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Publication of this paper sponsored by Committee on Engineering Geology.

Effect of Vegetation on Slope Stability

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ABSTRACT

Two ways are considered in which vegetation can affect slope stability: changes in the soil moisture regime and contribution to soil strength by the roots. Simple analytical models that may be used to calculate water infiltration into soil and soil reinforcement by roots are reviewed and their applications to stability problems are illustrated by examples. The need for reliable field data to support the analytical models is emphasized.

Different types of vegetation affect slope stability in different ways. These include the ability of grasses to stabilize steep slopes on sand (1), the buttressing by stems of trees (2,pp.253-306), and the reinforcement of the soil by roots of the vegetation (3,4). In addition, vegetation plays an important role in the soil moisture regime. To limit the scope of this paper, only stability problems analyzed by conventional methods of limit equilibrium will be considered. In such an analysis the shear strength(s) along a potential slip surface (Figure 1) is considered to be fully developed at the point of failure. In an effective stress analysis, the shear strength of the soil is

$$s = c' + (\sigma - u)\tan \phi' \qquad (1)$$

where

c' = cohesion,
ϕ' = angle of internal friction,
σ = normal stress, and
u = pore pressure.

The shear strength of the soil is determined by means of appropriate laboratory tests, and u must be estimated or measured in situ.

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. 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 frequency of slope failures was found to be much greater on slopes after clear-cutting (5-8). Creep movements on clear-cut slopes have been found to be larger than those on forested slopes (9). 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.

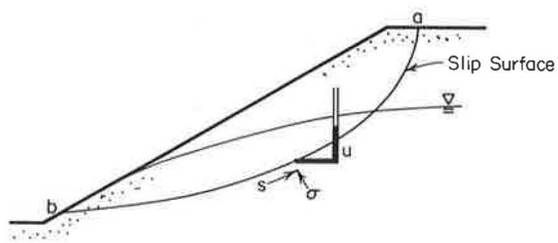

FIGURE 1 Slip surface for limit equilibrium analysis.

SOIL MOISTURE REGIME

Vegetation may influence the soil moisture regime in many ways. The forest canopy intercepts a portion of the rainfall, which is evaporated back into the atmosphere. Certain types of vegetation may increase snow accumulation on the slopes and retard melting. Evapotranspiration from plants removes water from the soil. In addition, vegetation may influence the soil moisture regime indirectly. Roots of plants and organic material contributed by decay of plant material may alter the hydraulic properties of the soil. It is not possible to account for all these influences because some of the phenomena are still not well understood. Nevertheless, it is possible to analyze the infiltration of surface water, because the theory of flow through porous media is well known. Some of the factors may then be studied indirectly through their effect on infiltration.

Infiltration

The governing equation for flow through porous media is (10,pp.215-296)

$$k\nabla^2 h = C(\partial h/\partial t) \qquad (2a)$$

where

- h = piezometric head,
- k = coefficient of permeability, and
- C = slope of the moisture-suction curve.

At the ground surface, the infiltration (q) should be added to the left-hand side to give

$$k\nabla^2 H + q = C(\partial h/\partial t) \qquad (2b)$$

The infiltration is

$$q = p - r - i \qquad (3)$$

where

- p = precipitation,
- r = runoff, and
- i = interception.

In addition, water is removed from the soil by evapotranspiration (e) and drainage (f). Although the theory of flow has been known for a long time and numerical solution schemes are available, the predictions based on this equation involve a great deal of uncertainty because of the difficulties associated with the choice of the parameters. The uncertainties about k and C due to variations in soil properties and errors in testing are at least familiar. However, even greater difficulties are encountered in the estimate of q. The amount of infiltration depends on the conditions at the ground surface, which include the initial moisture content, ground slope and roughness, and vegetation. Empirical data are usually used to estimate infiltration, but their accuracy is questionable when applied to specific sites. Water evaporation from leaves has been extensively studied. However, it is difficult to use these results to compute evapotranspiration for plant communities because of the complex nature of evaporation. Kramer (11) gives an excellent review of this topic. Evapotranspiration may be based on the results of lysimeter studies. Considerable data are available on evapotranspiration by crops and grasses [e.g., U.S. Department of Agriculture Technical Bulletin 1367 (12)], but data on forest trees are less plentiful. Theories are available for estimating the potential evapotranspiration. The most successful of these is the Penman equation (13,14). These all give average values over a period of time. Where the piezometric level fluctuates rapidly, estimates based on average values may lead to substantial errors.

Experimental Evidence

There are considerable data to show that vegetation has a strong influence on the soil moisture regime. Results of detailed model tests by Brenner (15) indicate that the soil moisture tension in slopes with trees is much higher than that without trees. Gray (9) measured soil moisture suction in forested slopes and in clear-cut slopes in Oregon. The measured suctions were higher in forested slopes. A detailed example is given to illustrate the problems. Figure 2 shows a slope in the Maybeso Valley of Alaska. Piezometric levels were measured 4 years after clear-cutting. Nine years later, pore pressures were measured at the same location, which was covered with regrowth, and in an adjacent slope, which had not been cut. The measured pore pressures are shown in Figures 3 and 4. It can be seen that pore pressures in 1965 were about equal to or higher than those in 1974, although the rainfall in 1965 was considerably less than that in 1974. This can 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 (16,pp.231-260). 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.

