

Effect of Suction on Mechanical Behaviour of Unsaturated Soil: A Review

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Abstract

This study reviews the mechanical behaviour of unsaturated soil under various Geotechnical problems like bearing capacity failures and the slope stability failures. To obtain a rational solution for any Geotechnical problems, field tests & numerical modelling were performed. Moreover various empirical equations and new innovating methods used to obtain desire parameters required for unambiguous analytical as well numerical modelling related to unsaturated soil were also discussed. Also, a detailed review on effect of influencing parameters on mechanical behaviour of unsaturated soil is done.

Keywords

Unsaturated Soil, Suction, Factors affecting Shear Strength of Unsaturated Soil.

Introduction

Now a days significant change in climatic conditions were observed mostly due to Global warming. Many countries experienced either longer rainfall or higher rainfall for shorter time period as rainfall is most frequent triggering factor for slope failure in different parts of world. Moreover the rainwater infiltration and variation in ground water are predominant factor which affected by soil properties. These change in soil pressure responsible for the distinct mechanical behaviour of unsaturated soil under different Geotechnical problems. So the understanding of the mechanical behaviour of unsaturated soil and related parameters which affect the overall behaviour of unsaturated soil is very important. Slope failures in residual soils may occur due to several factors, such as weathering processes, geological activities, human interference, hydrological effect, topographical features, vegetation and climatic conditions. Infiltration of rainwater into soil changes the state of soil from unsaturated to saturated soil. It is well know that negative pore-water pressure which occurs in unsaturated soil increase the shear strength of soil. As soil will gets saturated, Soil suction decreases which finally results in decrease in shear strength. (Fredlund1993)[1]. Fig. 1 represents slope stability failure due to infiltration.

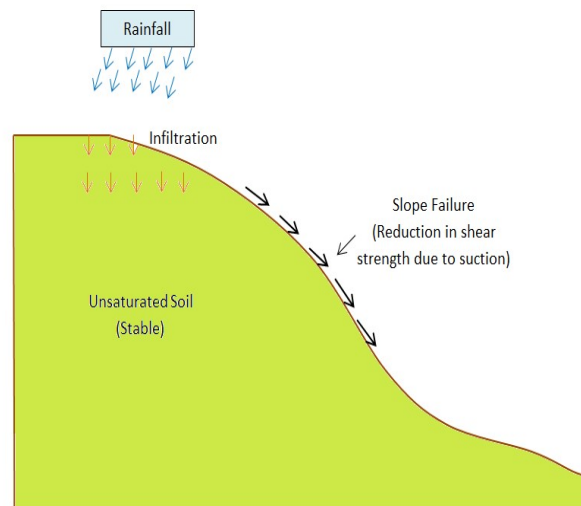


Figure 1: Effect of Rainfall and Suction on Slope Failure

Factors Affecting Mechanical Behaviour of Unsaturated Soil

It is very useful to understand the unsaturated soil properties, i.e., SWCC required for analysis of seepage or infiltration of water through soil with respect to soil suction. The properties such as shear strength will be required for stability analysis.

Shear Strength

Unsaturated shear strength of soil is important parameter which affects mechanical behaviour of soil. Higher shear strength contributes to higher FOS against stability of slopes and bearing capacity failures. The shear strength of partially saturated soil is controlled by net normal stress and ψ value [1]. Change in the ψ value due to saturation causes the change in shear strength. A Summary of various empirical equations proposed by previous researchers is shown in table 1.

No.	Equation	Reference
1.	$\tau = c' + (\sigma_n - u_w) \tan \phi'$	Terzaghi[2]
2.	$\tau = c' + (\sigma_n - u_w) \tan \phi' + (u_a - u_w) \tan \phi^b$	Fredlund et al. [1]
3.	$\tau = (c' + [\sigma_n - u_a] \tan \phi') + [(u_a - u_w)(\Theta k) (\tan \phi')]$ OR.	Vanapalli et al. [3], Fredlund et al. [1]
4.	$\tau = (c' + (\sigma_n - u_a) \tan \phi') + ((u_a - u_w)((s_k) (\tan \phi')))$	
5.	$K = -0.0016Ip^2 + 0.0975Ip + 1$	Vanapalli et al. [3]
6.	$\tan \phi^b = [S^k] (\tan \phi')$	
7.	$C = c' + (u_a - u_w) \tan \phi'$	Fredlund et al. [1]
8.	$C = c' + r_c \sqrt{(s - s_c).P_a}$	Fredlund et al. [1]
9.	$r_c = r_k \frac{\sqrt{3(3-\sin\phi')}}{6 \cos\phi'}$	

Table 1: Various Equations Proposed by Previous Researchers for Calculation of Shear Strength of Unsaturated Soil

Bearing Capacity of Unsaturated Soil

Number of studies shows that the Bearing Capacity in unsaturated soil is affected by soil suction. In many studies the uniform and linear suction distribution is considered for analysing bearing capacity.

