains in the soil to compact closer together, reducing the soil pores. Water then quickly fills the spaces between the soil grains. This occurs so quickly that even coarse-grained soils cannot dissipate the excess pore water pressures. This phenomenon is known as liquefaction. Sometimes the dynamic forces are so great that the pore water pressure is increased to values near total vertical stress, resulting in the total effective stress to approach zero.

Rainfall

A slope experiencing prolonged periods of rainfall may be susceptible to failure. Rain saturates, softens and erodes soil by entering cracks in the soil and weakening soil layers due to increasing seepage forces. Failure in these cases can lead to mud slides.

External loading

Loads placed on top of a slope add to the gravitational load and may cause a slope to fail. Conversely, loads placed at the toe of the slope, also known as a berm, increase the stability of the slope. Piling rocks, for example at the berm of a slope can help stabilize weak slopes.

Tension cracks

Although tension cracks may not always be a significant factor in slope failures, they are worth mentioning because they are quite common. Firstly, a tension crack modifies the slip surface. When a tension crack is present, the slip surface intersects the base of the tension crack and not the base surface of the road (Budhu 2007). Secondly, when a tension crack is filled with water, there is a hydrostatic pressure applied along the depth of the crack (Budhu 2007). The result is a decrease in the factor of safety due to an increasing moment of force. Lastly, the tension crack provides an opening for water to seep through the slope and into underlying soil layers. This can induce seepage forces, which compromise the slope.

Figure 3: Tension crack on road surface (Photo: D. Bendickson)

Hydrological Role of Roots

Shallow slope failures can occur when the pore water pressure is increased and effective stress is decreased due to large rainfall events. Site-specific factors, such as "preferential hydrological flowpaths, slope steepness, soil thickness, and material properties" can also contribute to slope failure (Roering 2003).

Roots are responsible for creating macropores and cavities in the soil thereby improving infiltration. However, an increasing rate of infiltration also leads to a higher water table, thus increasing seepage pressures (Ruebens 2007). The contiguous chain of macropores beneath the forest floor that transports subsurface water is known as pipeflow. Pipeflow plays a role in slope stability and landslide initiations "since the spatial variation in hydrologic response is attributed to the influence of pipeflow" (Uchida et al 2001). Researchers have discovered that 50-90% of landslide scars contained soil pipes at the headscarps or origin of the slide. During intense rainfall events, closed ended soil pipes can cause slope instability by preventing the dissipation of water. This causes the pore water pressure to increase, thus lowering the effective stress in the soil mass.

When water enters the cavity of a soil pipe, it accelerates and a frictional drag is exerted on the soil particles. When seepage occurs at high velocities, it can cause erosion. This erosional process is known as piping. This can cause the pipe wall to collapse and result in sediment discharge. Consequently, soil pipes can improve slope stability by improving drainage and lowering pore water pressures (Uchida et al 2001). However, repetitive pipe erosion over prolonged periods of time can be detrimental to slopes. The collapse of a soil pipe will typically divert water to a different outlet, but if the water cannot flow through a different cavity, it will become trapped (Uchida et al 2001). This can cause a large build up of pore pressure that lowers the effective stress of the slope and eventually initiate a landslide.

A majority of the slope failures in unsaturated conditions result from large rainfall and infiltration events. As negative pore water pressure is reduced, the shear strength of the soil decreases below the critical value along the potential slip surface, causing failure. When soils drain rapidly, suction occurs and creates negative pressure. The soil has no real strength and will fail. Decreasing the degree of saturation would decrease the permeability of the soil (Budhu 2007). Increasing the degree of saturation in a soil mass causes an increase in permeability because the existing water film on the soil particles result in a lower frictional resistance to flow. If the soil is not completely saturated, the rate of flow would decrease as the inflow of water works to saturate the soil by filling the voids and forming thin films of water around the dry soil particles (Budhu 2007).