Numerical Solutions

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. As an illustration, a simple model is used to evaluate the effect of evapotranspiration and moisture-suction relation on the piezometric level in the slope shown in Figure 2. The simplified one-dimensional model is shown in Figure 5a. H is the thickness of the pervious soil. Equation 2 reduces to

$$k(\partial^2 h/\partial z^2) = C(\partial h/\partial t) \qquad (4)$$

Precipitation (q) enters at the top and d is the discharge, which is the sum of evapotranspiration (e) and drainage down the slope (f). The values of e and f were estimated to be 1.0 and 0.8 cm/day, respectively (17). The range in the parameters is also shown in Figure 5a and the values that are considered to be the best estimates are given in parentheses. Curve A in Figure 6 shows the piezometric levels calculated with the 1965 precipitation record and the best estimates of the parameters. To study the sensitivity of the model to the parameters, C, k, and e were changed. The results are shown as curves B, C, and D in Figure 6. Only the changed parameters are shown in Figure 6. It can be seen that the model is very sensitive to all the parameters. The effect of reduced evapotranspiration on the maximum piezometric level is obvious when curves B and A are compared. In a fifth trial, a surface layer with $C = 2\ m^{-1}$ is added to simulate the organic layer near the ground surface (Figure 5b). Comparison of curves E and A shows the effect of destruction of the organic layer, as may occur dur-

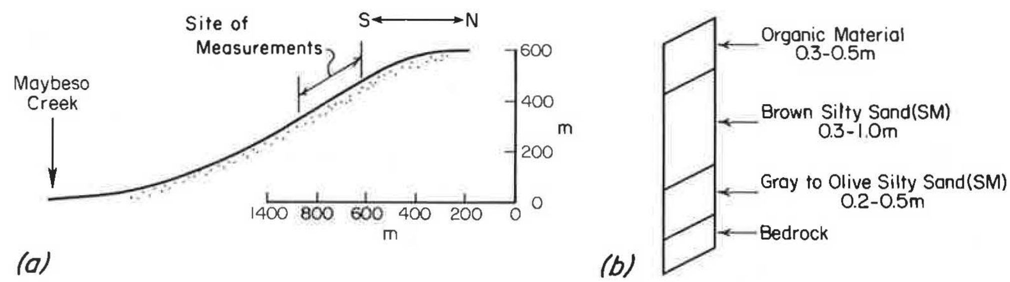

FIGURE 2 Slope in Maybeso Valley, Alaska: (a) slope profile and (b) soil profile.

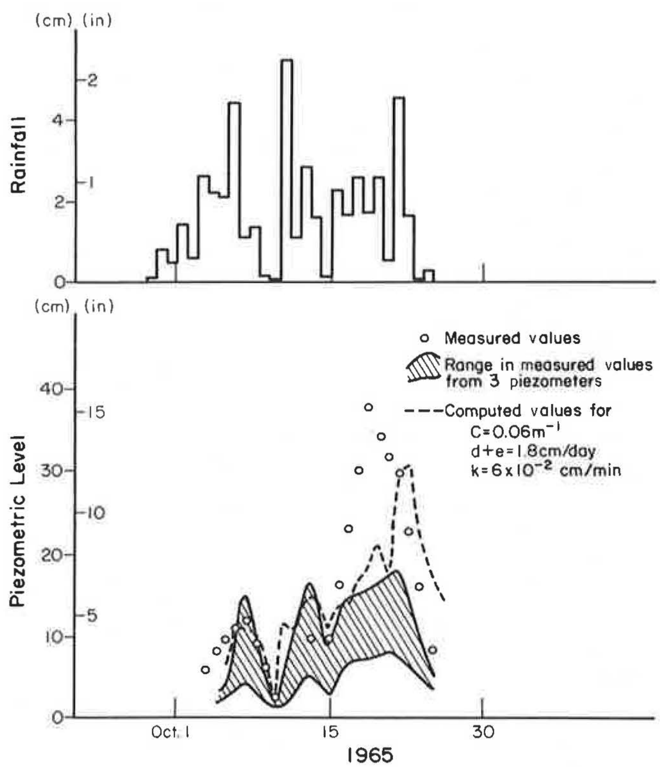

FIGURE 3 Measured and computed pore pressures, 1965, Maybeso Valley.

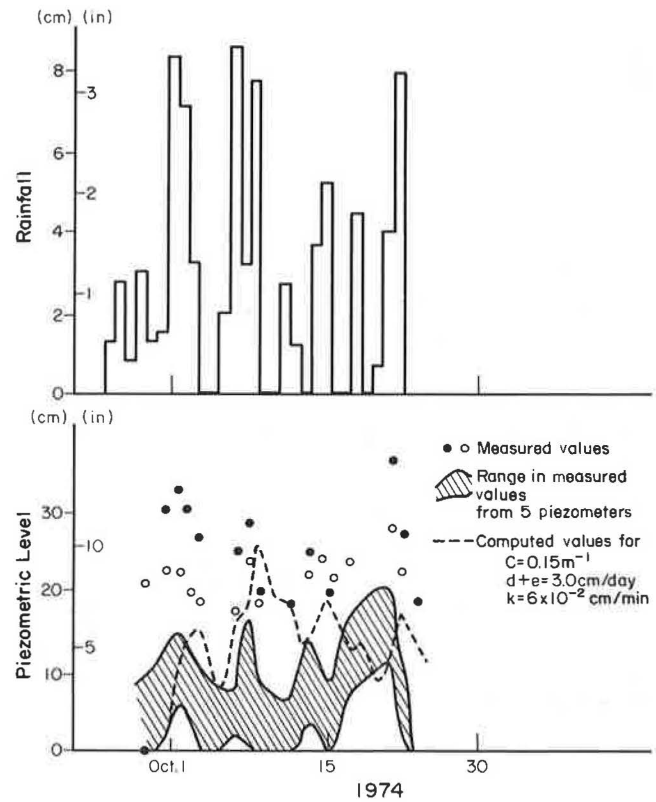

FIGURE 4 Measured and computed pore pressures, 1974, Maybeso Valley.

ing a fire or clear-cutting. These examples serve to illustrate some of the effects of vegetation on infiltration.

