DOI 10.1007/s11204-016-9378-4
Soil Mechanics and Foundation Engineering, Vol. 53, No. 3, July, 2016 (Russian Original No. 3, May-June, 2016)

SOIL MECHANICS

FRICTION AND COHESION AS MULTIFACETED FACTORS OF SOIL SHEAR RESISTANCE

V.I. Osipov
Sergeev Institute of Environmental Geoscience,
Russian Academy of Sciences, Moscow, Russia.

UDC 624.131.439

Aspects are examined of dispersive soils that are conditioned by the mechanism and magnitude of their shear resistance. From a general physicochemical perspective, we study factors not considered in the Mohr-Coulomb theory that explain its departure from experimental data-mineral and granulometric composition, morphology of structural elements, the degree of lithification, the adsorption films and hard "liners" on the surface of minerals, the effect of the disjoining pressure on the real effective stresses, the mechanism of friction, and structural changes during deformation.

Introduction

According to the Mohr-Coulomb theory, shear resistance τ is based on the following two principles: a) the linear dependence of the angle of repose (internal friction) on external stress, b) structural cohesion independence of external stress, i.e., its invariance over the entire range of normal stresses σ in response to a shear

$$\tau = \sigma \tan\varphi + c, \tag{1}$$

where c is the interval cut by the shear curve on the cohesive strength axis, φ is the slope of the shear curve to the stress axis (the internal friction angle).

Numerous experimental data show that for friable and cohesive soils, the envelope of stress circles (Mohr circles) is curvilinear and only some intervals of that envelope can be approximated by the linear Mohr-Coulomb equation. Very noticeable departures are observed when weakly lithified soils undergo shear in the range of normal stresses up to 300 kPa. For higher stresses, the nonlinearity of shear curves smoothes out.

The curvilinear shape of the envelope is indicative of the variability in the angle of repose and cohesion as a function of the stressed state. This observation spurred the authors to extensively study the interpretation of experimental results that provide a best fit for them within the basic scope of the Mohr-Coulomb theory. Several methods were proposed that were capable of solving this problem by approximating the envelope curve by a straight line corresponding to (1).

The reason behind this mismatch between experimental evidence and theoretical results lies in the fact that the Mohr-Coulomb theory does not take into account many factors that have an effect on the friction and shear resistance of soils and does not fully reflect the properties of dispersive systems and the nature of deformation processes that occur during shear. Such factors include the friction mechanism at contacts, the nature of the structural strength and structural cohesion, structural changes in the shear zone,

Translated from Osnovaniya, Fundamenty i Mekhanika Gruntov, No. 3, pp. 2-8, May-June, 2016.

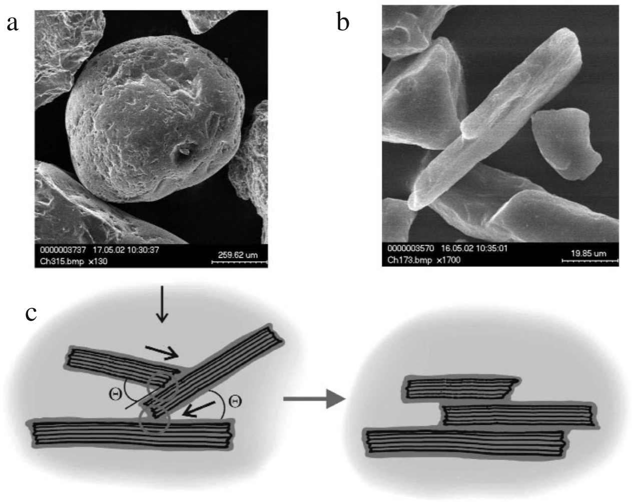

Fig. 1. Types of friction in dispersive soils.

the effect of soil mineral and granulometric composition, as well as morphometric peculiarities of structural elements and solid films of foreign bodies on their surface, the disjoining pressure of thin hydrate films and real effective stresses, and the variation in density and soil moisture in response to shear.

