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A RATIONAL APPROACH FOR THE DESIGN OF FOREST SLOPES

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ABSTRACT

Both low and high volume roads for traffic are commonly constructed on slopes in forest regions. The rational design of these slopes should be based on soil properties, slope geometry, loading and environmental factors. Since classic principles of <u>saturated</u> soil mechanics are inadequate to address environmental factors, additional elements of soil mechanics must be utilized. A rational design approach is proposed in this paper using recent concepts of <u>unsaturated</u> soil mechanics applied to slope stability problems in the forest industry. Several soil properties are necessary to do such an analysis. The Soil-Water Characteristic curve, saturated coefficient of permeability and saturated shear strength parameters are the most important soil property functions required. A complete treatment of all the variables is beyond the scope of the paper. While the fundamentals are explained, the paper concentrates on the relationship between the Soil-Water Characteristic and the shear strength. The extension of the proposed approach to limit equilibrium methods for determining the factors of safety is briefly addressed.

RESUME

Des routes à faible trafic ou à fort trafic sur des terrains en pentes dans les régions forestières sont souvent construites. L'étude et la conception des pentes doivent s'appuyer sur la connaissance des propriétés mécaniques des sols, de la géométrie des pentes, de la charge appliquée et des facteurs environnementaux. L'application des principes classiques de la mécanique des sols <u>saturés</u> ne permet pas de prendre en compte, correctement, les facteurs environnementaux. Ainsi, l'approche rationnelle proposée dans cet article s'appuie sur l'emploi des concepts de la mécanique des sols <u>non saturés</u> pour l'étude de la stabilité des pentes. Parmi les nombreux variables nécessaires pour une telle approche se trouvent la courbe de rétention d'eau des sols, le coefficient de perméabilité hydraulique et les paramètres de la résistance mécanique à l'état saturé des sols. Cet article ne traite pas l'ensemble des paramètres mais présente les éléments fondamentaux et se consacre à la relation entre la rétention d'eau et la résistance mécanique des sols. Enfin, l'extension de l'approche proposée à la méthode de l'équilibre limite pour la détermination des facteurs de sécurité est brièvement exposée.

INTRODUCTION

Both low and high volume roads are frequently required on slopes in forested regions. The rational design of these slopes requires input of soil properties, slope geometry, loading and environmental factors (i.e., infiltration, evaporation, transpiration, vegetation, etc.). The principles of classical saturated soil mechanics are inadequate to characterize the variables that influence the stability of these slopes. Therefore, additional elements of soil mechanics and engineering analysis are required. It is important to recognize that the upper part of the soil profile which forms the slopes is generally unsaturated. Several natural processes such as evaporation and transpiration contribute to changes in the pore-water pressures in the soil. These pore-water pressures are generally negative (i.e., suction) in the unsaturated zone. Vegetation on forest slopes can be cited as a factor which contributes to increases in suction due to transpiration. From a mechanistic point of view, the shear strength of the soil increases due to unsaturated conditions which in turn contributes to the stability of slopes.

The concept of stress state variables to describe the behavior of an unsaturated soil was introduced by (Fredlund and Morgenstern 1977). The stress state variables which govern the unsaturated soil behavior are the net normal stress, $(\sigma-u_a)$ and the matric suction, (u_a-u_w). The rational approach to describe the engineering behavior of unsaturated soils in terms of these stress state variables using the principles of continuum mechanics is described in Fredlund and Rahardjo, (1993). A rigorous treatment of unsaturated soils requires additional soil parameters which must be either obtained experimentally or empirically estimated. However, experimental studies on such soils are costly, time consuming and are difficult to conduct. Approximate predictions of unsaturated soil properties appear to be sufficient for most practical applications.

