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STRESS STATE VARIABLE AND SHEAR STRENGTH BEHAVIOUR OF UNSATURATED SOILS

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ABSTRACT

Mechanical behaviour of an unsaturated soil is commonly viewed as being more complex and more difficult to be understood than that of a saturated soil. This is caused by the presence of pore air and pore water pressure together in the unsaturated soils model. Most of civil constructions are built over soils in unsaturated condition, in contras they are designed using saturated soil mechanics concept that is relatively different with unsaturated soil mechanics concept. This therefore can be understood because unsaturated soils have not been yet implemented in practical work. To produce more realistic solution for various soil mechanics problems, unsaturated soil mechanics have to be ready for application in standard engineering practice. It will require much more research to investigate mechanical behaviour of unsaturated soils that will provide subsequently confidence on the part of the practicing engineer. This paper concern to describe part of mechanical behaviour of unsaturated soils i.e. stress state variable and shear strength behaviour. Unlike saturated soils, two of three stress parameters $\sigma - u_a$, $\sigma - u_w$ *and* $u_a - u_w$ *need to describe fully stress state of an unsaturated soil. The relationship between shear strength and suction are not consistent. There need an investigation to clarify this relationship and to develop an equation to calculate shear strength of unsaturated soils.*

Key words: unsaturated soils, stress, shear strength, suction

INTRODUCTION

Soils are material that consists of a network of solid particles which enclose voids or pores. The voids may be filled with water or air or both. By this mean, soil is then a multi-phase material consisting of solid (usually mineral particles), liquid (usually water) and gas (usually air). In two-phase condition, soils may contain solids and air (dry condition) or solids and water (saturated condition) whereas in three-phase condition, soil may contain three different components. The later soil is then called as unsaturated soil. In other word, in saturated and dry soils the pore space are filled with a single medium, either water or air. In unsaturated soils the pore space are filled with a mixture of two or more media, most commonly air and water.

Indonesian soils which classified as tropical soils will be met mostly in unsaturated condition. It bring consequence that ideally construction foundations should consider unsaturated soil mechanics. Although the concept of unsaturated soils has not been yet implemented in practical work, engineer should judge some problems caused by unsaturated soils. Therefore, the characteristics of unsaturated soils should be well-understood by engineer.

This paper concern to describe a part of mechanical behaviour of unsaturated soils i.e. development to define stress state variable and shear strength behaviour included reporting of development of oedometer apparatus to use investigating unsaturated soil specimen.

2. CATEGORIES OF UNSATURATED SOILS

Wroth & Houlsby (1985) proposed categories of unsaturated soil on the basis of continuity of the fluid phases. The three different categories proposed are:

- Air phase discontinuous and water phase continuous;
- Air and water phases both continuous;
- Air phase continuous and water phase discontinuous.

The engineering behaviour of an unsaturated soil is commonly viewed as being more complex and more difficult to understand than that of a saturated soil. In many situations in the field the air is connected to the atmosphere, so that relative to atmosphere pressure. The air pressure (u_a) is equal zero (u_a=0) and therefore pore water pressure (u_w) will be negative value ($u_w \leq 0$). Unsaturated soils generally have negative pore water pressures, but it is the wide range of associated degrees of saturation that produce a broad spectrum of soil behaviour. **Fig. 1** shows that an unsaturated soil can be near to 100% saturation in the capillary zone (if capillary zone is as B) and almost dry near the ground surface.

3. UNDERSTANDING OF PORE PRESSURE AND SUCTION IN THE UNSATURATED SOILS MODEL

Because of pore space of unsaturated soils are filled by air and water, there are two pore pressures i. e. pore air pressure (u_a) and pore water pressure (u_w). The mechanical behaviour of unsaturated soil is strongly influenced by both the pore air pressure and the pore water pressure. Because of surface tension at the air water interface, so that pore air pressure is not equal by pore water pressure.

The value of pore air pressure is always higher than the pore water pressure ($u_a \geq u_w$) because the contact angle θ that measured on the water side and a function of the material properties of the liquid, water and soil particle is very small (approaching 0^o).

