Effect of Vegetation on the Stability of Slope: An Analytical Approach for Chandil Site

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Abstract. There are several environmental factors which affect the stability of slope namely, pollution intrusion, rainfall, seasonal effects, tree roots, wind effect, etc. More recently, soil bioengineering has adopted the method of using vegetation to improve soil slope stability against erosion & failure. The Vegetation can affect soil slope stability by either changing the soil moisture regime or contributing to soil strength by roots. This paper provides a critical review on the importance of vegetation for soil stability on a slope by simple analytical models that may be used to calculate soil reinforcement by the roots and water infiltration into the soil with the help of limit equilibrium method. For the analysis purpose, a real case of Chandil site near Jamshedpur has been studied on forested and clear-cut slope. The effect of the presence of vegetation on pore pressure due to change in water regime and reinforcement of soil by roots have been studied. Simple models have been made to evaluate the effect of evapotranspiration, suction relation on peizometric head in slope, root reinforcement and soil root interaction mechanism. Based on the root density and root geometry, the improved shear resistance of soil on slope in case of forested and clear-cut condition has also been determined. Some concluding remarks have also been made related to soil moisture suction and evapotranspiration on forested slope.

Keywords: Soil Bioengineering; Soil Moisture Regime; Limit Equilibrium Method (LEM)

1 Introduction

Different kinds of vegetation in different manner may influence the stability of slopes viz. the ability of grasses to stabilize steep slopes on sand (Olson, 1958), the buttressing by stems of trees (Gray, 1978), and the reinforcement of the soil by roots of the vegetation (Waldron, 1977; Wu et al., 1979). In addition to the above, vegetation also plays an important role in the soil moisture regime (Nagamatsu and Miura, 1997). To limit the scope of this paper, only the effect of vegetation on stability analysis by conventional methods of limit equilibrium has been considered. In such an analysis the shear strength(s) along a potential slip surface (Fig. 1) is considered to be fully developed at the point of failure. In an effective stress analysis, the shear strength of the soil is

$$s = c' + (\sigma - u)\tan\phi' \tag{1}$$

Where,

c' = cohesion

ϕ' = angle of internal friction

σ = normal stress, and

u = pore water pressure θ

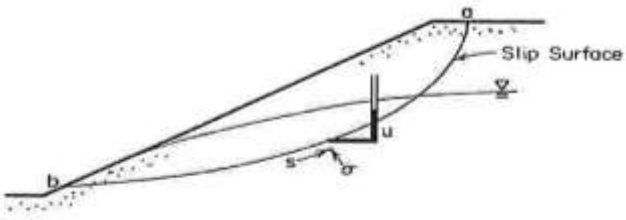

Fig. 1. Slip Surface for Limit Equilibrium Analysis

Soil bioengineering (SBE) has become increasingly popular in riverbank restoration works and in the management of hill and upland slopes. Usually the living as well as the dead plants have been used to stabilize soil against erosion and slope failure. Over the years, numerous applications of SBE in different climatic zones worldwide have been reported in the literature (Wu et al., 2015). However, it is an well accepted fact that SBE is still far from the sophistication of conventional engineering practice with the safety factors coded in standards and norms. This is largely due to the difficulties in quantifying the effect of vegetation on the slope stability. Moreover, there are some uncertainties associated with the SBE applications concerning safety level, life time and load combinations (Wu et al., 2015).

In general, vegetation can be beneficial for slope stability in several ways (Wu et al., 2015), namely, "(a) the leaves of plants act as cushion and reduces the impact of rain drops reducing the surface runoff and the susceptibility of surface erosion and soil degradation. The canopy of plants provides a protective cover against precipitations. The positive effect of vegetation in erosion control is well recognized but difficult to quantify. Since the safety is usually not relevant for erosion control, a quantitative analysis of the effect of vegetation is not necessary. However, plant canopy has significant influence on the amount of surface runoff and infiltration water, which have important bearing on the stability of slopes. Moreover, the infiltration water is used as boundary condition for some advanced analyses. Often the runoff and infiltration depend on the climatic conditions, vegetation cover and species and soil conditions.

