THE STUDY ON SIMPLE SHEAR OF CLAY SOILS TO REDUCE THE RISK OF LANDSLIDES

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Abstract

The authors determined the critical shear deformation of clay soils as the critical shear angle $\gamma°$*, corresponding to the peak shear strength of clays during multi-plane shear at a deformation rate of* $2 \cdot 10^{-7}\, m/s$*. The study deals on elastic-plastic behavior and cracking of two different clays with differing monomineral and monoionic compositions, depending on preconsolidation pressure, the plasticity of these clays that were experimentally evaluated by measuring the critical shear angle under slow (*$V = 2 \cdot 10^{-7}\, m/s$*) multi-plane shear, corresponding to the peak shear strength. The obtained dependencies of the critical shear angle on compaction pressure are characterized by a curve with a maximum. This maximum corresponds to the transition from a plastic to an elastic state of the system. Based on the data obtained on the interaction of elementary micro-aggregates of clays of different mineral types and their mutual sliding during shear, the authors conclude that the critical deformation of two-phase clays is determined by the adhesive strength of contacts and the rheological properties of the pore fluid, and therefore by the friction coefficient. The observed increase in* $\gamma^0_{cr.}$ *values at relatively low compaction pressures (*P_n*) for all clays is associated with an increase in contact strength. The subsequent decrease in* $\gamma^0_{cr.}$ *is apparently caused by the difficulty of relative particle displacement, indicated by an increase in the friction co efficient* $tg\varphi$*. The authors found that under natural conditions, during landslide formation on isotropic clay slopes, the deformation zone develops as a deep shear zone no more than* $1.0\, m$ *thickness. In this zone, clay micro-aggregates begin to align parallel to the forming slip surface, which appears in the simple shear zone. Monitoring deformations in this shear zone allows for the timely application of engineering protective measures, significantly reducing the risk of catastrophic landslide development on clay slopes.*

Keywords: clay soils, deformation, risk, landslide, national condition, simple shear, slope

I. Introduction

The study of shear deformations in clay soils has been the subject of research by many scholars. Notable monographs include by M.N. Goldshtein [1], V.D. Kazarnovsky [2], I.P. Ivanov and Yu.B. Trzitsky [3], L.I. Kulchitsky and O.G. Usyarov [4], N.N. Maslov [5], E.M. Dobrov [6], and others.

As noted by S.V. Nerpin and A.F. Chudnovsky [7], during the formation of the structure of clay soil, aggregates of various sizes typically form. Such a structure is characterized by a high degree of pore size heterogeneity. This heterogeneity in pore size distribution leads to a corresponding heterogeneity in the stiffness of the system, which is distributed over micro-areas under isotropic compression of the soil. Shear deformations in such a system will cease when as a result of a new, more uniform pore size distribution, the condition for shear strength is satisfied and the creep threshold is not exceeded.

II. Methodology and Regularities of Simple Shear in Clay Soils

Let us consider a prismatic soil specimen subjected only to shear stresses τ_{xy} applied to opposite faces with equal magnitude (Fig. 1a). A pair of shear stresses acting on two opposite faces produces known as *simple shear*, in which infinitesimally thin layers slide relative to each other while maintaining their original length and thickness (Fig. 1b). As a result, the volume of the elements remains unchanged, and only the shape of the soil specimen is distorted.

A similar shear deformation occurs under the action of shear stresses τ_{yx} (Fig. 1c), applied to another pair of opposite faces of the soil specimen.

The two pairs of shear stresses shown in Figs. 1b and 1c tend to rotate the element about its center of gravity in opposite directions. Therefore, if the deformed element does not undergo rotation under the simultaneous action of both pairs, then the sum of the moments from the two stress pairs τ_{xy} and τ_{yx} must be equal to zero. From this follows:

$$\tau_{xy} = \tau_{yx} \tag{1}$$

This is the essence of the so-called *law of shear stress symmetry (or reciprocity),* known from the theory of elasticity. In simple shear, when only one pair of shear stresses is applied, the resulting moment - so as to prevent rotation of the considered element - must be balanced by a moment produced by non-uniformly distributed normal stresses acting on the top and bottom surfaces of the soil specimen. Thus, as noted by Professor M.N. Goldshtein, although the so-called simple shear test is widely used in soil mechanics, the resulting stress state is rather complex [1].