Soil strength in response to shear deformation is an involved parameter depending on four groups of factors:

$$\tau = f\,[(M,\ G,\ Sh,\ S),\ (c,\ \rho,\ W),\ (\sigma',\ F(h),\ \sigma''),\ (H,\ D,\ T,\ \varepsilon,\ \dot{\varepsilon})]. \qquad (2)$$

1) factors governing the nature and mechanism of friction at contacts: the mineral and granulometric compositions of soil (*M*, *G*), the geometric and morphometric peculiarities of structural elements (*Sh*), and the presence of solid "liners" and the adsorption of water films on the surface of particles (*S*).

2) The second group involves the structural cohesion (*c*), which is related to the formation of structural bonds in soils, as well as the density (ρ) and moisture (*W*), which have an effect on the number and strength of contacts.

3) The third group of factors is the stressed state of soil, which depends on the effective stress (σ'), the wedge-effect of hydrate films *F*(*h*), and the true effective stress (σ'').

4) The fourth group combines the factors depending on the methods and conditions of experiments: the soil load history (*H*), the soil drainage conditions under shear (*D*), the temperature (*T*), the deformation rate ($\dot{\varepsilon}$), and the total deformation (ε).

A fairly complete account of the last group of methodical factors may be found in [1-6]. Below we shall consider the first three groups of factors underlying the theory of soil shear and requiring an explanation from the viewpoint of physicochemical mechanics.

Friction mechanism and structural changes with shear

Depending on the development mechanism, internal friction is subdivided into the following four types: rolling friction, rolling friction with cohesion, slipping friction, and mixed (composite) friction (Fig. 1).

Rolling friction. This mechanism is typical for sand grains and coarser structural elements. Because of the complexity of the form and the irregularity of the surface, the grain motion path is fairly complicated. Grains rotate, roll, expand, descend, or ascend. In addition, there is constant grain motion due to rolling. The resistance of grains to motion under shear will be called the rolling friction (Fig. 1a).

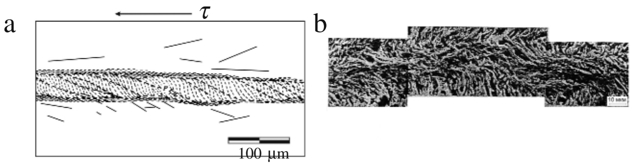

Fig. 2. Shear zone (a) and shear planes (b) formed after shear occurs in clay soil.

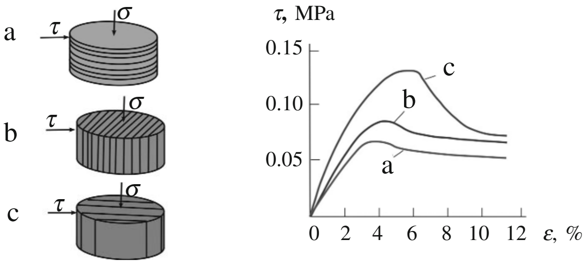

Fig. 3. The effect of clay texture (orientation of particles) on shear resistance: a) shear along the stratification; b) across the stratification and layers; c) across the stratification, along layers.

Rolling friction with cohesion. When angular grains undergo shear, the process of grain cohesion while rolling plays an important role. Roll with cohesion is an energy intensive type of motion that is characterized by the highest values of friction parameters. The impact of roll with cohesion increases as the packing density of grains increases (Fig. 1b).

Slipping friction. As the clay mineral content in soil increases, slipping friction becomes the dominant effect. In compacted clays featuring oriented microtexture, slipping friction develops between clay particles and their aggregates at basal-cleavage and basal-basal contacts (Fig. 1c).

Mixed friction. As a rule, the friction mechanism in natural soil is of mixed character, i.e., one may simultaneously observe various kinds of friction with one or another predominating.

The study of structural changes in response to shear in the context of clay soils was studied in several countries in the 1970s [7-10]. It was shown that, for deformation under planar shear, a shear zone is created in clay soil (Fig. 2a). Its width, depending on the soil structure and its state, may vary from fractions of a millimeter to several millimeters. Soil deformation and failure under shear takes place not in the entire volume, but in the mobilization zone of shear stresses, where the zone and shear planes are formed.

In a detailed study of shear zones in clay soils using electron microscopy, Sokolov and Osipov [11] revealed a strong orientation of clay particles in the shear plane (Fig. 2b).