(b) Consumption of water by plants from ground for their growth is done by transpiration. The water content in the vicinity of plant roots is often reduced, which gives rise to lower pore water pressure and higher suction force. Transpiration by plants may have large influence on the pore water pressure and water content in soil. A detailed study of the problem requires a coupled analysis of the hydrological and mechanical systems of soil and plant roots. Moreover, climatic boundary conditions and initial conditions of water content need to be specified. Transpiration is most active in dry weather with high temperature but negligible in wet weather with low temperature.

(c) Plant roots penetrate through soil to acquire water and nutrients, which gives rise to a composite material of soil and fibrous plant roots. Stronger roots can grow across failure surfaces to provide strong anchoring points. Compared with (a) and (b), soil reinforcement by plant roots is highly relevant for the structural stability of slopes and can be reliably quantified. The degree of reinforcement depends mainly on the root architecture and root mass. As plants and their roots grow, the root reinforcement will change along with time. For SBE slopes, the slope stability immediately after the installation of plants is usually the most critical phase since the plants grow and become stronger."

When vegetation is present, the roots may intersect the potential slip surface. The contribution of roots to the shear strength should be evaluated. In addition, in the effective stress analysis, it is necessary to estimate the pore pressure. Then the effect of vegetation on the soil moisture regime should be considered. Thus, when the stability of a slope with vegetation is compared with that of a bare slope, the effect of vegetation on slope stability is composed of two elements: differences in pore pressure due to changes in the soil moisture regime and soil reinforcement, which is the contribution to the soil strength by the roots. The roots are loaded under tension and compression depending upon the location also affects the strength of soil (Schwarz et al., 2015) as shown in Fig. 2. There is much empirical evidence in support of these concepts. Observations have been made to compare the stability of forested hillside slopes with that of slopes after the trees had been removed by clear cutting. The slope failure frequency was found to be much greater on slopes after deforestation (Bishop and Stevens, 1964; Megahan and Kidd, 1972; Swanston, 1970; O'Loughlin, 1974). Creep movements have been found to be larger on clear-cut slopes than those on forested slopes (Gray, 1977). To make quantitative predictions of slope stability and account for the effect of vegetation is extremely difficult. In this paper the basic mechanisms that control pore pressure and soil reinforcement are summarized, available data are examined, and possible applications are indicated. Inadequacies in current knowledge and needs for research are also presented.

2 Methodology

2.1 Location

Coordinates of Chandil site are 22.97°N 86.05°E. It has an average elevation of 246 meters (807 feet). Chandil is a census town in Seraikela, Kharsawan district in the state of Jharkhand, India. Chandil is surrounded by green mountains, hills, streams, and rivers. The forests of Chandil come under the category "Dry peninsular Sal (Shorea *robusta*)" and "Northern Dry Mixed Deciduous Forest". Most part of Chandil forests shed leaves in the summer and attains its full bloom at the onset of monsoon (Bhattacharya et al, 2015).

2.2 Data Collection

The samples and other data were collected from the Chandil forest area and the allied slopes. The soil samples were collected from the slopes which were disturbed, and recent clearing of the vegetation has been done for the highway project. Other data like rainfall intensity, precipitation and evapotranspiration were obtained from the website of the Indian Meteorological Department. Lab tests were also performed to obtain the properties of the soil sample collected.

2.3 Numerical Methods

The limit equilibrium method (LEM) assumes the equilibrium along a failure surface, where the soil strength is fully mobilized simultaneously, e.g. Bishop's method of slices. The LEM is easy to use and requires few material parameters (unit weight, friction angle and cohesion). Usually the minimum safety factor is obtained by comparing the safety factors of many possible failure surfaces (Metya and Bhattacharya, 2016a, b). The simplest case of analysis using LEM is an infinitely long slope. This failure surface is relevant for shallow slides, where the sliding plane is parallel to the slope surface (Baum et al., 2008). Forces due to anchorage (soil nail), geogrid reinforcement, earthquake and seepage can be easily incorporated. The LEM can be easily adapted to consider the reinforcing effect of SBE. Plant roots can be considered individually as discrete elements or collectively as enhancement of the soil shear strength. Individual plant roots can be treated similar to anchor elements and geogrid reinforcement. In this case, the root orientation relative to the sliding surface need be considered. For plants with large number of fibrous roots, a smeared approach of increasing soil cohesion seems more appropriate. Although the major difficulty is the characterization of root architecture and root mass.