Parameter	Linear Suction Distribution	Nonlinear Suction Distribution
Cohesion	$C(z) = C_o - \lambda z$ $C_o = s \tan(\phi^b)$ $\lambda = \frac{s \tan(\phi^b)}{hw}$	$c(z) = s \left(\frac{hw-z}{hw} \right) \tan(\phi^b)$
Hydrostatic suction distribution	$(q_s)_{hydro} = \frac{H}{2hw} s \tan \phi^b (\tan(\alpha) - e^{\frac{3}{2}x \tan \phi'}) +$ $\frac{3}{\cos \alpha} X \frac{1}{8 \cos^2 \phi' - 9} X (e^{\frac{3}{2}x \tan \phi'} \sin(\frac{\pi}{4} + \frac{3}{2} \phi') +$ $\cos(\frac{\pi}{4} + \frac{3}{2} \phi') + 2 \sin \phi' (e^{\frac{3}{2}x \tan \phi'} \cos(\alpha) - \sin(\alpha))$	$(q_s)_{hydro} = \frac{H}{2hw} s \tan \phi^b (\tan(\alpha) - e^{\frac{3}{2}x \tan \phi'} +$ $\frac{3}{\cos \alpha} X \frac{1}{8 \cos^2 \phi' - 9} X (e^{\frac{3}{2}x \tan \phi'} \sin(\frac{\pi}{4} + \frac{3}{2} \phi') +$ $\cos(\frac{\pi}{4} + \frac{3}{2} \phi') + 2 \sin \phi' (e^{\frac{3}{2}x \tan \phi'} \cos(\alpha) - \sin(\alpha))$
Bearing capacity	$q_u = [c' + c_{aev}] N_c \xi_c + q N_q \xi_q + 0.5 B \gamma N \gamma \xi \gamma + s N_s \tan \phi^b \xi_s,$ $N_s = (N_s)_l$	$q_u = [c' + c_{aev}] N_c \xi_c + q N_q \xi_q + 0.5 B \gamma N \gamma \xi \gamma + s N_s \tan \phi^b \xi_s,$ $N_s = (N_s)_{nl}$

Table 2: Equations for Calculating Bearing Capacity with Linear and Nonlinear Suction Distribution Suction

A major variation in shear strength value may occur due to suction which finally results in increase in slope stability failures. So, it is important to measure suction variation. Various Direct and Indirect methods of suction measurement is given below:

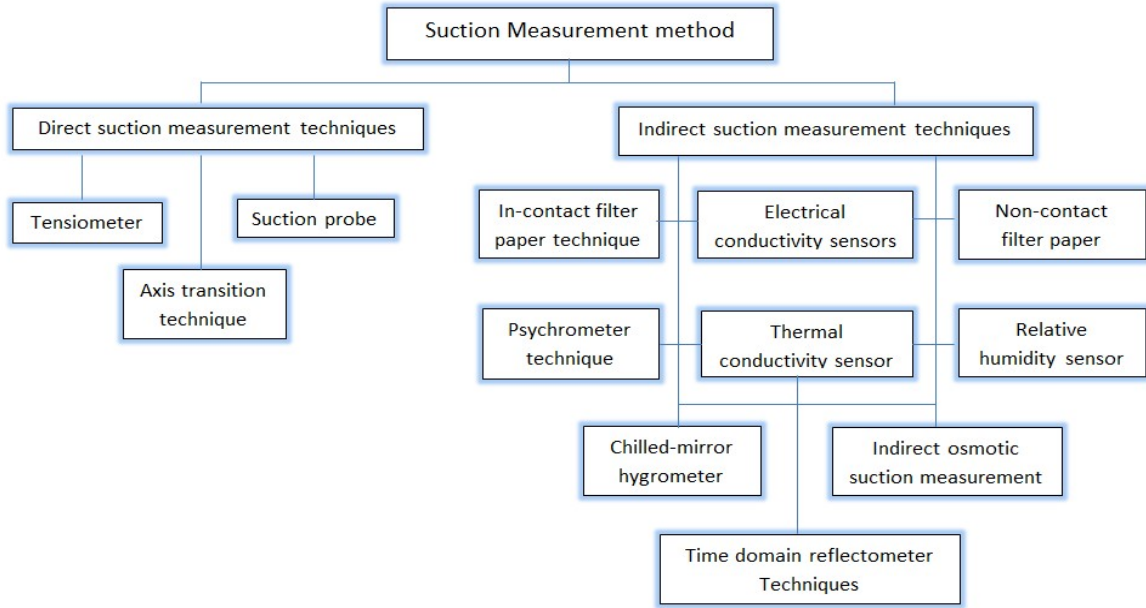


Figure 2: Suction Measurement Techniques.