Although it is realized that the model is too simplified and cannot be used to make predictions, numerical methods can be a powerful tool in the analysis of observed data. The simple model may be used to estimate the drainage rate (d) and other parameters from the observed data in Figures 3 and 4. Calculations were made with different values of d and C to obtain the best fit to the data. The dashed curves in Figures 3 and 4 are considered to fit the three highest piezometric levels in each plot. The values of d and C that give the best fit may be taken as empirically determined characteristics of the site. It can be seen that d and C for the forested slope are different from those for the clear-cut slope. These values of d and C may be considered to be calibrated for the site and may be used to estimate changes in the piezometric level at this or similar sites. It should also be noted that there is

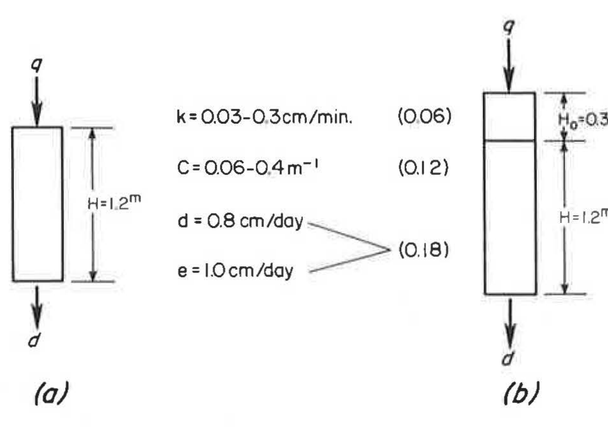

FIGURE 5 Simplified infiltration model: (a) soil layer only and (b) soil layer and organic layer.

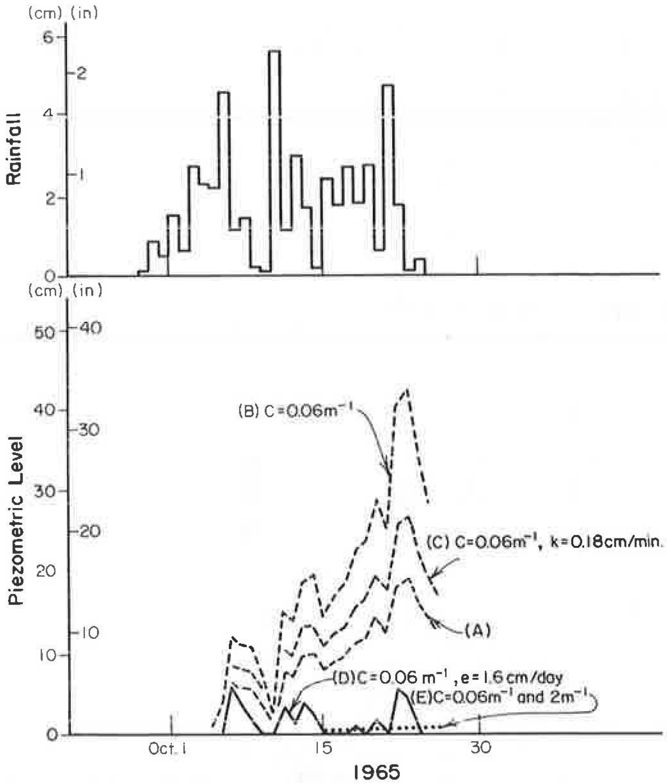

FIGURE 6 Computed pore pressures, Maybeso Valley.

a large scatter in the observed piezometric levels. Any model used for prediction should account for this scatter as well as the model error.

Other models and methods for evaluation of aquifer characteristics from observed data have been proposed (18;19,pp.657-679;20). The site conditions may be expected to have a strong influence on the accuracy of a particular method. Research in this direction should yield significant benefits.

ROOT REINFORCEMENT

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

$$\sigma_r = A_r t_r / A \tag{5}$$

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 a cohesion (c_r) (21).

The root system of marram grass [Figure 7a (22,23)] may be approximately isotropic. However, the root systems of vegetation are usually not isotropic and are complex. Several examples are shown in Figure 7. Figure 7b shows the plate-shaped root system of two trees (24,25), in which most of the roots lie within a shallow soil layer, which is usually the B-horizon. From these lateral roots, small vertical sinker roots may penetrate deeper into the C-horizon. A tree with a heart-shaped root system (26) is shown in Figure 7c. There is a tap root that penetrates deeply into the soil and the lateral roots also grow well below the surface. Although the different shapes are generally associated with different species of trees, it is also known that the root system of the same species may acquire different shapes because of differences in soil and groundwater conditions.