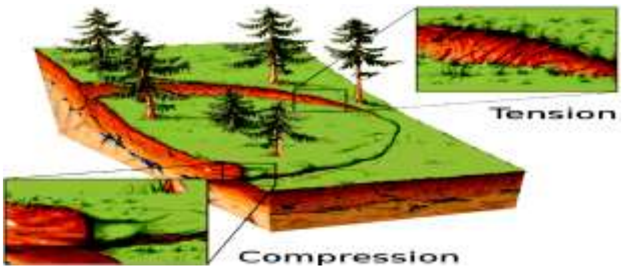

Fig. 2. Loading of roots under tension and compression depending on their position (lateral or at the toe of the slope) during the triggering of a shallow landslide. The unstable soil mass pushes down, creating passive earth pressure conditions in the down slope edge (after Baum et al., 2008).

3 Observed Data

Although skepticism about the ability to predict the soil-moisture regime should be maintained, it is also known that analytical models are useful in the study of effects of various parameters on infiltration and soil moisture. Many such studies have been done. Wu (1984) used a simple model to evaluate the effect of evapotranspiration and moisture-suction relation on the piezometric level in the slope. The results obtained from the model can be interpreted as the increase in evapotranspiration leads to increased piezometric head and thus the pore water pressure increases. On the basis of evapotranspiration data (Fig. 3), it can be interpreted that pore pressures in 2014 were about equal to or higher than those in 2018, although the rainfall in 2014 was considerably less than that in 2018 (Fig. 4). This data can also be interpreted to mean that evapotranspiration is higher on the slope with regrowth and forest cover than on the cut-over slope. Nevertheless, it is premature to make a general statement on the basis of the limited number of observations because the effect of trees may well depend on climatic factors, particularly the relative amounts of evapotranspiration and precipitation (Rice et al., 1972). Because of the difficulties encountered in predicting the piezometric level or soil moisture suction by analytical methods, empirical data obtained from well-designed field measurements will remain the most important source of information for some time to come. Moreover, it has been found that the root geometry and root density also contribute to the reinforcement of soil (Waldron and Dakessian, 1981). It was also found some species have similar behaviour in stabilization of soil slope. In view of the above, a comparative study has been carried out in this paper with the vegetation of Chandil area and the previous research works on other species (Table1, Fig. 5).