The same authors also examined the effect of the primary texture (orientation of particles) of clay soil on shear strength. The shear strength was determined by the planar shear method following the method of fast unconsolidated test parallel to (Fig. 3a) and perpendicular to (Fig. 3b) the formation and along the layers (Fig. 3c).

The tests showed that the greatest strength is characteristic of a specimen sheared perpendicular to the formation along the layers, which is explained by maximum energy expenditures for the structural rearrangement of soil, including the rotation of particle basal planes perpendicular to the shear direction and their subsequent rotation (incline) along the shear direction.

The following conclusions can be drawn from the study of structural changes of clay soils in the shear zone: a) the energy expenditures for structural rearrangement in the shear zone have an effect on soil strength, which increases in proportion to the structural changes; b) the ultimate strength is attained after the formation of the shear zone and orientation of particles in the shear planes; c) under equal test conditions, the soil shear strength is smaller if there exists an oriented microtexture along the shear direction, and vice versa, it is larger if the particles are oriented orthogonal to the shear direction.

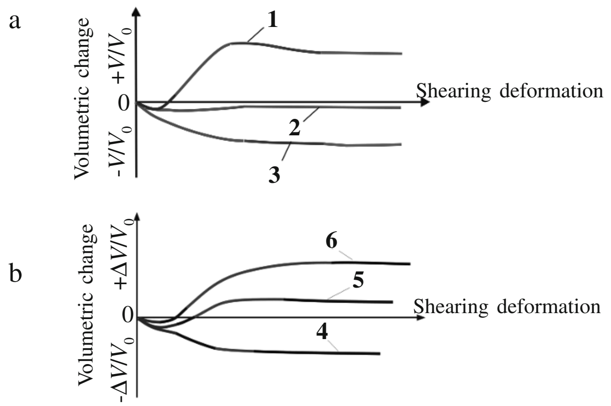

Fig. 4. Volumetric changes (dilatancy) for sand (a) and clay (b) soil with shear:1) tight sand; 2) with critical porosity; 3) loose; 4) plastic clay; 5) semi-hard; 6) hard.

The soil shear strength is closely related to the volumetric changes [12] taking place in the shear zone during the structural rearrangement. For sandy soil, the character and volume of such changes depend on its density (porosity) and the morphological peculiarities of grains, and for clayey soil, on its density and consistency.

It is seen from Fig. 4a that a positive dilatancy develops in tight sands over the entire process of deformation, i.e., the specimen loosens in the shear zone. On the other hand, loose sands are characteristic of negative dilatancy and with compaction. For a specimen with critical porosity there are practically no volumetric changes observed in response to shear.

The strength of sandy soil is determined not only by the number of contacts between structural elements, but also by the energy consumed for its loosening in the shear zone. Tight sand has the most strength, loose sand has the least strength.

For clay soil, the character and magnitude of dilatancy depends not so much on density as on consistency. For plastic clay, it is usually of a negative character. Positive dilatancy is observed when semisolid clay undergoes shear, which increases when transitioning to heavy clays of hard consistency (Fig. 4b).

Friction coefficient and determining factors

In Amonton's general theory of friction, the friction coefficient is considered constant for solid bodies, depending only on their composition and applied external normal stress; it is less influenced by the temperature and relative shear velocity. In addition, the friction coefficient is assumed to be independent of the contacting surface area.

These postulates are not supported in the context of soil systems. This is related to the fact that the friction mechanism of dispersive systems is different from that of solid bodies and depends on many factors.

Friction at the interface of two solid bodies depends on the friction resistance in the area of real contact (τ_b), which is a function of the composition of rubbing bodies, as well as of the area of real (dry) contacts ($a_{c(s)}$), which is in turn a function of the micro-hardness of minerals and the normal external stress

$$T = a_{c(s)}\tau_b. \tag{3}$$

The softer the wearing surface the greater is the area of real contacts and the higher is the friction resistance; that is, the friction coefficient decreases with increasing micro-hardness of minerals [13-15]. It is known that friction between absolutely dry monomineral dispersive systems, the angle of shear resistance (φ) for quartz, feldspar and calcite is 50% to 25% that of softer mica and chlorite (Fig. 5).

