Problems in areas with special geological conditions: Foundation problems in arid zones

AMOS KOMORNIK, Prof., Discussion Leader

Eleventh International Conference on Soil Mechanics and Foundation Engineering, San Francisco, 1985.

As Prof. Ter Stephanian wrote in his theme lecture, soils in areas with special geological conditions have different properties and composition - their physical properties and geological histories are connected functionally. With change in environmental conditions these soils and their properties change as well.

The variation in climatic and environmental conditions will cause deformation to occur in the foundation soil (settlement, collapse, swelling, underground cavities, thawing, etc.) which will be reflected in damage to structures, canals, pipe lines, slopes etc.

Attempts at minimizing changes in the environmental conditions have been limited in their success. In order to cope with the variability in the changes of soil properties, studies of field behavior of soil and structures, in conjunction with laboratory testing of soils, models and special field testing must be carried out. The development of new theories to cope with these special changes in soil parameters with development of special technics to measure the various parameters, will help in understanding the behaviour of structures founded in these areas and thus will reduce foundation failures.

In preparing this special session it was quite clear that the scope is too wide as can be seen from the 17 papers submitted by authors from 14 countries. Trying to select them in groups of common nature or subject show the complexity of organizing the discussion session:

A. Theme lecture - General Aspects of Geotechnical Engineering.
B. Soft soils.
C. Rock.
D. Particular geological conditions.
E. Mapping.
F. Collapsible soils.
G. Swelling clays.

As anticipated some of the papers deal with special theoretical problems and others deal with practical engineering problems and case histories.
Because of these variations it was decided to choose one major topic "Foundation Problems in Arid Zones" to be presented in four lectures by Profs. Fredlund, Nelson, Burland and Wiseman concentrating on the following subjects:

1. Theory and testing of unsaturated soils: volume change and shear strength. (2 lectures).
2. Recent studies on the mechanism of collapse due to wetting.
3. Case histories of behaviour of structure on unsaturated soils.

Following are summaries of these lectures:

D.G. Fredlund - "Theory Formulation and Application for Volume Change and Shear Strength Problems in Unsaturated Soils".

INTRODUCTION

During the past half century, the principles of saturated soils mechanics have been developed and successfully applied in geotechnical practice. At the same time, much less attention has been given to many serious problems common to dry soils in arid areas. The behavior of these soils can be classified as unsaturated soil mechanics. The objective of this presentation is to summarize the basic equations for: i) the formulation of a theory for the volume change and shear strength of unsaturated soils and ii) the application of these theories in geotechnical practice.

THEORY FORMULATION

Soil mechanics theory and technology has developed based on a few classic equations. The three most important equations are: i) the volume change constitutive relations, ii) the shear strength equation, and iii) the flow of water through porous media. The formulations associated with the first two categories are summarized for unsaturated soils and compared to the equivalent saturated soil equations.

STRESS STATE

Two independent stress state variables most commonly used to describe the stress state of an unsaturated soil. These are, $(\sigma - u_a)$ and $(u_a - u_w)$ where u_a = pore-air pressure. The term $(u_a - u_w)$ is referred to as matric suction and is the pore-water pressure referenced to the pore-air pressure. The use of the above stress state variables provides a smooth transition from the case of an unsaturated soil to a saturated soil and vice versa. The above stress state variables have been repeatedly demonstrated as being adequate for describing the volume change and shear strength behavior of unsaturated soils.

VOLUME CHANGE CONSTITUTIVE RELATIONS THEORY

The classic volume change relations for a soil can be presented in one of several forms; namely, i) the elasticity form, ii) the compressibility form, and iii) the soil mechanics terminology form. All forms for the unsaturated soil can be shown to specialize back to the commonly used forms for saturated soils (Table 1). It is noted that more than one constitutive relation is required for the unsaturated soil due to the number of phases involved.

SHEAR STRENGTH THEORY

The classic shear strength equation for a saturated soil has been extended to embrace unsaturated soils and the form of the equation is shown in Table 2. The cohesion of the unsaturated soil can now be visualized as having 2 components.

APPLICATION OF UNSATURATED SOIL THEORIES IN GEOTECHNICAL PRACTICE

Several practical problems could be considered which involve unsaturated soils. However, only 2 examples are selected and a summary of relevant equations are presented in table form. The examples are:
i) the prediction of heave or swelling and ii) the computation of the factor of safety for an unsaturated soil.