Soil Type	Index properties of soil	Technique used	Reference
Unsaturated Sand	Particle range: 0.1 to 0.5mm Fine Sand : 7.0% Medium Sand : 93.0 C _u : 1.20 D ₁₀ : 0.21mm Specific gravity : 2.65	Triaxial constant water content test (CW modified triaxial test)	A. Farouk, L. Lamboj, J. Kos (2004) [4]
Poorly Graded Sand	Particle Range: 1mm to 0.1 mm C _u : 1.5	Suction – controlled simple shear test	Kiyoshi Shimada*; (1998)[5]
Sandy Clay	G _s : 2.62 W _L (%): 39.83 W _P (%): 24.07 Maximum Dry Density, MDD (kN/m ³) : 15.14 OMC (%) ; 23.00 GSA fraction: % passing 75 micron:61.39 % retaining 75 micron : 38.61	Conventional Triaxial (UU) test. Soil Suction: Filter paper method.	Fredlund et al. [1]
Silty Soil	Fine grained silty soil with zero cohesion.	Modified conventional triaxial cell. Soil suction: Pressure plate apparatus, salt solution desiccators and relative humidity control chamber.	T. Nishimura, [6]

Highly Plastic clay	Grain size analysis;	Unconfined compression test Soil Suction: In-contact filter paper method. Fredlund et al. [1]
	Gravel : 1%	
	Sand : 15%	
	Clay : 32%	
	Silt : 52%	
	Atterberg Limits:	
	LL : 51%	
	Pl : 20%	
	SL : 14%	
	FSI : 30%	

Table 3: Influence of Matric Suction on Shear Strength Behaviour of Various Unsaturated Soil

Soil Water Characteristic Curve (SWCC)

A Soil water characteristic curves (SWCC) is defined as variation of water content due to matric suction. SWCC is represented graphically as degree of saturation(s), gravimetric moisture content (w), volumetric moisture content (θ_w) on ordinate versus matric suction on abscissa in logarithmic scale. The method for estimating SWCC from the AEV which depends on grain size distribution curve which has high Air entry value. Laboratory experiments to obtain SWCC can yield only few data coordinates on varying suction values hence, Fredlund et al. [1] obtained equation using lease-square method as follows;

$$\theta_w = C_{(\psi)} \frac{\theta_s}{\{ \ln [e + (\frac{\psi}{a})^n] \}^m}; C_{(\psi)} = 1 - \frac{\ln (1 + \frac{\psi}{\psi_r})}{\ln (1 + \frac{10^6}{\psi_r})}$$

where,

θ_w =volumetric w_c , θ_s = saturated w_c , ψ = soil suction, (a , n & m) = fitting correction, $C_{(\psi)}$ = Correction, and ψ_r = residual water content occurs suction.

Some Sustainable Solution for Slope Stability and Land Slides

Capillary barrier system consists of layered soil. It is based on well-known principle that the permeability of fine grain soil is lower and coarse grained soil. Figure 3 shows the processing of capillary barrier system in having minimized the infiltration of rainwater into the soil slopes.

While designing the CBS following points will be considered: Rahardjo et al. [7]

- i) The passage of water through fine & coarse grain layers.
- ii) Permeability of coarse and fine grained soil.

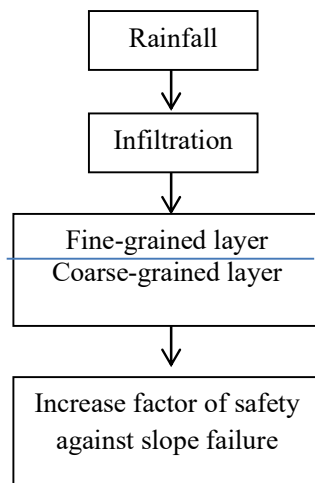


Figure 3: Capillary Barrier System working Mechanism.

Parametric study results showed that vegetation can be used to improve slope stability. The use of type of vegetation depends on various hydrological factors such as soil properties, temperature, evaporation and transpiration rate, rainfall intensity. Generally Vetiver and Orange Jasmine are most commonly used type of vegetation. Vetiver is perianal grass having of fast and deep growing property up to 3.0m depth. It has mat-like horizontal spreading system cultivated in tropical area of the world. Orange Jasmine is found in tropical region, can grow up to 7.0 m tall. It is evergreen plant. However, vegetation contribution is not significant in improving the slope stability as compared to matric suction.

A. Laboratory Experiment		
Proposed by:	Technique Used	References
Yang et al. (2004)	Infiltration test through soil layers were performed using one-dimensional (1-D) soil column.	Yang, H., Rahardjo, H., Wibawa, B. and Leong, E.C. (2004) [8]
Tami et al. (2004a)	Residue water Infiltration	Fredlund et al. [1]
Indrawan(2006)	Use of various soil mixtures in fine-layers of CBS	Yang, H., Rahardjo, H., Wibawa, B. and Leong, E.C. (2004) [8]
Krisdani et al. (2006)	Use of geosynthetic material with proper gradation	Yang, H., Rahardjo, H., Wibawa, B. and Leong, E.C. (2004) [8]
B. Field Experiments		
Rahardjo (2010)	Measured pore water pressure using tensiometers and piezometers	Yang, H., Rahardjo, H., Wibawa, B. and Leong, E.C. (2004) [8]

Table 4: Effects of Capillary Barrier System on Various Properties of Soil

Conclusion

As above stated parameters adversely affects the slope failures and bearing capacity failures of unsaturated soil, an engineer should have a keen knowledge about all these parameters. To fulfil these requirements new innovative methods studied by previous researchers were reviewed to obtained sustainable solution of related geotechnical problems.

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