The unsaturated shear strength parameters depend on the amount of water in the soil, which in turn depends upon the soil suction. The relationship between the water content and soil suction is called the Soil-Water Characteristic curve. Several investigators have proposed empirical functions for predicting the coefficient of permeability with respect to suction for unsaturated soils by using the Soil-Water Characteristic curve (e.g., van Genuchten 1980, Fredlund, Xing and Huang 1994). An important extension of this approach is the use of the Soil-Water Characteristic curve to predict the variation of the shear strength of an unsaturated soil with respect to suction (Vanapalli 1994).

This paper outlines the elements of a model for analyzing a slope where the soils are unsaturated. While a rigorous analysis is desirable, it is unduly complex, time consuming and costly. As a result efforts are ongoing to minimize the amount of field data, laboratory testing and overly complex numerical analyses and yet to maintain a rational engineering approach to slope stability problems.

METHODOLOGY

Figure 1 provides a flow chart showing the rational engineering approach to calculate the factor of safety of a typical slope where unsaturated soils prevail and where environmental effects such as evaporation, infiltration and vegetation influence the stability. The suction in the soil is dependent on the environmental processes which in turn influence the stability of the slope. The following text briefly describes each element of the flow chart.

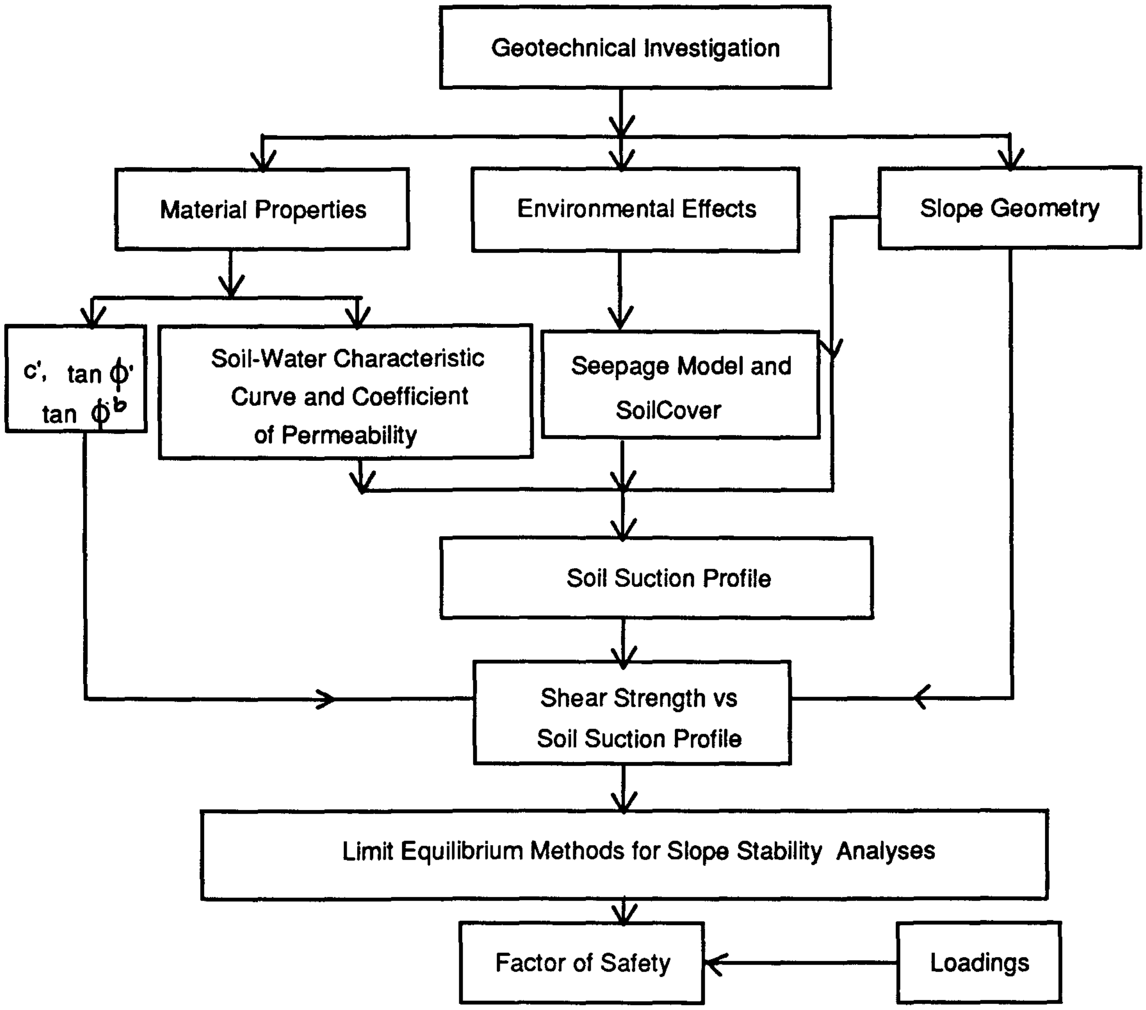


FIGURE 1. Schematic showing the details of a rational engineering approach for estimating the factor of safety of a slope

Geotechnical Investigation
Using traditional procedures, geotechnical investigations should be taken up to a depth sufficient to determine the geology of the site, the soil profile, the natural ground water level, undisturbed and disturbed soil samples, and other important geotechnical data.

Material Properties