Soil-Root Interaction Models

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 Figures 8 and 9. In Figure 8a, the potential slip surface (ab) intersects the roots of the tree at c. For 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 Figure 8b. The forces on the root are T_n, T_s, and M. If a three-dimensional failure surface is considered (Figure 9), 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 (27). One simplification is that at large shear displacements associated with failure, θ = 90 degrees. Then the root's contribution to shearing resistance along ab (Figure 8b) 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 Figure 9. However, because the roots have different initial orientations, they will not be loaded equally at the same shear displacement and will not fail simultaneously. Hence, their total contribution will be less than the sum of the tensile strengths of the individual roots. Solutions for some special problems have been formulated and these are described in the following.

Example 1

One comparatively simple problem is shown in Figure 10. A shallow layer of a comparatively weak soil lies over a stronger soil. The potential failure surface is the boundary between the weak and the strong soils. The sinker roots that enter the strong soil are assumed to grow in the vertical direction. In addition, it is assumed that there is little displacement of the root in the strong soil in the s direction. Then T_n and T_s can be calculated for a given shear distortion θ. Waldron (3) and Gray and Ohashi (28) considered the elastic elongation of the root in the shear zone, whereas Wu et al. (4) used the tensile resistance of the root and θ at failure. Both analyses lead to the expression

$$c_r = B \sum_i T_{ri} / A \tag{6}$$

where

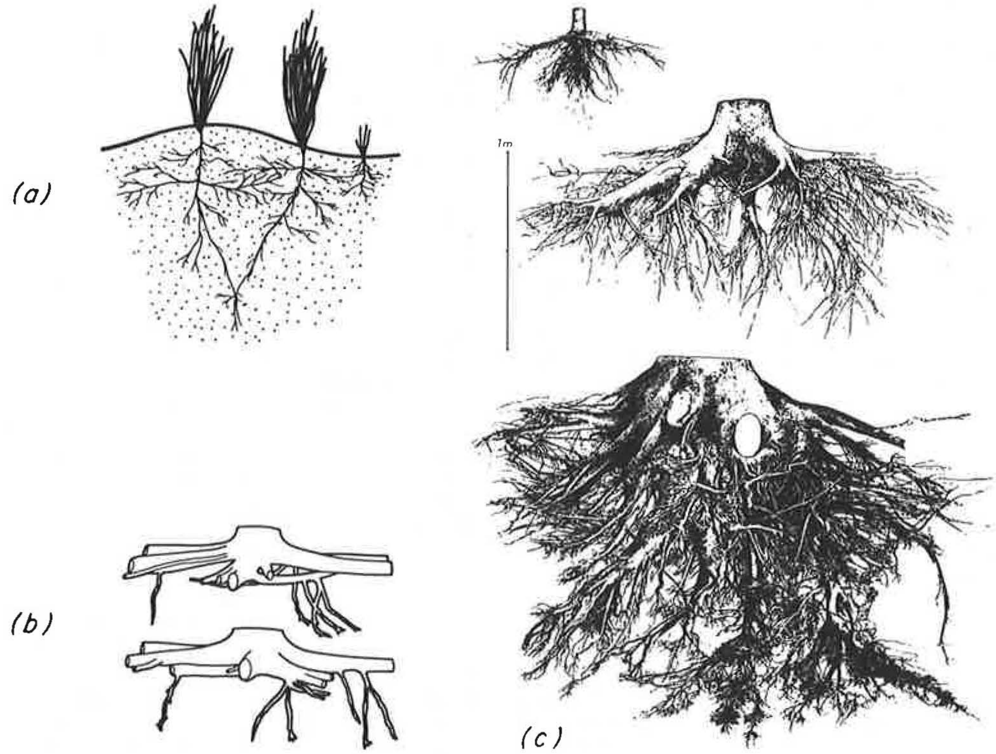

FIGURE 7 Root shapes: (a) marram grass *(22, 23)*, (b) plate-shaped root of *Larix laricina* (top) and *Picea mariana* (bottom) *(25)*, (c) heart-shaped root of Douglas fir *(26)*.