The difference between the pore air pressure and the pore water pressure is defined as the ‘matrix suction’ or called as ‘suction’. This value is depend upon the surface tension (T) and the principle radii of curvature of the menisci (r_1 and r_2), and then there is equation below

$$u_w r_1 d\theta_1 r_2 d\theta_2 - u_a r_1 d\theta_1 r_2 d\theta_2 + 2Tr_1 d\theta_1 \sin\frac{d\theta_2}{2} + 2Tr_2 d\theta_2 \sin\frac{d\theta_1}{2} = 0 \quad (1)$$

then

$$u_a - u_w = T\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \quad (2)$$

where air-water interface at 20^0 C the value of T = 0.07257 N/m

As a soil is gradually dried from a fully saturated state, at S_r =1, the water within the soil retreats into smaller and smaller voids. The air-water interfaces become increasingly curved, and the matrix suction u_a - u_w rises as the degree of saturation S_r falls.

The curve of degree of saturation S_r against matrix suction is called the water retention curve or soil-water characteristic curve. The water retention curve for a given soil is not unique because drying paths and wetting paths follow different curves. This is known as hydraulic hysteresis (**Fig 2**). The reason for hydraulic hysteresis is that when a given void is about to empty of water at A during a drying path the menisci are at the narrow entry points to the void (the radius of curvature is therefore small and the matrix suction correspondingly high), whereas when the same void is about to re-fill with water at B during a wetting path the menisci are about to coalesce at location well inside the narrowest entry points (the radius of curvature is therefore larger, and the matrix suction correspondingly lower).

Fig. 3 shows that there are two type of pore water within an unsaturated soil, i. e. bulk liquid and meniscus liquid. The negative pore water pressure within bulk water acts in the same way as in a saturated soil (except that it acts in only the water-filled voids) whereas the negative pressure within meniscus water produces an additional inter-particle force that is

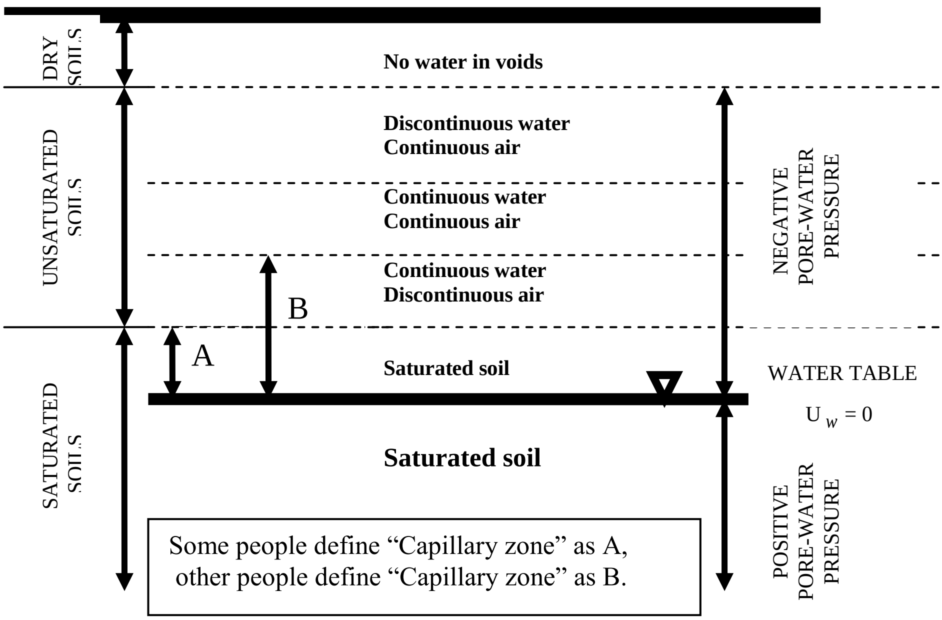

Fig. 1 Classification of the regions within a saturated-unsaturated soil profile

normal to the inter-particle contact at each particle contact. To illustrate this, consider the idealised case of a lens of meniscus liquid at the contact between two spherical particles in **Fig. 4**, with pore liquid confined by a meniscus, and gas at higher pressure acting outside it.

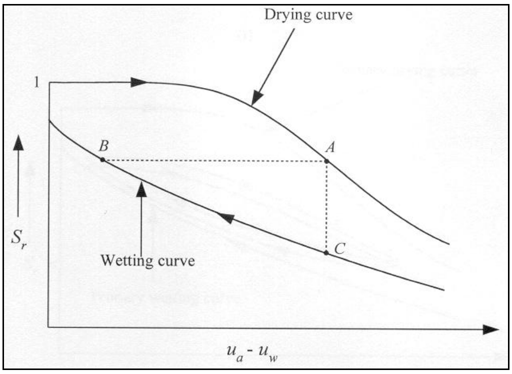

Fig. 3 Hydraulic hysteresis

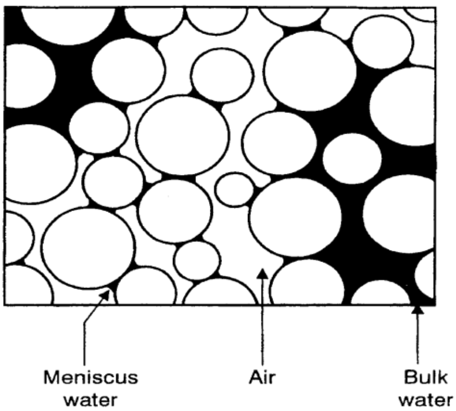

Fig.4 Schematic of bulk and meniscus liquid (after Wheeler and Karube, 1995)

