Chapter 2
The Terzaghi Theory of Effective Stress

The theory of effective stress was developed by Terzaghi in the early 1920s (Terzaghi 1925). Its principal positions on stress in soils imply the following: (a) in the water-saturated soil with open porosity, effective stresses represent the excessive stress in the soil skeleton over the neutral stress; (b) effective stresses control the strain-and-stress state, volume variation, and strength independently of neutral stress.

A large body of experimental data supports the validity of these conclusions. Terzaghi theory was successfully used for solving problems in consolidation of porous permeable soils, for explaining reasons of sand liquefaction during earthquakes, as well as for a number of other tasks.

At the same time, the practical experience indicates that the Terzaghi theory cannot be adequately applied to low-permeable fine-grained soils (clay) with closed porosity, as it leads to the discrepancy between calculated and experimental data. The main areas of concerns are the following:

1. The Terzaghi theory uses the total average stresses (σ) produced by external forces; it does consider internal forces creating additional stresses in the soil skeleton. The latter are becoming significantly more important with the finer grain-size of soil.
2. At the same height of the water column, the pore pressure (u) measured in a clay system may differ from the pore (hydrostatic) pressure in a permeable porous body (u_0).
3. Effective stresses are transmitted to the skeleton through the contacts between structural units. Even if the total effective stress is constant, the effective contact stresses may differ due to the disjoining effect of hydrate films, changing amount of contacts, orientation of contact sites, and area of contacts. All these factors influence the strength and deformational properties of soils.

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Skempton was one of the first scientists who noted unreliable assessment of effective stresses in the Terzaghi theory (Skempton 1960). He introduced the correction for the area of contacts (a_c) to the equation of effective stress:

$$\sigma' = \sigma - (1 - a_c)\,u, \tag{2.1}$$

where a_c is the ratio between the area of contacts and the total loaded area.

However, like Terzaghi, he also did not take into account the effect of physicochemical forces on effective stresses. Therefore, the introduced correction allowed updating the (σ') values only for some soils, cements, and hard rocks.

Mitchell and Soga analyzed in detail the nature of the effective stresses with the consideration of physicochemical phenomena in clay systems (Mitchell and Soga 2005).

They scrutinized the main physicochemical interactions in the contact zone, such as electromagnetic attraction (Van der Waals forces), electrostatic repulsion and attraction, and chemical forces. Most important, the authors analyzed the stresses in soils at the level of intergrain interaction. For this purpose, they composed the equation of forces acting in soil, including the forces of physicochemical origin:

$$\sigma a + Aa + A'a_c = ua + Ca_c, \tag{2.2}$$

where σ is the external stresses transmitted to the contact; a is the total area of contact where the chemical and physicochemical forces are present; a_c is the area of actual (immediate) contact between particles; A is the far-distance molecular Van der Waals and electrostatic attraction forces; A' is the close-distance attraction forces responsible for the chemical bond and cementation; u is the far-distance electrostatic forces of repulsion equal to $u(a - a_c)$; since $a \gg a_c$, the repulsion may be assumed to be ua; and C stands for the close-distance Born and hydration repulsion forces.

From Eq. (2.2), we may find the stress transmitted to the unit horizontal area equal to the total area of unit contact:

$$\sigma = \left(C + A'\right)a_c/a + u - A. \tag{2.3}$$

Expression $(C + A')a_c/a$ represents the total stress acting at the true contact in realtion to the total contact area. If we denote the intergrain stress (σ_i') obtained by relating the stress at the true contact to the total contact area (from (2.3)) by $(C + A')a_c/a$, then:

$$\sigma_i' = \sigma + A - u. \tag{2.4}$$

In a similar way, the interparticle effective stresses may be calculated in the partially water-saturated soil. For this purpose, it is necessary to know the pressure in the pore water (u_w) and in the pore air (u_a), as well as the shares, per particle, of areas occupied by water (a_w) and air (a_a):

$$a_w + a_a = a(a_w + a_a)$$

The resulting formula is:

$$\sigma_i' = \sigma + A - u_a - \frac{a_w}{a}(u_w - u_a). \tag{2.5}$$

The equation obtained (2.5) looks similar to that derived earlier by (Bishop 1960):

$$\sigma_i' = \sigma - u_a + \chi(u_a - u_w), \tag{2.6}$$

where $\chi = a_w/a$.

These calculations prove that effective stresses at the contacts can be estimated taking into consideration close- and far-distance physicochemical forces. However, the following questions remain unresolved, specifically, how to: (1) find A and u values in Eq. (2.4), (2) estimate the number of contacts and their area, and (3) transition from assessment of the inter-particle effective stresses σ_i' to assessment of the actual effective stress in soil and rock (σ'').

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