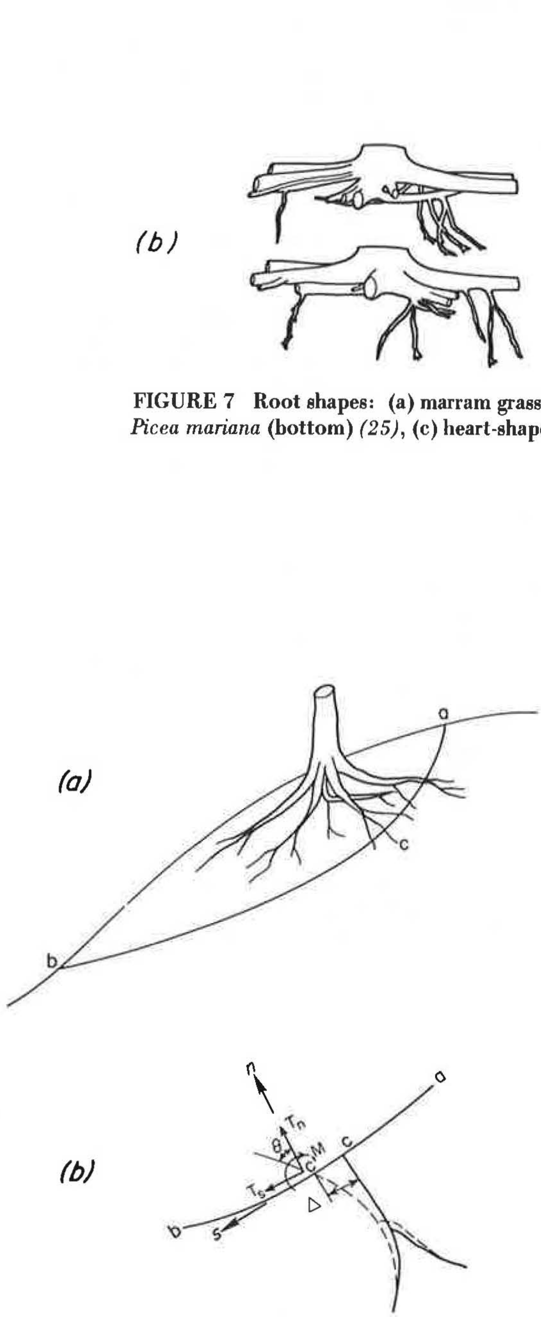

FIGURE 8 Soil reinforcement by roots: (a) intersection of roots with slip surface and (b) forces on root and root displacement.

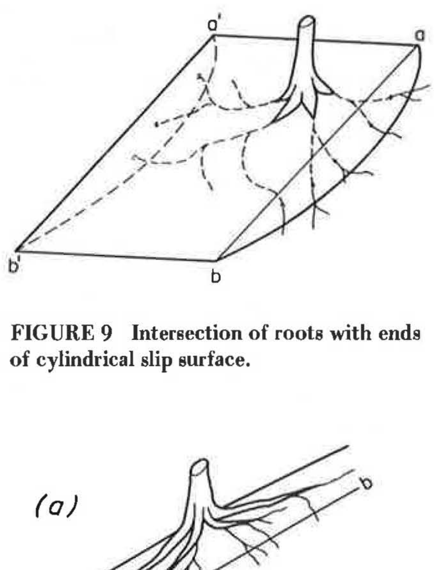

FIGURE 9 Intersection of roots with ends of cylindrical slip surface.

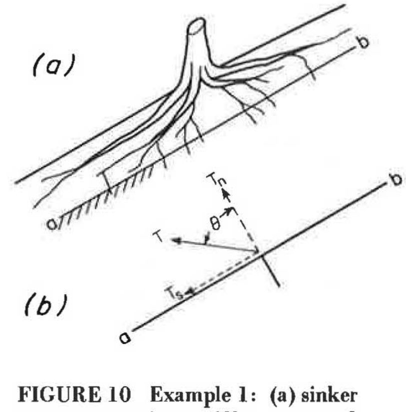

FIGURE 10 Example 1: (a) sinker roots penetrating a stiff stratum and (b) simplified representation of root displacement.

c_r = equivalent cohesion due to root reinforcement,
B = factor that accounts for the direction of the roots and is about 1.2 for ϕ = 30 degrees,
T_{ri} = resistance of the ith root, and
A = area of the shear surface.

Laboratory tests by Gray and Ohashi (28) and Waldron (3) generally support this model.

Applications of this model to a slope have been described by Wu et al. (4). The stability of several forested and clear-cut slopes in the Maybeso Valley of Alaska was analyzed. 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

$$s_r = s + c_r = c' + \sigma' \tan \phi' + c_r \quad (7)$$

in which c_r is as given by Equation 6. Because the tensile strength of roots varies with the root diameter, the quantity ΣT_{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 Sitka spruce and western hemlock and about 0.9 after the trees have been removed. This difference includes the effect of the change in the piezometric level due to tree removal. The computed safety factors are in general agreement with observed performance. Many failures occurred on the slopes a few years after clear-cutting, whereas failures were few on the forested slopes. A similar study has been made by Riestenberg and Sovonick-Dunford (29). For slopes on soils with low cohesion, the contribution by c_r can have a significant in- fluence on the stability.

There are several potential applications of this solution. For cuts in cohesive soils, the initial stability is governed by the undrained shear strength. Long-term stability under the drained condition is controlled by the effective stress parameters c' and ϕ'. If c' = 0, as is the case for many clays (30), 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 mine reclamation, broken shale from spoils may be used to build slopes of 30 degrees or more because of the angular shape of the fragments. However, weathering may reduce some types of shale to clay in a few years. The ϕ' of the clay is usually well below 30 degrees and c' is usually close to 0. Then the slopes become unstable. If the slopes are reforested, one may expect the roots of trees to contribute to the stability of such slopes.

Example 2

Three-dimensional failure surfaces are common in reality. Most natural slopes are not uniform. There are spatial variations in the soil and root strengths and in slope geometry. Drainage depressions that run in the downslope direction usually concentrate groundwater flow, and the piezometric surface is closer to the ground surface in these depressions than it is in the surrounding area (31). 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 Figure 11. Such failures have been described by Swanston (7) and Riestenberg and Sovonick-Dunford (29), among others.