4. STRESS STATE VARIABLES

a. Attempts to define a single effective stress

Terzaghi (1936) stated that all the measurable effects of a change in stress, such as compression, distortion and a change in shearing resistance are exclusively due to changes in the effective stress.

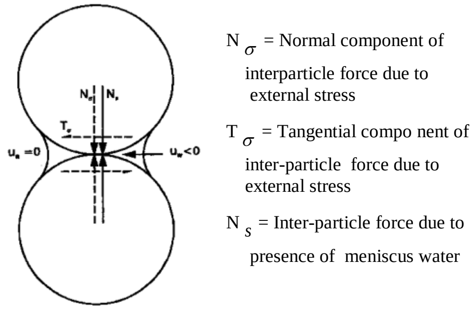

Fig. 4 Inter-particle force (after Wheeler and Karube, 1995)

In saturated or dry soil the effective stress (σ') is found to be equal to the total stress (σ) minus the pore fluid pressure (u):

$$\sigma' = \sigma - u \qquad (3)$$

Bishop (1959) proposed the equation of effective stress for unsaturated soils:

$$\sigma' = \sigma - \chi u_w - (1-\chi) u_a$$
$$= \sigma - u_a + \chi (u_a - u_w) \qquad (4)$$

u_a was the pore air pressure, u_w was the pore water pressure and χ was a parameter which was unity for saturated soils and decrease as the degree of saturation fell, reaching zero for dry soils.

Jenning and Burland (1962) stated that if the single effective stress concept were valid, swelling of soil sample would be expected during wetting due to the reduction in the effective stress as proposed by Bishop (1959). The reduction in soil volume sometimes observed during wetting (collapse compression) was exactly the reverse of the behaviour predicted by Bishop equation and this case serious doubt on the single effective stress concept as applied to volume change. Jennings and Burland (1962) suggested a two-way mechanism to explain collapse behaviour on wetting of unsaturated soils as follow:

a) bonding between the saturated soil packets will be removed, resulting in collapse of the packet structure into the air-filled inter-packet voids;
b) each saturated packet take in water and swells i.e. collapse of the macro-structure, but swelling of the micro-structure of each packet.

The overall volume changes depend upon the void ratio within the packet and the strength of each packet available to prevent breakdown.

There is apparent unable to represent collapse compression on wetting by Bishop equation (1959). There was other idea that a single effective stress approach might work if there were only bulk water (similar condition with saturated soils). It is the presence of meniscus water which causes the difficulties. An increase of suction within meniscus water (as u_w goes more negative) increases the normal forces at inter-particle contacts. This has several effects.

a) **Elastic strains**. A rise of suction causes elastic deformation of particles, produce elastic compression of soil. This is like an increase in effective stress in a saturated soil.
b) **Plastic strains**. Increasing the normal force without change of tangential force will reduces possibility of slippage of frictions inter-particle contacts. This will be followed by reducing the possibility of yielding and occurring the plastic strains. This is like a decrease in effective stress in a saturated soil.
c) **Shear strength**. Increasing the normal force at inter-particle contacts will be followed increasing shear strength. This is like an increase in effective stress in a saturated soil.

These mean that an increase in suction within meniscus water is, in some sense, like an increase in effective stress, but, in other senses, like a decrease in effective stress. By this mean, it can not just combine σ, u_a and u_w into single effective stress. It is not just Bishop's equation that is wrong, but there can no satisfactory definition of a single effective stress for unsaturated soils.