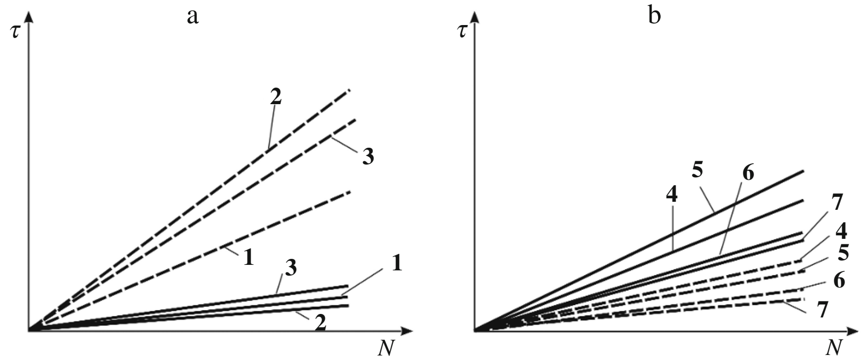

Fig. 5. Shear resistance of mineral dispersive systems consisting of simple (a) and layered (b) silicates in dry ([solid line]) and wet ([dashed line]) conditions: 1) quartz; 2) feldspar; 3) calcite; 4) muscovite; 5) phlogopite; 6) biotite; 7) chlorite.

Numerous experimental data are also indicative of sand resistance to shear as grain size increases. It is assumed that for tight sands, φ is 36° (very fine sands), 43° (coarse-grained sands), and 30-38° (loose sands); see [16]. This dependence is based on the following: 1) an increase in the size of anisometric grains results in an increase in the cohesion effect, which in turn is responsible for an increase in dilatancy under shear and an increase in the friction coefficient; 2) an increase in the size of grains results in an increase of their mutual collisions when transported in air or water, and sand undergoes amorphization and surface loosing, which increases the friction coefficient.

Considering the above we may say that the dispersion effect on the friction coefficient in sandy soil is clearly related not only to grain size, but mostly with the degree of their angularity (roundness) and the state of the surface.

Under natural conditions, diagenetic and supergenic processes result in the formation of a thin covering ("soil liner") on the surfaces of sand grains, consisting of clayey particles, organic compounds, ferrous sesquioxides, and manganese, carbonates and other foreign formations [17-19]. The resulting films modify the surface of rubbing minerals and change the friction coefficient.

In addition, during weathering and numerous collisions of sand in the process of their transportation in air or water the mineral substance on their surfaces undergoes amorphization-a "liner" of amorphized substance is formed on the surface of crystal grains. The interaction of such liners with water results in an increase of the coefficient and angle of internal friction. Chemical refining of grain surfaces decreases the effect of amorphization on the friction coefficient [20].

In addition to solid "liners", thin hydrate films are also formed on the surface of minerals [21, 22]; this is very typical of clay minerals. Such films create a disjoining pressure at particle contacts and give rise to the mechanism of boundary slipping friction in clayey systems. Hence, the angle φ substantially decreases with the appearance of coagulation contacts and the disjoining pressure on interfacial films. From Fig. 5b it is seen that, for friction between absolutely dry surfaces, the value of φ is 17-27° for muscovite, phlogopite, biotite and chlorite; in the wet state, this value is 7-13°.

The friction coefficient of plastic clay soils depends on the viscosity of hydrate films and decreases insignificantly as their thickness decreases.

The above data show that for minerals of framework silicates, moisturization results in an increase in the friction coefficient, while on the other hand, the formation of a film of bound water on the surface of clay minerals (layered silicates) results in a decrease in the friction coefficient.

A large effect on the friction coefficient also comes from the *morphology of structural elements*, which is understood to be the form (the external appearance) and the nature of grain and particle sur-

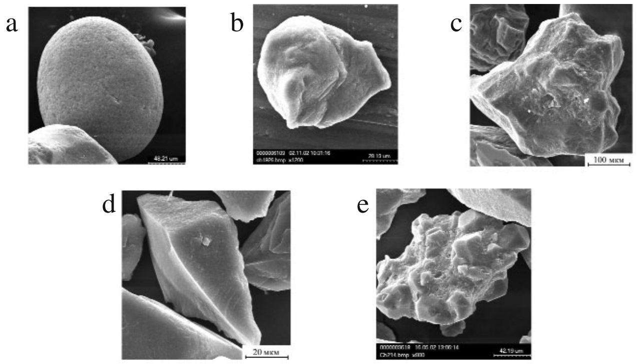

Fig. 6. Sand morphology: a) rounded; b) subrounded; c) subangular; d) angular; e) of complex shape.