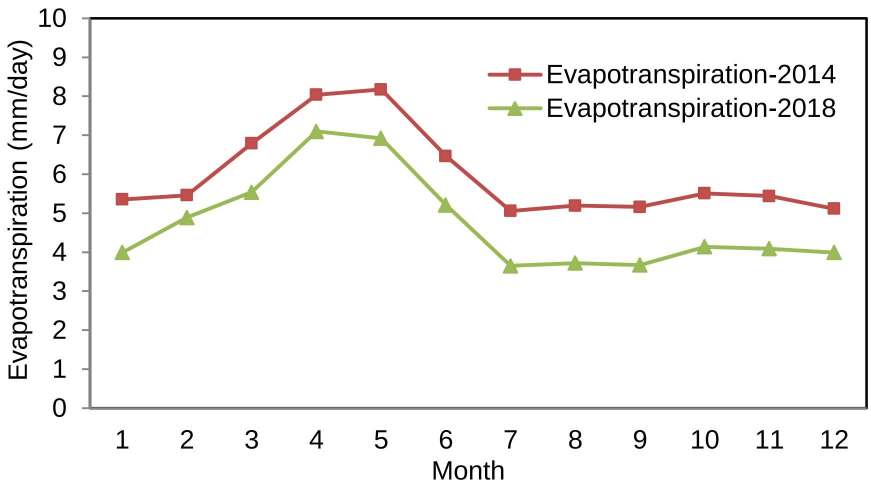

Fig. 3. Graph showing Evapotranspiration during the year 2014 and year 2018

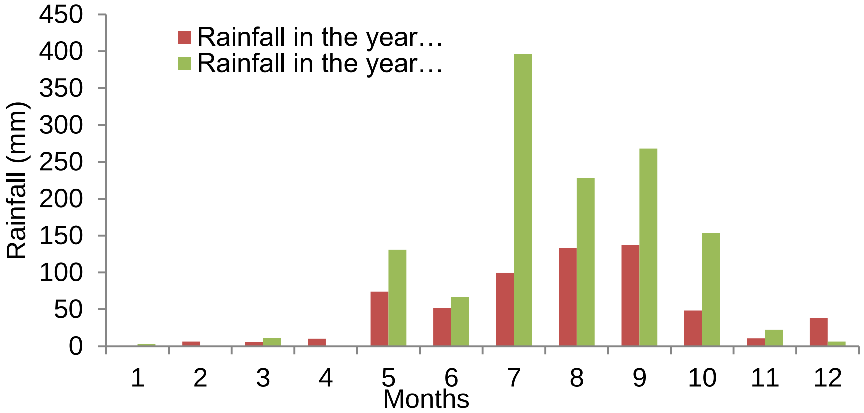

Fig. 4. Graph showing rainfall during the year 2014 and year 2018

Table 1. Measured Root Density in Chandil Area with the data available from Maybeso Valley (Wu, 1984)

S. No	**Tree & Dia. (m)**	**Depth of Pits (m)**	**Area of Pit (m^2)**	**Root Density (m^{-2}) according to Dia (mm)**												
				0.8	**1.6**	**2.4**	**3.2**	**4**	**4.8**	**5.6**	**6.4**	**7.9**	**9.5**	**11**	**12.7**	**$\sum T_{ri}/A$**
1	Sorea Robusta, 0.51	0.51	3.2	29.8	31.2	19.4	6.9	2.4	0.8	0.27	0.98	0.6	0.1	0.7	0.24	4.8
2	Hemlock, 0.15	0.45	6.8	14.5	15.7	7.9	8.7	1.4	1	0.7	0.3	0.3	0.8	0.1	0.7	5.6
3	Sitka Spruce, 0.36	0.48	2.9	38.6	40.8	18.6	8.5	1.7	1	0.3	0.9	0.3	0	0	0	4.3

From Table 1, closeness of results have been observed between the Sorea *robusta* (in the present study) and the Sitka *spruce* (Wu, 1984) in terms of the contribution of i^{th} root to resisting shear stress (**$\sum T_{ri}/A$**) based on root density of the species.

4 Analytical Analysis

The strength of a soil containing roots can be considered as a special problem of reinforced earth. The simplest model, in which the reinforcement is equal in all directions (isotropic reinforcement), considers the reinforcement to increase the minor principal stress by

$$\sigma = \frac{A_r t_r}{A} \tag{2}$$

Where,

A_r = area of reinforcement,

t_r = tensile stress in reinforcement, and
A = area of soil

The result is that the reinforcement is equivalent to cohesion (c_r) (Wu, 1976). Because of the variety of root morphology, a complete solution of the root reinforcement problem is likely to be complex. However, it is possible to outline the general concepts of root reinforcement as shown in Figs. 3 and 4. In Fig. 3(a), the potential slip surface (ab) intersects the roots of the tree at c. In case of failure to occur along ab, the roots must also fail in tension, shear, or bond or some combination of all three. The position of a root c after shear displacement Δ has occurred along· the slip surface is shown in Fig. 3(b). The forces on the root are T_n, T_s, and M. If a three-dimensional failure surface is considered (Fig. 4), the roots that intersect the end surfaces would be displaced in a similar manner. To evaluate the contribution of the roots to stability, T_n, T_s, and M must be determined. If the root is small and flexible, M = 0 and simplified solutions may be found (Wu, 1984). One simplification is that at large shear displacements associated with failure, $\Theta = 90^{\circ}$, then the root's contribution to shearing resistance along ab [Fig. 3(b)] is simply T_r, which may be taken to be the tensile resistance of the root. Here tensile resistance is used to denote the maximum value of T that can be resisted by the root. Failure usually occurs as a combination of tension and bond failures. A similar simplification may be made for the shearing resistance on the end surfaces shown in Fig. 5.