Material properties such as the type of soil and their grain size play a major role in determining the permeability of a soil mass and ultimately, slope failure. Permeability is important because it relates directly to pore water pressure. Fine-grained soils such as clay have much greater surface areas and thus absorb large amounts of water and cause swelling and undrained conditions, while coarse-grained soils are looser packed and have large void ratios. Permeability is indirectly controlled by particle size (Budhu 2007). Since void ratio is a function of particle size, fine particles that exist within the sand would interfere with water flowing through the relatively large pores between the coarse-grained particles. As the fine particles migrate and accumulate in the soil sample, the blockage of water flowing will increase and the result will be a decreased permeability.

Mechanical Role of Roots

Roots provide mechanical support to a soil mass through its tensile strength, adhesive and frictional properties (Ruebens 2007). Roots growing perpendicular to the soil surface provide resistance to shearing forces acting on the soil. Roots extending parallel to the soil reinforce the tensile strength of the soil zone. A soil mass is reinforced not only by these two strengthening aspects but also in terms of the spatial distribution it occupies.

Fine roots (1-2 mm in diameter) are a tertiary root system and represent less than 5% of a tree's biomass but provide more than 90% of the water and nutrient uptake of all roots (Schwarz et al. 2009). Coarse roots are greater than 2 mm in diameter and consist of 15-25% of a tree's biomass. They can be broken down into four classes: taproot, lateral roots, basal roots and adventitious roots (Schwarz et al. 2009). These classes can be subdivided to primary and secondary roots, with secondary roots stemming from primary roots that originate from the root system. There is documentation proving a positive correlation between fine roots and soil reinforcement but the same cannot be said of coarse roots as its data is unproven. The effectiveness of coarse roots highly depends upon its depth and spatial density. If the spatial density is not sufficient, the strengthening effect of the roots is negligible as the soil can easily move around the roots. In general, fine roots are more effective at soil reinforcement but for shallow slope stability, the advantage of fine roots is less obvious. The major factors that govern shallow slope stability are: number, size, tensile strength and bending stiffness of roots penetrating the failure planes (Ruebens 2007). A greater quantity of fine roots is more effective at reinforcing the soil than a smaller number of coarse roots since tensile strength increases as root diameter decreases. Furthermore, during a slope failure, fine roots tend to break off but remain fixed within the soil, while coarse roots can simply slip out. However, only coarse roots can penetrate great depths and firmly anchor the soil mass. Moreover, by extending deeply, coarse roots can fix large volumes of soil and reinforce shallow slopes. Coarse roots also have a higher bending stiffness meaning it can withstand greater bending stresses than fine roots. It is ideal to have a combination of both fine and coarse roots. A large density of fine roots in the upper layers of the soil stratum aids in resisting tension while coarse roots extending deep into the soil and crossing shear planes provide stability from bending and shearing forces.

The effectiveness of mechanical slope stabilization depends on the depth of the weakest soil zone, the likely failure mechanism and the steepness of the slope (Ruebens 2007). The environment surrounding the soil plays a large role in determining the effectiveness of root fixation. Factors that hinder the growth of roots, including but not limited to rocks and a water table, reduce the significance it has on a slope. The soil type also plays a significant role in determining the effectiveness of roots for the texture of the soil can influence the resistance of uprooting while the soil's nutrient level may dictate the spatial density and distribution of roots.

Root reinforcement of slopes - Hardwoods vs. Softwoods

Tree species has an effect on slope stability due to the variability of root strength between species. Each species has its own unique root depth, density and spatial distribution. Some species have shorter life spans while others are more prone to disturbances. Hardwoods, specifically red alder, are noted to have a competitive advantage over softwoods in recently disturbed areas and are often the first to regenerate (Roering 2003). Studies conducted in the Oregon Coast Range have shown that many landslides have occurred in close proximity to hardwoods. It was discovered that over 60% of the landslides occurred an average of 6 m or less away from a live hardwood while nearly 80% of the landslides were a distance of 6 m or greater from a live conifer (Roering 2003). Due to the short life span of red alder and some hardwood species, there may be periods where soil reinforcement from root penetration is lacking.