TABLE 1

Comparison of Constitutive Relations for Unsaturated and Saturated Soils

Forms	Unsaturated Soils	Saturated Soils
Elasticity	Soil Structure $\epsilon_x = \frac{(\sigma_x - u_a)}{E} - \frac{\mu}{E}(\sigma_y + \sigma_z - 2u_a) + \frac{(u_a - u_w)}{H}$ $\epsilon_y = \frac{(\sigma_y - u_a)}{E} - \frac{\mu}{E}(\sigma_x + \sigma_z - 2u_a) + \frac{(u_a - u_w)}{H}$ $\epsilon_z = \frac{(\sigma_z - u_a)}{E} - \frac{\mu}{E}(\sigma_x + \sigma_y - 2u_a) + \frac{(u_a - u_w)}{H}$ Water Phase $\theta_w = \frac{(\sigma_x + \sigma_y + \sigma_z - 3u_a)}{3H'} + \frac{(u_a - u_w)}{R}$	Soil Structure $\epsilon_x = \frac{(\sigma_x - u_w)}{E} - \frac{\mu}{E}(\sigma_y + \sigma_z - 2u_w)$ $\epsilon_x = \frac{(\sigma_y - u_w)}{E} - \frac{\mu}{E}(\sigma_x + \sigma_z - 2u_w)$ $\epsilon_z = \frac{(\sigma_z - u_w)}{E} - \frac{\mu}{E}(\sigma_x + \sigma_y - 2u_w)$
Compressibility (Isotropic Compression)	Soil Structure $d\epsilon = m_1^s\, d(\sigma - u_a) + m_2^s d(u_a - u_w)$ Water Phase $d\theta_w = m_1^w d(\sigma - u_a) + m_2^w d(u_a - u_w)$	Soil Structure $d\epsilon = m_v d(\sigma - u_w)$
Soil Mechanics Terminology (K_o loading)	Soil Structure $de = a_t d(\sigma_y - u_a) + a_m d(u_a - u_w)$ Water Phase $dw = b_t d(\sigma_y - u_a) + b_m d(u_a - u_w)$	Soil Structure $de = a_v d(\sigma_y - u_w)$

TABLE 2

Comparison of the Shear Strength Equations for Saturated and Unsaturated Soils

Soil Type	Shear Strength Equations
Unsaturated Soils	$\tau = c' + (u_a - u_w) \tan \phi^b + (\sigma_n - u_a) \tan \phi'$
Saturated	$\tau = c' + (\sigma_n - u_w) \tan \phi'$

PREDICTION OF HEAVE

The prediction of one-dimensional heave equation is shown using the: i) elasticity form for volume change and ii) then converted to the compressibility form and iii) the soil mechanics terminology forms (Table 3).

SLOPE STABILITY ANALYSIS FOR UNSATURATED SOILS

The principles involved in the derivations are the same as for saturated soils with the exception that the unsaturated soil shear strength equation is used. The derived equations for the i) normal force at the base of a slice, the ii) moment equilibrium factor of safety and the iii) force equilibrium factor of safety are presented in Table 4.

SUMMARY

The theory for the volume change and shear strength behavior of unsaturated soils appears to be well established. Equations derived in saturated soil mechanics can readily be extended to encompass unsaturated soil behavior.
A summary of many of the relevant references can be found in the paper entitled "Soil Mechanics Principles that Embrace Unsaturated Soils", presented to this conference (Fredlund, 1985).

REFERENCE

Fredlund, D.G. (1985). "Soil Mechanics Principles that Embrace Unsaturated Soils". XI International Conference on Soil Mechanics and Foundation Engineering, San Francisco, U.S.A.

TABLE 3

Summary of Equations for Heave

Forms	Unsaturated Soils	Saturated Soils
Elasticity (K_o loading)	<u>Soil Structure</u> $\epsilon_y = \frac{(1+\mu)(1-2\mu)}{E(1-\mu)}(\sigma_y - u_a) + \frac{(1+\mu)}{H(1-\mu)}(u_a - u_w)$ <u>Water Phase</u> $\theta_w = \frac{(1+\mu)}{3H'(1-\mu)}(\sigma_y - u_a) + \frac{3(1-\mu)H'H - 2ER}{3(H'HR(1-\mu))}(u_a - u_w)$	<u>Soil Structure</u> $\epsilon_y = \frac{(1+\mu)(1-2\mu)}{E(1-\mu)}(\sigma_y - u_w)$
Compressibility (K_o loading)	<u>Soil Structure</u> $d\epsilon_y = m_1^s d(\sigma_y - u_a) + m_2^s d(u_a - u_w)$ <u>Water Phase</u> $d\theta_w = m_1^w d(\sigma_y - u_a) + m_2^w d(u_a - u_w)$	<u>Soil Structure</u> $d\epsilon_y = m_v d(\sigma_y - u_w)$
Soil Mechanics Terminology (K_o loading)	<u>Soil Structure</u> $\Delta e = [m_1^s \Delta(\sigma_y - u_a) + m_2^s \Delta(u_a - u_w)](1 + e_o)$ $m_1^s = \frac{a_t}{1 + e_o}$ $\quad m_2^s = \frac{a_m}{1 + e_o}$ <u>Water Phase</u> $\Delta w = [m_1^w \Delta(\sigma_y - u_a) + m_2^w \Delta(u_a - u_w)]\frac{(1 + e_o)}{G_s}$	<u>Soil Structure</u> $de = a_v d(\sigma_y - u_w)$