4.1 Theoretical Approach

Waldron (1977) and Gray and Ohashi (1983) considered the elastic elongation of the root in the shear zone, whereas Wu et al. (1979) used the tensile resistance of the root and Θ at failure. Both analyses lead to the expression

$$c_r = B \sum_i T_{ri} / A \tag{3}$$

Where,

c_r = equivalent cohesion due to root reinforcement,
B = factor that accounts for the direction of the roots and is about 1.2 for $\phi=30^{\circ}$,
T_{ri} = resistance of the i^{th} root, and
A = area of the shear surface.

For the clear-cut slopes, the shearing resistance consists of the shear strength of the soil only. For the forested slopes the shearing resistance is

$$s_r = s + c_r = c' + (\sigma - u) \tan\phi' + c_r \tag{4}$$

In Eq. 4, c_r is as given by Eq. 3.Because the tensile strength of roots varies with the root diameter, the quantity $\sum T_{ri}$ must be calculated separately for the different size groups as shown in Table 1, The safety factor is about 1.3 for a slope covered with a mature forest of Sorea *robusta*, western hemlock& Sitka *spruce* and about 0.9 after the trees have been removed. For cuts in cohesive soils, the initial stability is governed by the undrained shear strength. Long-term stability under the drainage condition is controlled by the effective stress parameters c' and ϕ', If c' = 0, as is the case for many clays (Skempton, 1964), and the slope angle is greater than ϕ', shallow slips would occur during the wet season when the soil near the surface is saturated. If vegetation is present on the slopes, the roots contribute a cohesion c_r and may reduce the number of slips. In case of Chandil, the soil was of c-ϕ type with low cohesion and it was found that the value of 's_r' and 's' calculated were 18.3 kN/m^2 and 3.6 kN/m^2 respectively.

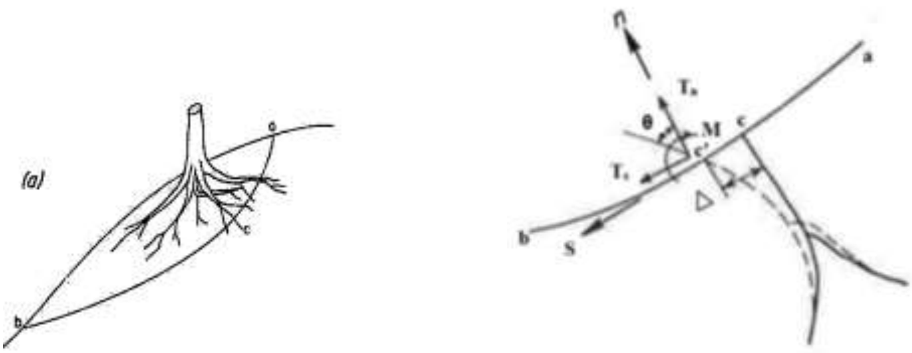

Fig. 5. Soil reinforcement by root (a) intersection of root with slip surface (b) forces on root and root displacement (after Wu, 1984)