It was discovered that both hardwoods and conifers have similar median rooting depth values. However, conifers were found to have over 25% of their roots penetrating depths greater than 60 cm and 10% of the roots at depths of 90 cm. In comparison, only 0.5% of hardwood roots reached depths of 90 cm (Roering 2003). A greater rooting depth can reinforce a larger volume of soil and potentially reduce the risk of landslides.

Spatial-temporal factors of roots

Three plantations of Japanese cedar were studied to determine the influence of various parameters on slope stability. The study helped to show the differences in root density and slope stability depending on stand age and structure. Root density was found to be highest in the juvenile stand, but decreased in the intermediate stand and increased again in the mature stand (Genet, 2008). Similar findings of root density over time have been documented in other species (Genet, 2008). It is unclear what causes peaks in root density over different ages of tree development. However, at the juvenile stage, root density increases quickly because younger trees need to allocate more resources to belowground biomass in order to uptake water and nutrients. As a tree reaches maturity, there is an increase in root density, perhaps due to the decrease in aboveground biomass as a result of a lack of nutrients. There is less demand for nutrient and water from fine roots at maturity because the productivity and relative amount of tree foliage biomass decreases (Genet, 2008). As a result, the fine roots eventually become coarse roots in order to provide structural support for the mature tree.

In the three plantations, root density was found to be greatest in the upper 0.20 m of soil. The upper soil layers consist of greater nutrients and better aeration and moisture content. Root density decreased dramatically with depth due to the lack of nutrients and favourable growing conditions.

Through the calculations of factor of safety, stage age and stand structure were found to have an effect on slope stability. Juvenile and intermediate stands were discovered to have the highest values of factor of safety while mature stands had the lowest. The factor of safety for juvenile stands without roots was 1.59 and 2.03 with roots, 1.58 and 2.03 for intermediate stands and 1.32 and 1.54 for mature stands (Genet, 2008). Vegetation increased the factor of safety at all stand ages by 15-27% but had the greatest increase in the juvenile stand (Genet, 2008). This can be attributed to the high stems per hectare and high root density of younger stands. A partial reason why mature stands had a lower factor of safety was a result of the large openings common in older stands. The factor of safety was also found to increase as the number of trees increased and the distance between trees decreased (Genet, 2008). It is therefore important to be extremely careful when planning to implement any silvicultural treatments on unstable slopes, especially in aging stands.

The Influences of Vegetation

The primary factors reflecting the effect of vegetation on slope stability are documented by J. R. Greenwood. These include: enhanced cohesion, additional weight added from vegetation, windthrow force, increasing strength of soil due to the removal of moisture by roots. Figure 4 shows the factors that Greenwood incorporates in his calculation of slope stability.

Enhanced Cohesion

The additional effective cohesion (*c'*) is difficult to measure and hence the contribution it has on slope stability is hard to quantify. Since the distribution of roots is concentrated within 1 m of the surface of the soil, the contribution of *c'* is limited to this area. Fine roots provide cohesion to the soil and values of *c'* are typically measured in the laboratory with direct shear tests.