Let du denote the displacement (Fig. 1c) occurring during simple shear. The ratio of du to the specimen height dh equal to:

$$\text{tg}\, \text{y}_2 = \frac{\text{du}}{\text{dh}} \tag{2}$$

It's convenient to adopt this ratio as a measure of shear deformation.
The angle γ_2 is referred to as the *shear angle* (or angle of shear).

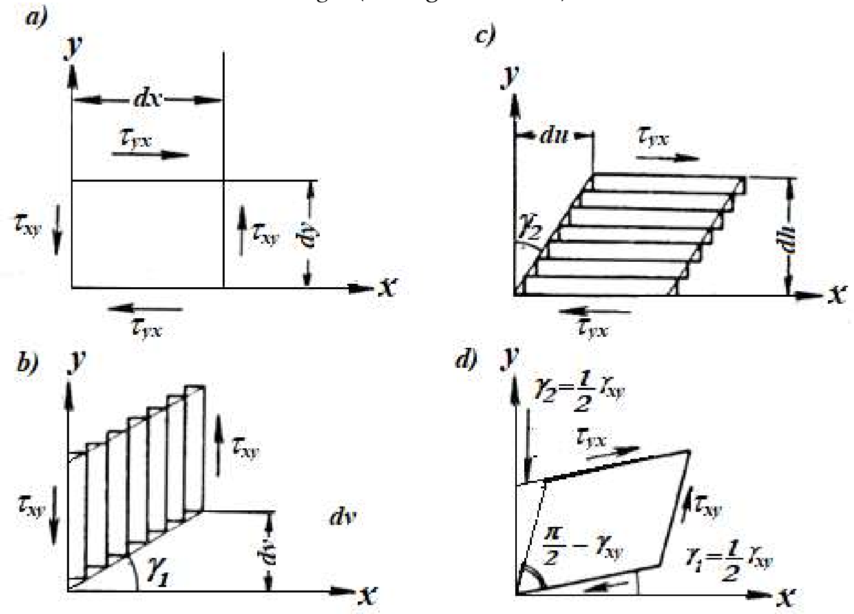

Figure 1: *Diagram of simple and pure shear of a specimen: a) initial, planar, analytical scheme of the prismatic soil specimen before shearing; b) simple shear scheme with shear stresses applied to opposite faces in the vertical plane; c) simple shear scheme with shear stresses applied in the horizontal plane; d) pure shear.*

The superposition of the two simple shear deformations shown in Figs. 1b and 1c results in the deformation illustrated in Fig. 1d (pure shear, since in this case no normal stresses act on any of the external faces of the specimen).

The amount by which the originally right angle between the specimen's faces decreases due to shear,

$$\gamma_{xy} = \gamma_1 + \gamma_2 \tag{3}$$

For a homogeneous and isotropic clay soil $\gamma_1 = \gamma_2 = \gamma$ and

$$\gamma_{xy} = 2\gamma \tag{4}$$

Thus, the angle γ_{xy} in pure shear is composed of two angles, each equal to $1/2\,\gamma_{xy}$, with one resulting from simple shear caused by the shear stress τ_{xy}, and the other from the action of stress τ_{yx}.

Professor M.N. Goldshtein notes that simple shear tests or "shearing tests" unlike direct shear tests, allow for the investigation of a soil's resistance to shape distortion. Fig. 2a shows the scheme of the multi-plane shear apparatus developed at the Dnipropetrovsk Institute of Transport Engineers (DITE). In this device, shearing of a specimen with a diameter of 6 cm is carried out by displacing the upper plate. The specimen, enclosed in a rubber membrane, is surrounded by flat metal rings placed around it with a gap of 1–2 mm between them. In this type of test, the entire volume of the specimen undergoes shape deformation. However, the moment that arises during simple shear causes a non-uniform distribution of shear forces across the cross-section of the specimen (Fig. 2b) distorting the test results [1].