The materials properties required are the water content, w, density of the soil, ρ, the saturated shear strength parameters c', and ϕ', the saturated coefficient of permeability, k_s. Undisturbed samples can be tested to obtain the Soil-Water Characteristic curve. The saturated shear strength and flow properties of the soil can be determined using traditional laboratory tests. The Soil-Water Characteristic curve can be determined using the pressure plate apparatus for soil suction ranging from 0 to 1,500 kPa. For soil suctions greater than 1,500 kPa, desiccator tests can be used. The Soil-Water Characteristic curve is probably a new test to some geotechnical engineers,

but it can be determined using reasonably well established procedures. It need no longer be considered an esoteric test and beyond the scope of conventional geotechnical laboratories.

Fredlund and Xing (1994) proposed an equation to define the Soil-Water Characteristic curve data over its entire range of suction (i.e., 0 to 10^6 kPa). Using this equation, an empirical soil function is available to predict the variation in the coefficient of permeability with respect to suction (Fredlund, Xing and Huang 1994). Along similar lines, a method to predict the variation of the shear strength of an unsaturated soil with respect to suction has been proposed (Vanapalli 1994).

Slope Geometry

The geometric details, such as the angle, height, etc., of the slope can be determined using conventional surveying techniques or topographic maps.

Environmental Effects

The moisture flux conditions with respect to moisture flow across the soil-atmosphere boundary is important because it controls the suction which in turn directly affects the permeability and the unsaturated shear strength function. The surface flux conditions can be predicted using heat and water transport model coupled to the atmosphere (Wilson, Fredlund and Barbour 1994). Present studies indicate that the Soil-Water Characteristic curve obtained from pressure plate tests adequately characterizes the relationship between soil suction and water content for most engineering purposes. This is true whether the soil is desaturating by evaporation from a bare soil column (Bruch 1992) or whether it is occurring by evapotranspiration (Tratch 1995). In summary, a Soil-Water Characteristic curve developed in the laboratory is used to incorporate the environmental influences and predict the engineering behavior of unsaturated soils for various field applications.