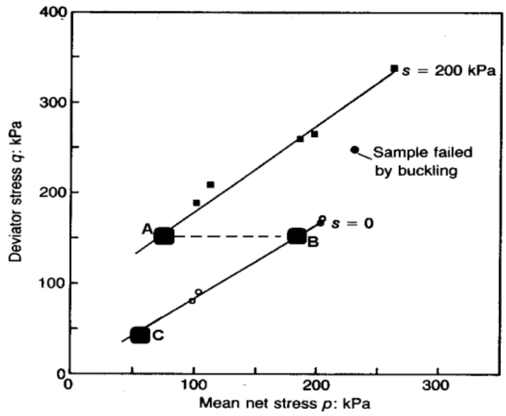

Fig.5 q-p at critical state

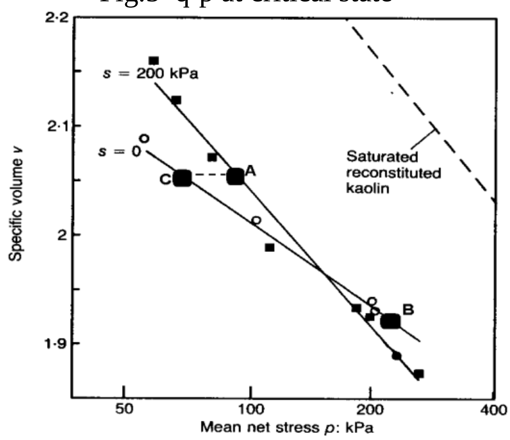

Fig. 6 v-p at critical state

Wheeler and Sivakumar (1995) presented critical state data for compacted kaolin (**Fig.5 and 6**) that show that it is impossible to state at unsaturated sample A (s=100 kPa) is at the same effective stress as a specific saturated sample (s=0). The two samples would have to have identical properties. Unsaturated sample A has same shear strength as saturated sample B, but same value of v as saturated sample C.

b. Use of two stress state variables

The failed attempting to represent all the effects of suction within a single stress parameter show the mechanical behaviour of unsaturated soils cannot be described in terms of a single state parameter, but an additional stress parameter is required.

Coleman (1962) and Bishop and Blight (1963) is the earliest use of two independent stress variables. Bishop and Blight then suggested a modified effective stress equation that may be expressed in quite general form, in which the effective stress was function of $\sigma - u_a$ and $u_a - u_w$:

$$\sigma' = \sigma - u_a + f(u_a - u_w) \qquad (5)$$

Matyas and Radhakrishna (1968) adopted the net stress $\sigma - u_a$ and the matrix suction $u_a - u_w$ as the independent stress variables to describe the mechanical behaviour of unsaturated soils.

Fredlund and Morgenstern (1977) stated that any two of the three stress parameters $\sigma - u_a$, $\sigma - u_w$ and $u_a - u_w$ would be sufficient to describe fully the stress state of an unsaturated soil. The stress $\sigma - u_a$ and $\sigma - u_w$ are tensor quantities, whilst the suction $u_a - u_w$ is a scalar quantity. The combination of net stress $\sigma - u_a$ and the matrix suction $u_a - u_w$ is usually selected, because u_a is commonly zero (relative to atmospheric pressure) in the field, and the net stress and the matrix suction then simplify to the total stress and the negative pore water pressure respectively. In addition, the pore water pressure in an unsaturated soil is generally negative, which is often difficult to measure accurately. This means an element of uncertainty will be only one stress variable if $\sigma - u_a$ and $u_a - u_w$ are selected, whereas the uncertainty will affect both the variables if $\sigma - u_w$ and $u_a - u_w$ are adopted.

Alonso, Gens and Josa (1990) proposed a critical state framework for unsaturated soil involving 4 state variables: mean net stress $\bar{p}$, deviator stress *q*, suction *s* and specific volume *v*, where *v* were defined in the normal way and *p*, *q* and *s* were given by:

$$\bar{p} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} - u_a \qquad (6)$$

$$q = \sigma_1 - \sigma_3 \qquad (7)$$

$$s = u_a - u_w \qquad (8)$$

5. SHEAR STRENGTH BEHAVIOUR

The shear strength of a soil is the maximum shear stress that can be applied to the soil. When this maximum has been reached, the soil is regarded as having failed, the strength of the soil having been fully mobilized.

In saturated soils, the shear strength of a soil is derived from the structural strength alone, the pore water having no shear strength. The resistance of the soil structure to shear arises from the frictional resistance, F, generated by the interparticle forces, N. The shear strength, τ_f (shear stress at failure), on any plane in a soil, is some function of the effective stress normal to that plane and has equation below.

$$\tau_f = c' + (\sigma_n - u) \tan \phi' \qquad (9)$$

where σ_n is the total stress normal to the plane, u is the pore-water pressure, c' is the cohesion intercept and ϕ' is the angle of shearing resistance, with respect to effective stress.