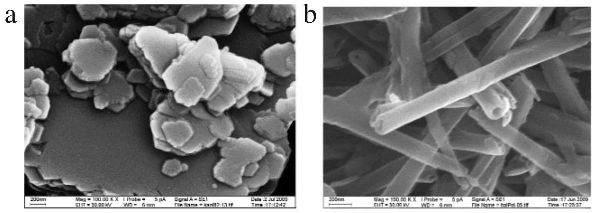

Fig. 7. The form and morphology of clay particles of plastic (a) and tubular (b) form.

faces. This factor is of utmost importance in estimating the friction coefficient of sand [23-26], etc. The interaction between the friction mechanisms depends on the morphology of sand grains.

Sand grains may have the following shapes: (rounded) rolled, subrounded, subangular, angular, and grains of complex shape: prismatic, laminar, corroded shape, etc. (Fig. 6).

Grain shape are most frequently estimated using factors proposed by Wadell [24]: the sphericity coefficient (β) and the rotundity coefficient (α).

Particle shape has an effect both on the friction coefficient and particularly on the anisotropy of shear resistance. Shear in clay soil results in cohesion and rotation of particles in the shear direction, which causes particles to slip in the basal planes and decreases the shear stress. The most difficult way for the shear process to develop, with the greatest energy consumption, is in clay formed by tubular and acicular minerals; the easiest way to develop is in clay formed by flat minerals (Fig. 7).

Soil structural cohesion and its defining factors

Structural cohesion in dispersive systems depends on surface forces of physicochemical and chemical nature [19, 20, 27-30]. Structural tenacity appears only when attractive forces between particles start to exceed their force due to gravity (F_c/F_g). Among the most important factors governing the magnitude of the structural tenacity is the degree of soil lithification and moisture.

Structural cohesion in dispersive formations is created in the process of settlement accumulation and its post-sedimentation transformation (*lithogenesis*). The largest change in lithogenesis is experienced in clay soil with the formation of contacts of various type between structural elements: remote and proximate coagulation, transit and phase contacts. The cohesion depends on the strength of the predominating type of contacts. In shear graphs of clay soil of various degree of lithification (Fig. 8), the magnitudes of intervals cut on the ordinate axis, which correspond to cohesion, varies from fractions of a kilopascal (for oozes with remote coagulation contacts predominating) to 300 kPa or more (for firm clays with phase contacts predominating).

There is no structural strength in friable (most of all, sandy) soils, which are in a dry or water-saturated state. In imperfectly saturated sands it appears in a certain range of moisture at the expense of

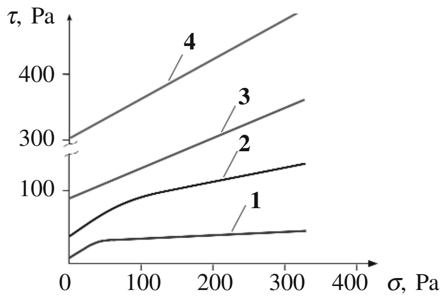

Fig. 8. Structural strength water-saturated clay materials of various lithification degree: 1) ooze; 2) plastic clay; 3) semi-solid clay; 4) firm clay

capillary forces. The structural strength of capillary nature is maximum when sand moisture is close to the maximum molecular moisture capacity and may exceed 10 kPa or more.

As distinct from sands, clay soils are considered as tenacious systems, which have structural strength both in water-saturated and in non-water-saturated states. It substantially increases with desiccation of clays, which is related with the formation of ion-electrostatic attraction on the contacts forces [31].