Soil Suction Profile

The negative pore-water pressures or suctions in a slope can be modelled using seepage models such as SEEP/W (Geo-Slope, 1994). The input parameters for this model are the saturated coefficient of permeability, k_s, and the Soil-Water Characteristic curve. However, to incorporate the influences of environment changes such as the infiltration, evaporation and transpiration and to assess the accompanying changes in soil suction a rigorous water mass and heat transport model must be used. The other alternative is to measure suctions in the field. A one-dimensional theoretical heat and water transport model coupled to the atmosphere through a modified Penman formulation which allows the calculation of evaporation from a saturated or an unsaturated soil surface was developed by Wilson, Fredlund and Barbour (1994). Several modifications have been made (and are still being made) to this physically based computer model at the University of Saskatchewan (Wilson 1990, Joshi 1993, Machibroda 1993, Cook 1995, Newman 1995, Tratch, 1995). The result is a one-dimensional finite element computer program called SoilCover. The input parameters for this model include the Soil-Water Characteristic curve data, the saturated coefficient of permeability data, and environmental data such as the average air temperature, net radiation, relative humidity, and wind velocity. The application of this model has been successfully tested on soil-cover systems on the fields for the prediction of field suctions, water contents and temperatures at mine tailings sand waste rock sites (Machibroda 1993; O' Kane 1995; and Swanson 1995). A similar formulation capable of modelling two-dimensional conditions is necessary to predict soil suction profiles on slopes. The suction profile in the soil slope can be modelled for the slope geometry using the saturated coefficient of permeability and the Soil-Water Characteristic curve while considering the influences of the environment as detailed earlier.

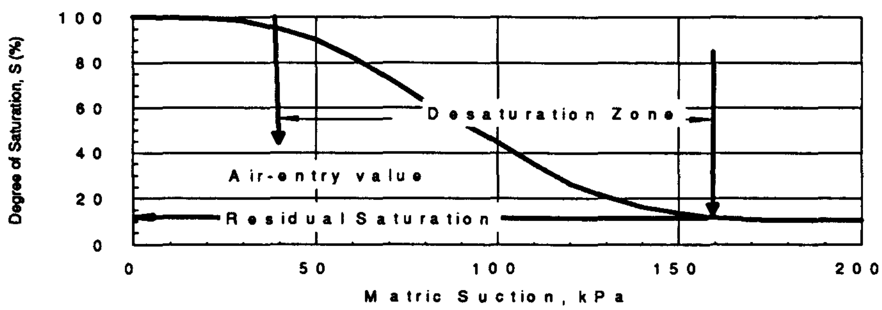
Strength versus Soil Suction Profile

Once the Soil-Water Characteristic curve and the saturated shear strength parameters are known, the variation of shear strength with suction can be predicted. Fredlund et al. (1978) initially proposed a linear shear strength of unsaturated soils equation in terms of two stress state variables namely; net normal stress, $(\sigma_n - u_a)$, and matric suction, $(u_a - u_w)$ as:

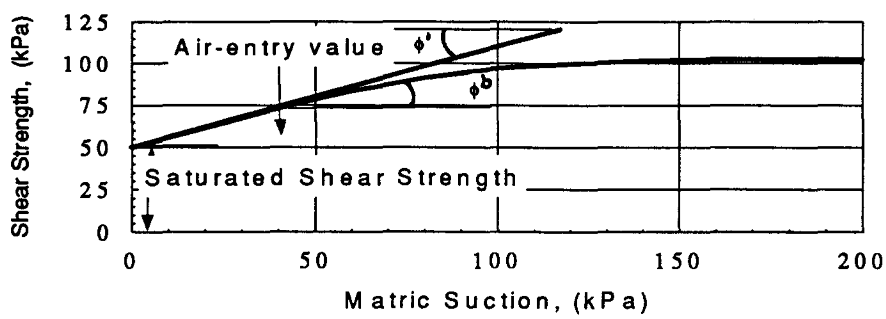
$$[1] \quad \tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$$

where:
τ_f = shear strength
c' = effective cohesion
ϕ' = effective angle of internal friction
ϕ^b = angle of shearing resistance with respect to a change in matric suction

Figure 2(a) shows a typical Soil-Water Characteristic curve plotted as the degree of saturation versus soil suction.



a) Matric Suction versus degree of saturation



b) Matric suction versus shear strength

FIGURE 2. General behavioral relationship between Soil-Water Characteristic curve and shear strength (from Vanapalli, 1994).