TABLE 4

Summary of Equations for Slope Stability

Soil Type	Variables	Equations
Unsaturated Soils	Normal Force at the Base of a slice	$N = \dfrac{W - (X_R - X_L) - \frac{c'\beta \sin \alpha}{F} + u_a \frac{\beta \sin \alpha}{F}(\tan \phi' - \tan \phi^b) + u_w \frac{\beta \sin \alpha}{F} \tan \phi^b}{\cos \alpha + \frac{\sin \alpha \tan \phi'}{F}}$
	Moment Equilibrium	$F_m = \dfrac{\Sigma\{c'\beta R + [N - u_w \beta \frac{\tan \phi^b}{\tan \phi'} - u_a \beta(1 - \frac{\tan \phi^b}{\tan \phi'})] R \tan \phi'\}}{\Sigma Wx - \Sigma Nf}$
	Force Equilibrium	$F_f = \dfrac{\Sigma\{c'\beta \cos \alpha + [N - u_w \beta \frac{\tan \phi^b}{\tan \phi'} - u_a \beta (1 - \frac{\tan \phi^b}{\tan \phi'})] \tan \phi' \cos \alpha\}}{\Sigma N \sin \alpha}$
Saturated Soils	Normal Force at the Base of a slice	$N = \dfrac{W - (X_R - X_L) - \frac{c' \beta \sin \alpha}{F} + u_w \frac{\beta \sin \alpha}{F} \tan \phi'}{\cos \alpha + \frac{\sin \alpha \tan \phi'}{F}}$
	Moment Equilibrium	$F_m = \dfrac{\Sigma\{c'\beta R + [N - u_w \beta] R \tan \phi'\}}{\Sigma Wx - \Sigma Nf}$
	Force Equilibrium	$F_f = \dfrac{\Sigma\{c'\beta \cos \alpha + [N - u_w \beta] \tan \phi' \cos \alpha\}}{\Sigma N \sin \alpha}$

DEFINITIONS OF VARIABLES

σ_x, σ_y, σ_z = total stress in the x-, y-, and z-directions, respectively

u_a = pore-air pressure

u_w = pore-water pressure

$(\sigma_x - u_a)$, $(\sigma_y - u_a)$, $(\sigma_z - u_a)$ = net total stress in the x-, y-, and z-directions, respectively

$(u_a - u_w)$ = matric suction

ε_x, ε_y, ε_z = linear strain in the x-, y-, and z-directions, respectively.

ε = volumetric strain; equal to $\varepsilon_x + \varepsilon_y + \varepsilon_z$

E = elastic modulus with respect to a change in $(\sigma - u_a)$

H = elastic modulus with respect to $(u_a - u_w)$

μ = Poisson's ratio

θ_w = net inflow or outflow from the element

H' = water phase (elasticity type) parameter with respect to $(\sigma - u_a)$

R = water phase (elasticity type) parameter with respect to $(u_a - u_w)$

m_1^s = compressibility of the soil structure with respect to a change in $(\sigma - u_a)$

m_2^s = compressibility of the soil structure with respect to a change in $(u_a - u_w)$

m_v = coefficient of volume change

m_1^w = slope of the $(\sigma_y - u_a)$ versus θ_w plot

m_2^w = slope of the $(u_a - u_w)$ versus θ_w plot

e = void ratio

w = water content

a_t = coefficient of compressibility with respect to a change in $(\sigma_y - u_a)$

a_m = coefficient of compressibility with respect to a change in $(u_a - u_w)$

a_v = coefficient of compressibility

b_t = coefficient of water content change with respect to $(\sigma - u_a)$

b_m = coefficient of water content change with respect to $(u_a - u_w)$

τ = shear strength

c' = the effetive cohesion

ϕ' = the effective angle of internal friction

ϕ^b = the angle of shear strength increase with respect to an increase in $(u_a - u_w)$

σ_n = total normal stress

e_o = initial void ratio

W = total weight of a slice of width 'b' and height 'h'

N = total normal force acting on the base of a slice. It is equal to $\sigma_n \beta$ where σ_n is the normal stress acting over the sloping distance, β.

X_L, X_R = interslice shear force on the left and right sides of a slice, respectively

R = radius or moment arm associated with the mobilized shear resistance

x = horizontal distance from the center of each slice to the center of moments

f = offset distance from the normal force to the center of moments

α = the angle between the tangent to the center of the base of each slice and the horizontal

F = factor of safety

F_m = factor of safety with respect to moment equilibrium

F_f = factor of safety with respect to force equilibrium