A simplified three-dimensional failure surface is shown in Figure 9. The end surfaces are assumed to be planes. The effect of the lateral roots that intersect the end surfaces is considered. Excavations made by Swanston have shown that most of the lateral roots are concentrated in the organic layer and the B-horizon as shown in Figure 12 (D.N. Swanston, personal communication). Ziemer (32,pp.343-361) has devised an in situ shear test that measures the shear strength of the soil-root system on the vertical faces abcd and a'b'c'd' of a soil block that contains lateral roots running generally in the horizontal direction (Figure 13). The measured strengths (s_r) of the soil-root system are correlated with the weight of the biomass as shown in Figure 14 (32). 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 Figure 15. In this zone the shear strength of the soil-root system is s_r. If Equation 6 is assumed to apply,

$$s_r = s + c_r \quad (8)$$

The shear strength of the soil (s) acts over the remaining portion of the end surface and on the cylindrical surface ab.

The simplified solution for the resisting moment about 0 is obtained as follows. Consider the slip surface shown in Figure 15c. The resisting moment of s on the cylindrical surface ac is

$$M_{R1} = sL2\theta_0 R^2 \quad (9)$$

The resisting moment of s on the end surfaces is

$$\begin{aligned} dM_{R2} &= s\, dA\, r \\ &= s\, Rd\theta [R - R(\cos\theta_0/\cos\theta)]\{R - (1/2)[R - R(\cos\theta_0/\cos\theta)]\} \\ &= (1/2) sR^3 [1 - (\cos^2\theta_0/\cos^2\theta)] d\theta \end{aligned} \quad (10)$$

and

TABLE 1 Measured Root Density in Slope of Maybeso Valley *(35)*

Location	Tree and Diameter (m)	Depth of Pit (m)	Area of Pit (m^2)	Root Density[a] (m^{-2}) According to Diameter (mm): 0.8	1.6	2.4	3.2	4.0	4.8	5.6	6.4	7.9	9.5	11.0	12.7	$\Sigma T_{ri}/A$ (kPa)
1	Hemlock, 0.15	0.45	6.8	14.5	15.7	7.9	8.7	1.4	1.0	0.7	0.3	0.3	0.8	0.1	0.7	5.6
2	Sitka spruce, 0.36	0.48	2.9	38.6	40.8	18.6	8.5	1.7	1.0	0.3	0.9	0.3	0	0	0	4.3
3	Two hemlocks, 0.75 and 0.30	0.30	0.6	43.7	57.0	0	46.5	0	21.4	0	6.6	0	0	0	0	12.6
4	Yellow cedar, 0.45	0.48	0.3	6.1	15.4	0	6.1	3.1	6.1	0	6.1	0	0	0	0	5.4

[a]Number of roots intersecting the boundary between B- and C-horizons *(35)*.

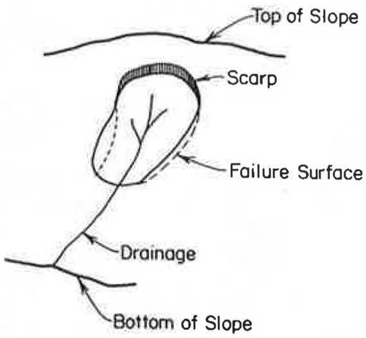

FIGURE 11 Slide at head of a drainage.

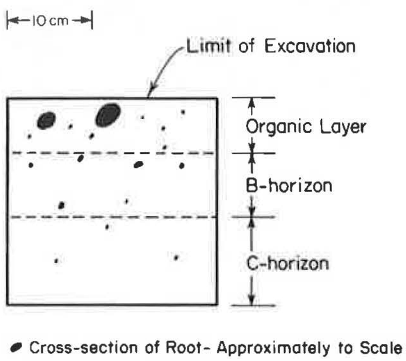

FIGURE 12 Roots intersecting the vertical wall of an excavation.

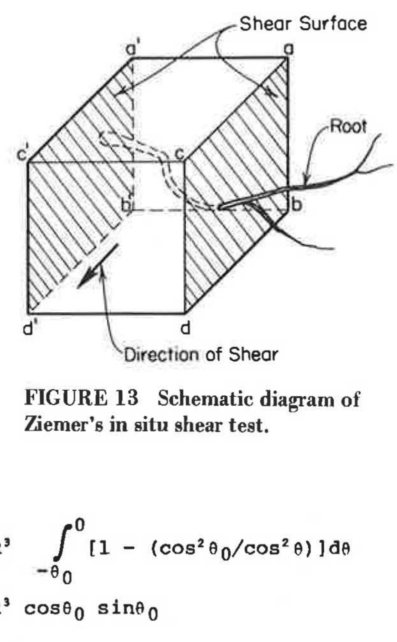

FIGURE 13 Schematic diagram of Ziemer's in situ shear test.

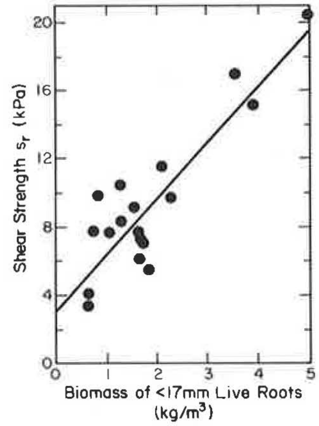

FIGURE 14 Relation between shear strength and biomass *(32)*.