The air-entry value of the soil, $(u_a-u_w)_b$, and the residual degree of saturation, S_r, are also shown. The air-entry value, $(u_a-u_w)_b$, can be defined as the matric suction value at which the specimen starts to desaturate. Desaturation continues as the suction is increased until a value is reached where an increase in suction produces little decrease in the degree of saturation. The degree of saturation at this value of suction is called the residual degree of saturation, S_r. Figure 2(b) shows a typical relationship between shear strength and increasing soil suction. The relationship between the shear strength and the Soil-Water Characteristic curves can be seen by comparing Figs. 2(a) and Fig 2(b). The rate of desaturation with respect to an increase in matric suction, (i.e., $dS/d(u_a - u_w)$) is greatest between the air-entry value and the suction corresponding to residual conditions. There is little or no desaturation in the soil up to the air-entry value (i.e., the soil behaves as a fully saturated soil up to the air-entry value of the soil). The shear strength contribution due to matric suction in unsaturated soils is primarily contributed through the wetted surface inter-aggregate contact area points. As there is little or no change in water content of the soil below the air-entry value, suction as a stress state variable is as effective as net normal stress in mobilizing the shearing resistance along all the contact area points. This infers that ϕ^b is equal to ϕ' below the air-entry value. Above the air entry value, the contribution of shear strength by suction decreases with the desaturation of the soil and results in a nonlinear variation of shear strength with respect to suction. Thus, there is a close relationship between the shear strength behavior of an unsaturated soil and the Soil-Water Characteristic curve.

A typical set of experimental results for determining the shear strength of a statically compacted glacial till under consolidated drained conditions using multistage direct shear tests on a specimen loaded to a net normal stress of 25 kPa is presented. The results are taken from (Vanapalli, 1994). The initial water content of the specimen was 16% and the dry density, γ_d, was 1.78 Mg/m^3. The effective cohesion, c' is equal to zero and the effective angle of shearing resistance, ϕ' is 23.5 degrees. The Soil-Water Characteristic curve with identical initial volume-mass conditions for the range of suction of 0 to 1,000,000 kPa is shown in Fig. 3. The residual degree of saturation is not clearly defined but appears to be about 65% and the corresponding matric suction is 1,500 kPa.

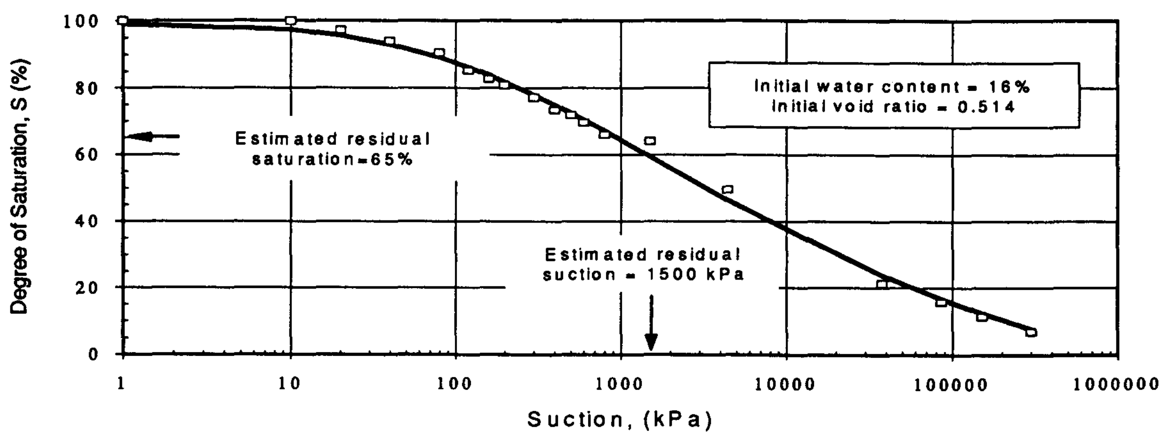


FIGURE 3. Soil-Water Characteristic curve for a compacted till with a preload of 25 kPa (from Vanapalli, 1994)

The variation of shear strength with soil suction using the model and experimental results is shown in Fig. 4. The symbols represent experimental results and the continuous line is the predicted variation in shear strength with respect to soil suction. There is a close correlation between the experimental results and the predicted values of shear strength. The procedural aspects of predicting the shear strength using the Soil-Water Characteristic curve and the saturated shear strength parameters are detailed in Vanapalli (1994). The proposed model for predicting the shear strength of unsaturated soils is in accordance with Eq. [1].