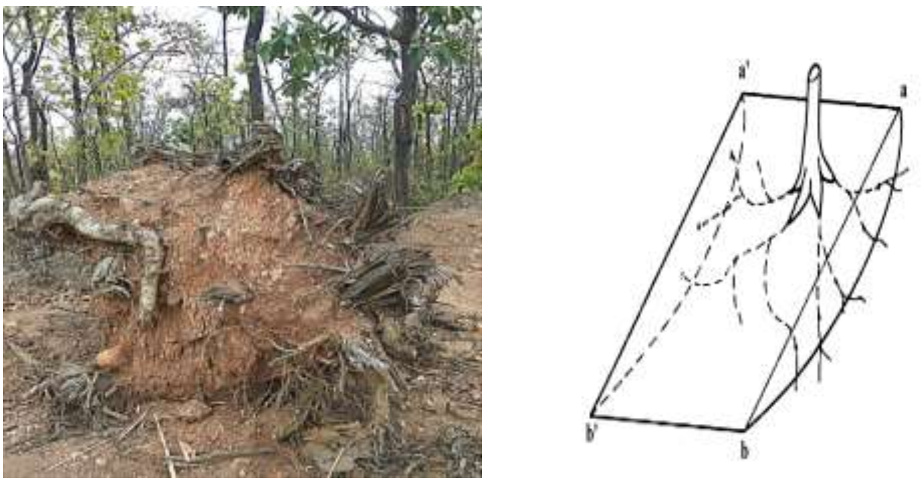

Fig. 6. Intersection of roots with the ends of cylindrical slip surface

4.2 Balancing the Resisting Moment

Three-dimensional failure surfaces are common in reality. Most natural slopes are not uniform. There are special variations in soil and root strengths and in slope geometry. Drainage depressions that run in the down slope direction usually concentrates groundwater flow, and the peizometric surface is closer to the ground surface in these depressions than it is in the surrounding area (Pierson, 1979). The slope at the head of a depression is also steeper than the average slope. Hence, failure usually involves a bowl-shaped surface, as shown in Fig. 5. Such failures have been described by Swanston (1970) and Riestenberg et al. (1983), among others. Simplified three-dimensional failure surface is shown in Fig. 6. The end surfaces are assumed to be planes. The effect of the lateral roots that intersect the end surfaces is considered. The measured shear strengths (s_r) of the soil-root system are correlated with the weight of the biomass. To compute the resistance of the end surfaces, the lateral roots are assumed to be concentrated in a layer with thickness H_r as shown in Fig. 6. In this zone the shear strength of the soil-root system is s_r. If Eq. 3 is assumed to apply,

$$s_r = s + c_r \tag{5}$$

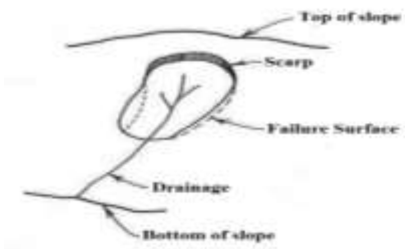

Fig. 7. Slide at the head of the drainage (after Wu, 1984)

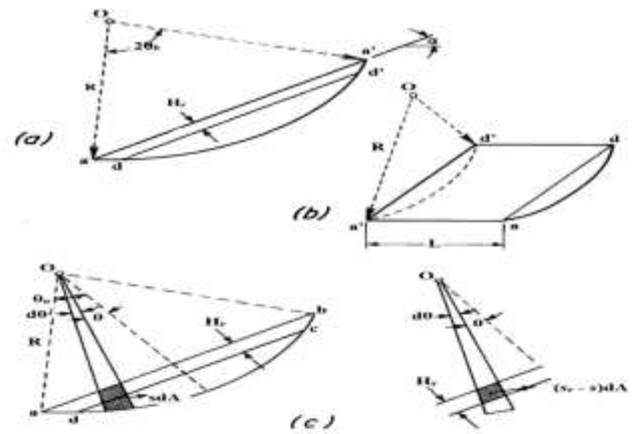

Fig. 8. Three Dimensional Slip Surface: (a) Side View, (b) Perspective View and, (c) Computing of resisting moment (after Wu, 1984)