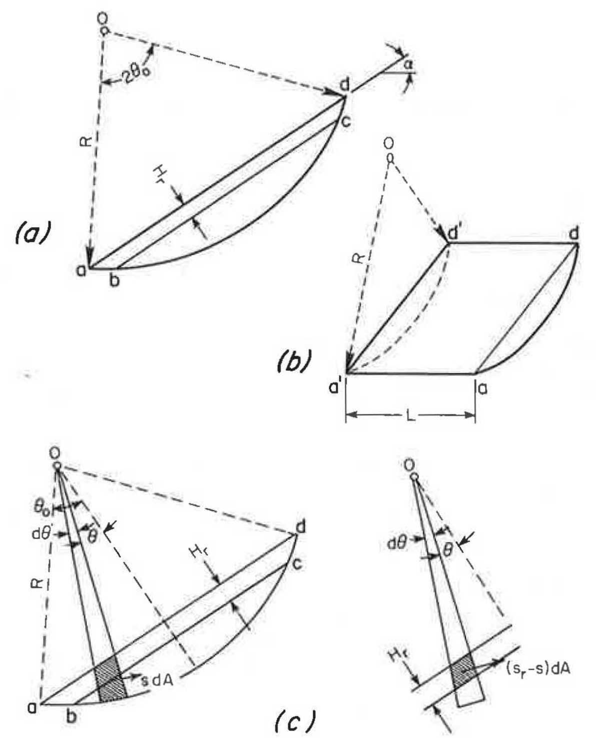

FIGURE 15 Three-dimensional slip surface: (a) side view, (b) perspective view, and (c) computation of resisting moment.

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

$$= 2sR^3 \cos\theta_0 \sin\theta_0 \quad (11)$$

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

$$\begin{aligned} dM_{R3} &= (s_r - s)dA \cos\theta(R\cos\theta_0/\cos\theta) \\ &= (s_r - s)[(R\cos\theta_0/\cos\theta)d\theta \cos\theta D] \\ &\quad \times \cos\theta(R\cos\theta_0/\cos\theta) \\ &= (s_r - s)DR^2 \cos^2\theta_0 d\theta \end{aligned} \quad (12)$$

$$\begin{aligned} M_{R3} &= 4(s_r - s)DR^2 \cos^2\theta_0 \int_{-\theta_0}^{0} d\theta \\ &= 4(s_r - s)DR^2\theta_0 \cos^2\theta_0 \end{aligned} \quad (13)$$

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

$$M_{R4} = 2(s_r - s)L(D/\sin\theta_0)R \quad (14)$$

The total resisting moment is

$$\begin{aligned} M_R &= M_{R1} + M_{R2} + M_{R3} + M_{R4} \\ &= 2sLR^2\theta_0 + sR^3(2\theta_0 - \cos\theta_0 \sin\theta_0) \\ &\quad + 4(s_r - s)DR^2\theta_0 \cos^2\theta_0 \\ &\quad + 2(s_r - s)LDR/\sin\theta_0 \end{aligned} \quad (15)$$

As an illustration the stability of the slope shown in Figure 16 is calculated. It is assumed that the stiff bottom restricts the slip surface as shown. 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 (Figure 14). The computed driving and resisting moments are as given in Figure 16. 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.

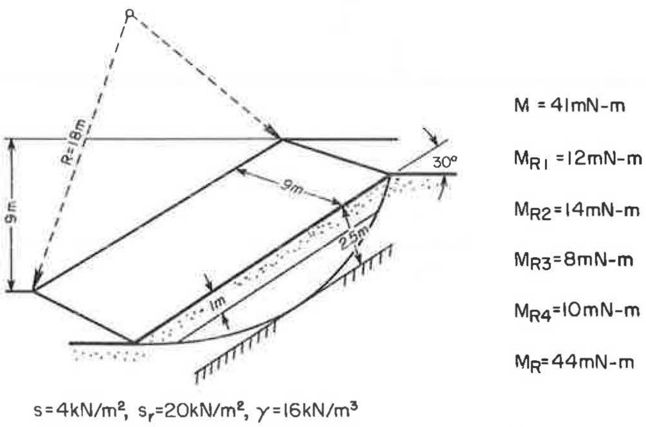

FIGURE 16 Example 2: stability and analysis for three-dimensional slip surface.

Root Geometry

The preceding examples illustrate the methods that may be used to analyze the contribution of root reinforcement to stability. However, accurate predictions about stability are difficult to accomplish. The major difficulty in evaluating root reinforcement lies in the scanty knowledge about root geometry--the number and diameter of roots that are present at different locations in the ground. Considerable information on root geometry has been obtained for some types of forest trees. Examples include root spread and root diameter of Douglas fir (33) and apple (34). Such data allow one to estimate the number and size of lateral roots as a function of distance from the stem.

Another aspect of the problem is to find the number of vertical sinker roots that penetrate the C-horizon. It has been observed that for Sitka spruce and western hemlock, there is a concentration of large and small roots in the central portion of the root system (Figure 17). This is the root mat that is pulled out of the ground when a tree is overturned. The size of the root mat may be correlated with the diameter of the tree (Figure 18), and the number of sinker roots within this zone is shown in Table 1 (35). The limited data suggest that the root contribution to strength is approximately 5 kPa within the area of the root mat of each tree. However, it is clear that such data are valid only for the species and site conditions investigated. A similar study was made by Riestenberg and Sovonick-Dunford (29) of the roots in a maple forest.