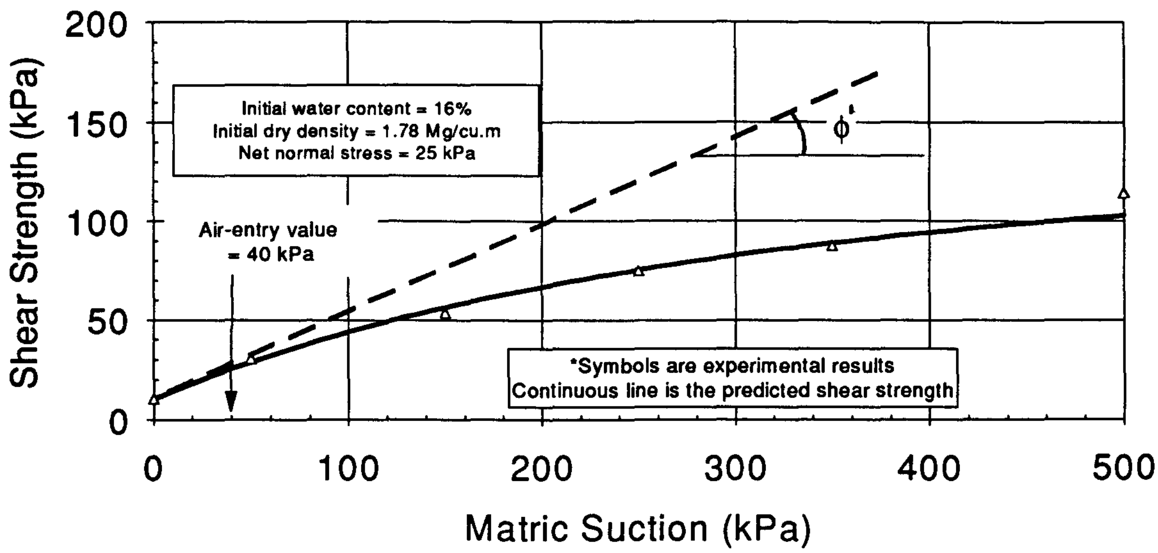


FIGURE 4. Comparison of experimental and predicted variation of shear strength with matric suction (from Vanapalli, 1994)

<u>Limit Equilibrium Methods to Determine the Factor of Safety of Unsaturated Slopes</u>
The soil functions developed for predicting the coefficient of permeability and shear strength of unsaturated soil can be incorporated in traditional limit equilibrium methods to estimate the factors of safety of the slopes while considering the influences of the environment and loading conditions.

SUMMARY

The suction profile in the slope can be predicted using heat and water transport models coupled to the atmosphere by considering the influence of the environmental variations. The input parameters for such models are the Soil-Water Characteristic curve, the saturated coefficient of permeability and environmental data. The Soil-Water Characteristic curve data and the saturated shear strength parameters are sufficient to predict variation of shear strength with respect to soil suction. The rational approach of predicting the factor of safety of forest slope is shown in Figure 1. Traditional limit equilibrium methods can be used to predict the factor of safety of these slopes (e.g., SLOPE/W by Geo-Slope, 1994) incorporating the influences of the environment. The proposed approach provides a rational engineering procedure since the environmental variables influencing the stability are considered in the analysis. A complete treatment of all the variables is beyond the scope of the paper. Only the procedural aspects have been addressed using the recent concepts for modelling the unsaturated soil behavior. The influence of several other parameters such as the mechanical reinforcement due to roots, freeze-thaw conditions, erosion aspects are not addressed in this paper.

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