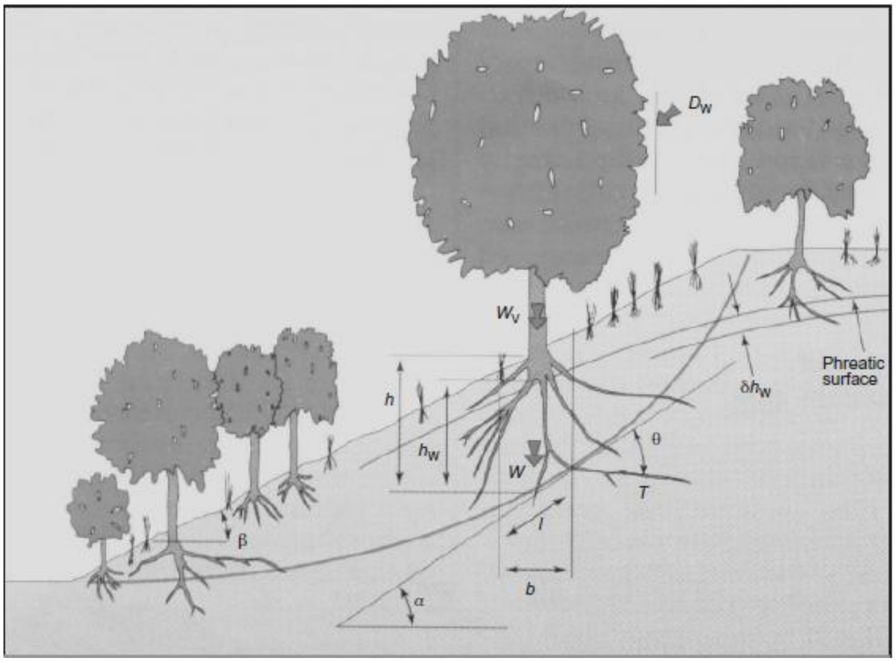

Figure 4- Role of vegetation in slope stability (Greenwood 2007)

Hw - average piezometric head at base of slice

h - average height of slice (m)

β - angle between wind direction and horizontal (often assumed equal to slope angle) (degrees)

Wv - increase in weight of slice due to vegetation (or surcharge) (kN)

Dw - windthrow force (downslope) (kN)

T - tensile root or reinforcement force on base of slice (kN)

W - total weight of soil in slice

l - length (chord) along base of slice (m)

α - length (chord) along base of slice (m)

θ - angle between direction of T and base of slip surface (degrees)

δhw - increase in average piezometric head at base of slice (due to vegetation) (m)

The mass of vegetation

When large trees with a diameter at breast height (dbh) greater than 0.3 m are present, their mass will influence the stability analysis (Greenwood 2007). A tree with a dbh of 0.8m and height of 30m will weigh approximately 100-150kN (Greenwood 2007). This tree, growing at the toe of a slope could add 10% to the factor of safety (Greenwood 2007). Conversely, the same tree growing on the top of the slope will cause external loading and the factor of safety could be reduced by 10%.

Windthrow forces

The influence of wind loading is significant when considering the stability of a single tree. The loss of a tree results in a reduction of moisture removal as well as soil anchorage. Furthermore, this could be critical on slopes of marginal stability. However, windthrow forces are not as significant compared to other parameters governing slope stability, especially when trees are clustered and are protected from pull out.

Figure 5: Windthrow initiated landslides along block boundaries (Photo: D. Bendickson)

Soil strength increase due to moisture removal by roots

The removal of moisture by roots, especially during periods of prolonged rainfall, narrows the window of failure (Greenwood 2007). Desiccation cracks caused by vegetation are similar to tension cracks; they provide a channel for water to seep into the ground surface and cause seepage forces. However, vegetation will typically exploit these cracks and extend their roots and follow these pathways.

Conclusion

The role of roots in assessing slope stability can be narrowed to two factors: mechanical and hydrological. From a mechanical perspective, roots help to stabilize the soil through their tensile strength, adhesive and frictional properties. The strength and spatial distribution of roots within the soil are major variables to consider when assessing the degree of soil reinforcement influenced by roots (Nilaweera & Nutalaya, 1999). In terms of the hydrologic effects of roots, they aid in reducing the soil moisture and effectively dissipating the pore water pressure through evapotranspiration and water absorption through the fine roots. Roots also create channels within the soil for water to travel, known as soil pipes. Soil pipes aid in infiltration and dissipation of moisture but over time soil pipes can become eroded and eventually block water flow, causing a large build up of water and eventually lead to slope failures. The role of roots in slope stability is an extremely important topic, especially when human lives and infrastructure are at risk. By focusing more research and efforts into understanding the mechanics of roots in slope stability, we can take advantage of utilizing trees and other vegetative options to stabilize slopes, as it is an inexpensive and environmentally friendly alternative to other methods.

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