Table 2, cases 1 and 2, gives the total cross-section areas of the roots and the values of c_r as computed by Equation 6 for the two sites in Alaska and Ohio. Results of shear tests on soils reinforced with grass roots (36) are also given in Table 2 (case 3). In case 4, the total area of roots of beach grass was estimated (22,23) and c_r was computed by Equation 6, assuming that

$$\Sigma T_{ri} = \sigma_T \Sigma A_{ri} \qquad (16)$$

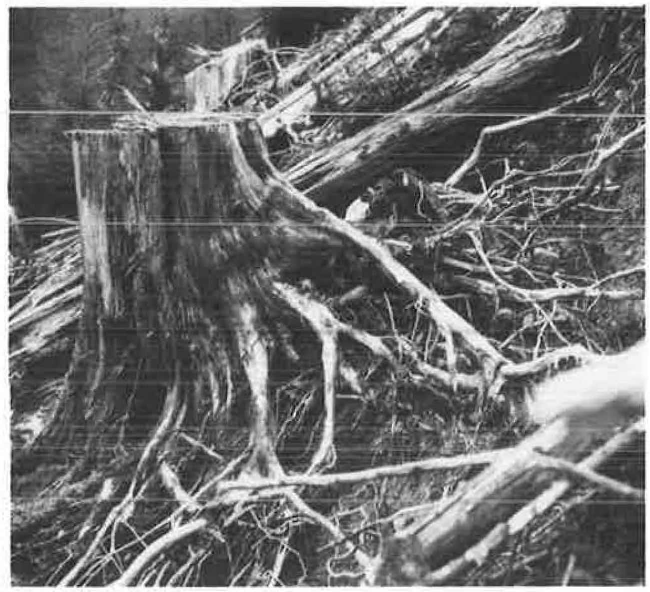

FIGURE 17 Root mat of Sitka spruce (photograph by D. N. Swanston).

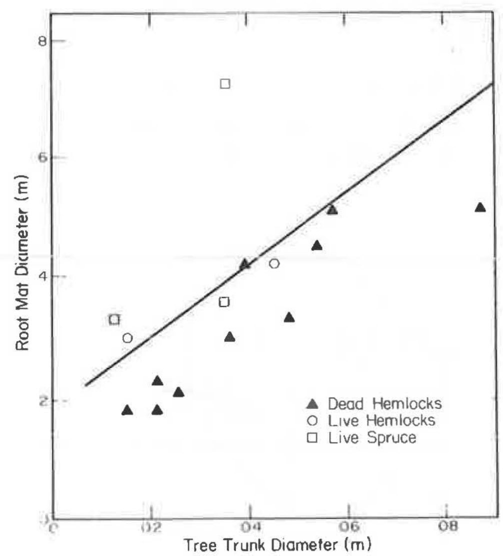

FIGURE 18 Diameter of root mats (35).

where σ_T is the average tensile strength and A_{ri} is the area of the ith root. It is surprising that c_r falls within a narrow range of 3 to 10 kPa.

As an approximation, Equation 6 may also be used to estimate c_r on vertical planes such as abcd in Figure 15a. Results obtained by Riestenberg and Sovonick-Dunford (29) are given in Table 2, case 5. Calculations made with Equations 6 and 16 and the results of excavations by Swanston and by Burroughs and Thomas (37) are also given. The large root area of Douglas fir relative to the other species serves as a reminder that c_r may be very different for different species and different site conditions. Additional research is needed to establish relations between the root geometry and site conditions that are of regional significance.

TABLE 2 Root Areas and c_r

Case	Predominant Species	Location	Soil	Area (cm^2/m^2)	S_r (kPa)	Reference
Boundary Between B- and C-Horizons						
1	Sitka spruce, western hemlock	Alaska	Silty sand	3.7	5	Wu *(35)*
2	Sugar maple	Ohio	Clay	1.4	4	Riestenberg and Sovonick-Dunford *(29)*
3	Grasses	California	Loam and sand	–	4-10	Waldron and Dakessian *(36)*
4	Marram grass	–	Sand	1.4	3.4[a]	Gray and Leiser *(22)* Adriani and Terwindt *(23)*
Vertical Section in B-Horizon						
5	Sugar maple	Ohio	Clay	2.3	7	Riestenberg and Sovonick-Dunford *(29)*
6	Sitka spruce, western hemlock	Alaska	Silty sand	2.25	7	Swanston (personal communication)
7	Douglas fir	Oregon, Idaho	Gravelly loam, sandy loam	17.5	40[a]	Burroughs and Thomas *(37)*

[a]Estimated with $\sigma_T = 25\ 000$ kPa.

SUMMARY AND CONCLUSIONS

This review has shown that the basic mechanisms of the influence of vegetation on the soil moisture regime and root reinforcement can be understood. Although refinements are needed and important new problems remain to be solved, application to a number of simple problems is possible at present. In many cases vegetation can make significant contributions to slope stability and promises to be an economical solution. Some data on cost effectiveness have been given by Gray and Leiser (22). It is also important to realize that important data on infiltration and evapotranspiration and root geometry that are necessary for analysis are available for only a few locations and species. Hence, any large program for use of vegetation to improve stability should be supported by considerable amounts of research to determine the essential parameters that are needed for analysis and design.

ACKNOWLEDGMENT

Much of the material presented in this paper was developed in the course of research supported by the National Science Foundation and by the Forest Service, U.S. Department of Agriculture. This support is gratefully acknowledged. The writer also wishes to thank D. H. Gray, D. A. Sangrey, D. N. Swanston, and R. R. Ziemer for their contributions to his understanding of the complex problems of soil-root interaction and the soil moisture regime and the reviewers of this paper for their criticisms and suggestions.

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Publication of this paper sponsored by Committee on Engineering Geology.