The simplified solution for the resisting moment about O is obtained as follows. Consider the slip surface shown in Fig. 6(c). The resisting moment of *s* on the cylindrical surface ac is:

$$M_{R1} = sL2\theta_0 R^2 \tag{6}$$

The resisting moment of *s* on the end surface is:

$$dM_{R2} = sdAr$$

$$= s\ R\ d\theta \left[R - R\left(\frac{cos\theta_0}{\cos\theta}\right)\right]\left\{R - \left(\frac{1}{2}\right)\left[R - R\left(\frac{cos\theta_0}{cos\theta}\right)\right]\right\}R^3\left[1 - \left(\frac{cos^2\theta_0}{cos^2\theta}\right)\right]d\theta$$

$$M_{R2} = 2sR^3\int_{-\theta_0}^{0}\left[1 - \left(\frac{cos^2\theta_0}{cos^2\theta}\right)\right]d\theta$$

$$M_{R2} = 2sR^3 cos\theta_0 sin\theta_0 \tag{7}$$

The resisting moment of (s_r - s) in zone abcd is:

$$M_{R3} = 4(s_r - s)DR^2cos^2\theta_0\int_{-\theta_0}^{0} d\theta = 4(s_r - s)DR^2\theta_0 cos^2\theta_0 \tag{8}$$

The resisting moment of (s_r - s) on the cylindrical surfaces ab and cd is:

$$M_{R4} = 2(s_r - s)L\left(\frac{D}{sin\theta_0}\right)R \tag{9}$$

The total resisting moment is:

$$M_R = M_{R1} + M_{R2} + M_{R3} + M_{R4}$$

$$M_R = sL2\theta_0 R^2 + sR^3(2\theta_0 - cos\theta_0 sin\theta_0) + 4(s_r - s)DR^2\theta_0 cos^2\theta_0 + 2(s_r - s)L\left(\frac{D}{sin\theta_0}\right)R \tag{10}$$

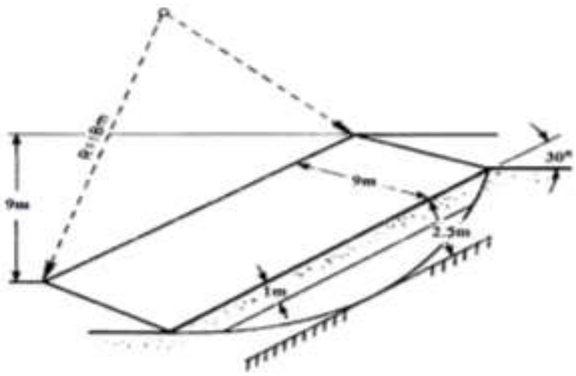

Fig. 9. Stability and Analysis of Three Dimensional Slip Surface (after Wu, 1984)

As an illustration the stability of the slope shown in Fig. 7 is calculated. It is assumed that the stiff bottom restricts the slip surface. The roots are assumed to be concentrated in the top 1 m. The values of s and s_r are taken from Ziemer's data (Ziemer, 1981). The computed driving and resisting moments are 12 mN-m, 14 mN-m, 8 mN-m, 10 mN-m, 44 mN-m and 41 mN-m respectively for M_{R1}, $M_{R2,}$ $M_{R3,}$ M_{R4}, M_R and M for the value of s, s_r and γ as 4 kN/m^2, 20 kN/m^2 and 16 kN/m^3 respectively. It can be seen that the lateral roots contribute, in this case, about 40 percent of the resisting moment. Without the contribution of the roots to shear strength, the slope would not be stable.

5 Summary & Conclusions

This paper shows the basic mechanisms of the influence of vegetation on the soil moisture regime and root reinforcement. From the results reported in this study, it can be interpreted that in case of Chandil site, the pore water pressure is higher on the slopes (with vegetation) than the clear-cut slope. Moreover, the soil containing vegetation is a special case of soil reinforcement in which the radial roots which penetrates through the slip surface contributes about 40% to the shear strength of soil. For the soil type present in Chandil site, it was observed that value of 'c' is relatively low and hence slope is more susceptible to failure viz. controlled by the roots of vegetation. The FOS for the year 2014 was more as compared to the year 2018. Thus, it has been observed that after the removal of vegetation due to the widening of Chandil Highway, landslides have become more common. However, the soil-plant system presents a complex coupled problem, which poses great challenge for numerical modeling. Further, it is not very easy (if not possible) to simulate all problems precisely with numerical modeling, because some parameters cannot be put in numbers.

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