Capillary forces up to 0.3-0.4 MPa may also be exhibited when clay soil is moistened [32]. An increase of moisture results in an increase in the adsorption of water films at contacts of clay particles, which decreases the energy of their interaction and changes the structural strength. Clay water-saturated soil with predominant metastable contacts of coagulation type have structural strength up to 100 kPa and exhibit plastic consistency. Soils of this type swell and may completely loose cohesiveness and melt as the load is removed and more moisture is added. Firm clays with phase contacts have structural strength 300-400 kPa; they practically do not soften when moistened, preserving the high value of cohesion.

For semisolid clay with mixed type of contacts, the structural strength may be as high as 150-200 kPa. It decreases only partially when moistened. Maslov [1] was the first to observe this effect. He pointed out that some for clay materials, structural strength decreases when they are moistened while at the same time it remains substantially higher than that of plastic clay materials. Maslov proposed to subdivide the structural strength of such clays into two components:

$$c = \Sigma_w + c_c, \tag{4}$$

where Σ_w is structural cohesion of aqueous-colloidal nature, which depends on the material moisture; it is reversible with shear; c_c is the rigid structural strength, which is independent of the material moisture and is irreversible at failure when sheared.

Wedging of interfacial hydrate films and real effective stresses

One of the most important factors not considered by the Mohr-Coulomb theory is the wedge-effect of interfacial hydrate films on coagulation contacts, which has an effect on the effective stress [21]. According to Terzaghi's theory, the effective stress (σ') transferred on the soil skeleton is the difference between the total stress and the pore pressure: $\sigma' = \sigma - u$. The pore pressure is regarded to be the only factor governing the effective stress. The same assertion holds only in relation to sandy and clay soil with phase contacts, in which direct ("dry") contacts of structural elements prevail, while the role of adsorption in hydrate films is minimal. Terzaghi's theory does not apply to clay soils with contacts of coagulation type.

In plastic clay soils, the effective stress depends (apart from the external load) on internal forces, which appear at the contacts as the result of the wedge-effect of hydrate films. The stresses in the skeleton of such soil, owing to the combined action of the external and internal forces, are called the *real effective stresses* [33].

In clay with coagulation contacts, if there is no external load, the internal repelling and attracting forces balance each other and keep the structural elements at a certain distance, forming thermodynamically balanced (stable) remote coagulation contacts. This equilibrium is disrupted with an external load, the hydrate films at contacts are compressed, and the electrostatic repulsion (opposite to the external stress) increases. The disjoining pressure of hydrate films appears at the contact. In such clays the coagulation contacts are in a metastable state.

Thus, as the load increases, the effective stress at contacts becomes to be balanced by the wedge-effect of hydrate films. According to [33], the effective stress (σ'') reads as

$$\sigma'' = (\sigma - u) - \chi F_{(h)} a_c, \tag{5}$$

where χ is the number of contacts in the share unit area; a_c is the average area of a single contact; $F_{(h)}$ is the internal disjoining pressure at a contact; σ is the external stress, and u is the pore pressure.

The above shows that in analyzing the shear stress in soils with coagulation metastable contacts one should use the real effective stresses, which (in analogy with the pore pressure) gives greater shear parameters for plastic clays in comparison with those predicted by the Mohr-Coulomb theory.

Conclusions

1. The Mohr-Coulomb theory does not take into account specific peculiarities of dispersive soils, which results in discrepancies between experimental and theoretical data in the study of their shear resistance.

2. Among the most important factors controlling the value of shear resistance and which are not taken into account in the Mohr-Coulomb theory are the friction mechanism and structural changes of dispersive soils under shear, the mineral and granulometric composition of soils, morphological peculiarities of structural elements of soils, the presence of hard "liners" and adsorption water films on the surface of minerals, the lithification degree of soils and the existence of contacts of various natures, the disjoining pressure of adsorption water films on the contacts of particles and its effect on the real effective stresses.

3. Consideration of the above factors may allow one to interpret the experimental evidence from the physicochemical positions and explain the regularities in the changes of soils against shear, which are inexplicable by the Mohr-Coulomb theory.

4. Taking into account the multifactorial nature of the shear resistance of dispersive soils, the idea of composing universal tables with shear strength factors of various soils should be abandoned. In each particular case, when subdividing the soils in terms of their strength, one needs to take into account their genesis, composition, state and the degree of lithification.

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