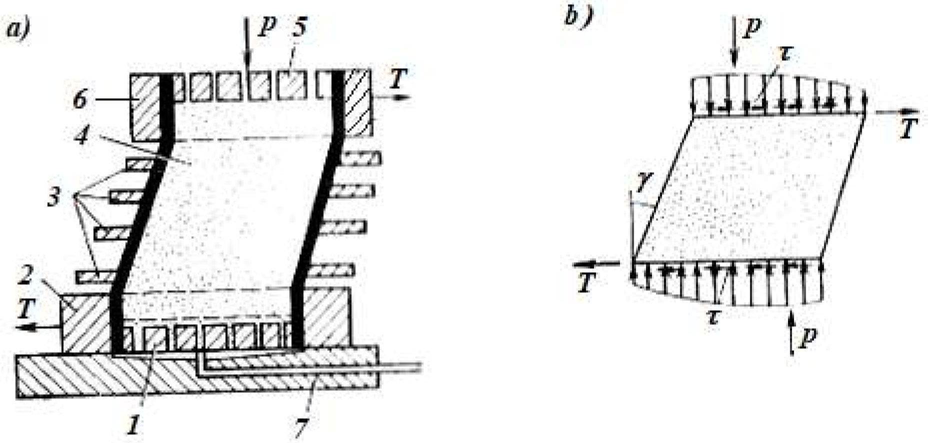

Figure 2: *Diagram of simple shear tests: a) schematic cross-section of the apparatus; b) diagram of non-uniform compression of the specimen; 1 and 5 – lower and upper porous pistons; 2 and 6 – lower and upper retaining rings; 3 – metal rings tightly fitted around the specimen enclosed in a rubber membrane; 4 – specimen; 7 – base of the apparatus.*

III. Study of the Critical Shear Angle of Clays under Simple Shear

It's possible determining the shear modulus G and its changes during deformation by varying the shear angle and knowing the magnitude of the applied shear stresses τ.

Plotting the graph of τ as a function of the shear angle allows one to establish the relationship between σ and τ for equivalent relative shear states (peak, residual and intermediate values), and to obtain the corresponding values of φ and c referred to as mobilized parameters (dependent on γ). Measurement of vertical deformations also makes it possible to determine the distortion values.

For the purpose of determining the critical shear angle of clay soils under simple shear, the authors developed a special attachment (Fig. 3) for the standard shear apparatus VSV-25. This attachment consists of a support bracket (1), assembled shearing rings (2), and fixation loops (3). The assembled rings (2) are made from round-section steel wire, allowing minimal contact between them when assembled. This design minimizes friction between the rings. Each ring (2) is equipped with two straight lugs located 180° apart around the circumference. When assembled into working condition, these lugs form flat stacks on each side, onto which the fixation loops (3) are placed. These loops ensure the preservation of the geometric sequence of specimen shearing (4) during multi-plane shear. The apparatus is also equipped with an extension containing an additional gearbox and an electric micromotor, allowing shear tests of clay soils to be conducted at various horizontal shear rates. The tests are conducted at deformation rates of $V_1 = 2 \cdot 10^{-4}\, m/s$ (quasi-instantaneous shear), $V_2 = 2 \cdot 10^{-7}\, m/s$ and $V_3 = 2 \cdot 10^{-8}\, m/s$ (quasi-long-term shear) [8].