Fredlund, Morgenstern and Widger (1978) proposed the equation for the shear strength of unsaturated soils that was predicted a linear increase of strength with suction (u_a - u_w).

$$\tau_f = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \qquad (10)$$

where $\sigma - u_a$ is net stress normal to plane of shearing, c' and ϕ' are cohesion and friction angle for saturated conditions and ϕ^b is friction angle with respect to suction.

Escario and Saez (1986) conducted drained direct shear tests on compacted Madrid clayey sand and have shown that ϕ^b is not constant. At low suctions, ϕ^b will be approximately equal ϕ' and then

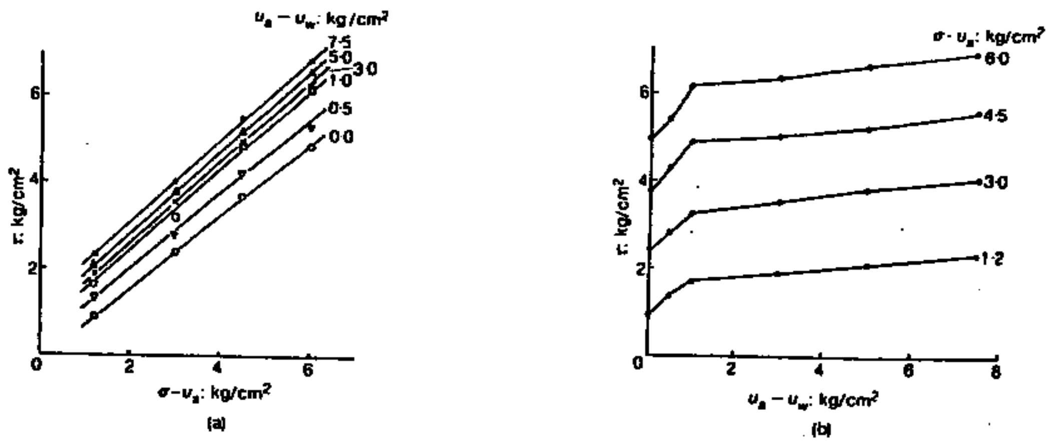

Fig. 7 Failure strength plotted for Madrid clayey sand (Escario and Saez, 1986)

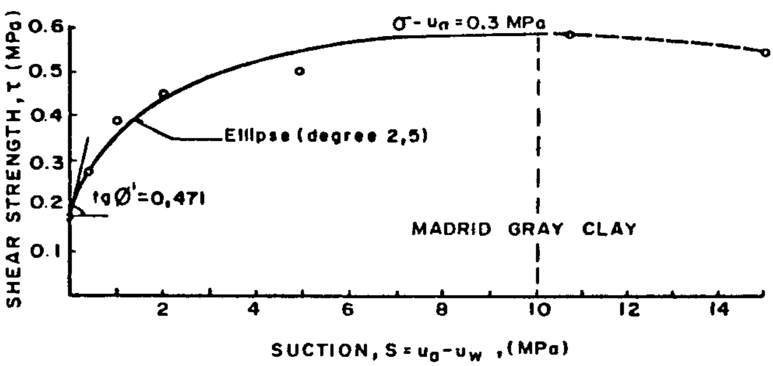

Fig. 8 Shear strength envelope (Escario and Juca, 1989)

tended to decrease as suction increased (**Fig. 7**). Escario and Saez also concluded that the value of ϕ' was unaffected by changes of the suction. Gan, Fredlund and Rahardjo (1988) also observed the non-linearity of shear strength with suction in triaxial tests conducted on a glacial till.

Escario and Juca (1989) examined the shear strength of unsaturated soil in a wide range of suction values from 0 to 14 MPa. **Fig. 8** shows the shear strength envelope plotted against suction on Madrid gray clay at a constant value of net normal stress. The shear strength reached a maximum at a particular value of suction and then started to fall and to be a negative value. Theoretically if the suction increases indefinitely the soil must ultimately reach a dry state and equation 10 should reduce to the normal Mohr-Coulomb relationship for dry soil.

6. CONCLUSSION

a. The mechanical behaviour of an unsaturated soil is commonly viewed as being more complex and more difficult to be understood than that of a saturated soil.
b. To describe fully stress state of an unsaturated soils, there need two of three stress parameters $\sigma - u_a$, $\sigma - u_w$ and $u_a - u_w$.
c. The result of investigation of relationship between shear strength and suction are not consistent. There need an investigation to clarify this relationship and to develop an equation to calculate shear strength of unsaturated soil.

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