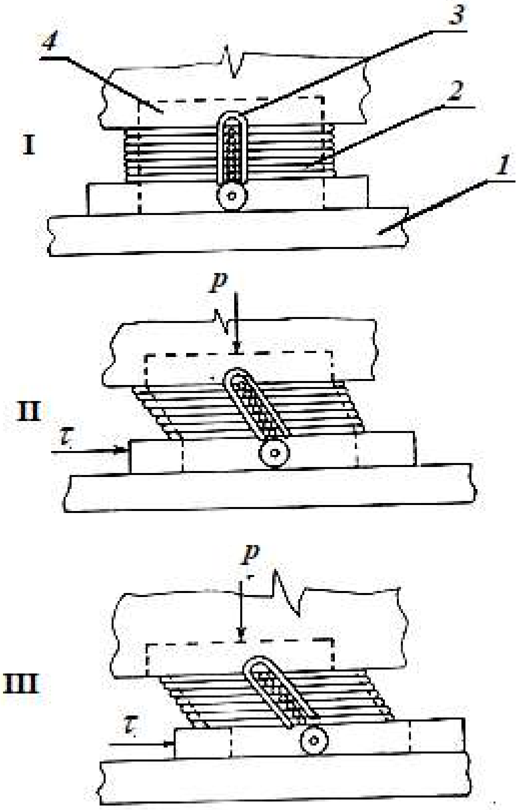

Figure 3: *Scheme of the device for testing clay soils under conditions of simple multi-plane shear: I – initial position; II – state during specimen shearing; III – state during specimen failure; 1 – carriage; 2 – rings; 3 – fixation loop; 4 – clay soil specimen.*

The critical shear strain of clay soils is defined in terms of the critical shear angle γ° corresponding to the peak shear strength of clay soils during multi-plane shear at a deformation rate of $2 \cdot 10^{-7}\, m/s$ and calculated by the following formula:

$$\gamma_{cr}^{\circ} = arctg\,\frac{l_{cr}}{H} \quad (5)$$

where $l_{cr.}$ is the critical displacement of the apparatus carriage, determined using a dial gauge indicator and corresponding to the peak shear strength of the clay soil; H – the height of the sheared specimen.

Professors L.I. Kulchitsky and F.G. Habibov studied the variation in elasto-plasticity and crack formation in two different clays of distinct monomineral and monocationic composition, experimentally evaluated the plasticity of these clays by measuring the critical shear angle during slow multi-plane shear ($V = 2 \cdot 10^{-7}\, m/s$), corresponding to the peak shear strength of the clays.

The resulting dependencies of $\gamma^{\circ}_{cr.}(P_n)$, presented in Fig. 4a, are characterized by a curve with a maximum. The last corresponds to the transition of the system from a plastic to an elastic state.

Fig. 4a presents that kaolinitic clays are characterized by the narrowest peak at the lowest compaction loads. These are followed by illitic clays and then by more aggregated montmorillonitic clays. A similar trend is observed in Fig. 4b, where the variation in the critical shear angle $\gamma^{\circ}_{cr.}$ is shown as a function of the thickness of the water films at microaggregate contacts, i.e., micropores h_0 (see the clay model proposed by L.I. Kulchitsky and O.G. Usyarov). Taking into account the data on the interaction between elementary microaggregates of clays with different mineral types and their relative sliding during shear, the authors conclude that the critical deformation of two-phase clays is determined by the adhesive strength of the contacts and the rheological properties of the fluid in the gap, and, consequently, by the friction coefficient.

The observed increase in $\gamma^{\circ}_{cr.}$ values at relatively low compaction loads (P_n) for all types of clay (Fig. 4a and 4b) is associated with an increase in contact strength. The subsequent decrease in $\gamma^{0}_{cr.}$ in the second part of the curve is presumably caused by the increasing difficulty of relative particle displacement, as indicated by the rise in the friction coefficient $tg\varphi$.

As is evident from Fig. 4b, the maximum plasticity and optimal mutual sliding of microaggregates in clays of different mineral types occur within a very narrow range of contact water film thicknesses $h_0 = 9 - 12A^0$. This phenomenon can be explained by the specific structure of contact water, characterized by reduced viscosity, i.e., an anomaly in its rheological properties within the given range h_0.

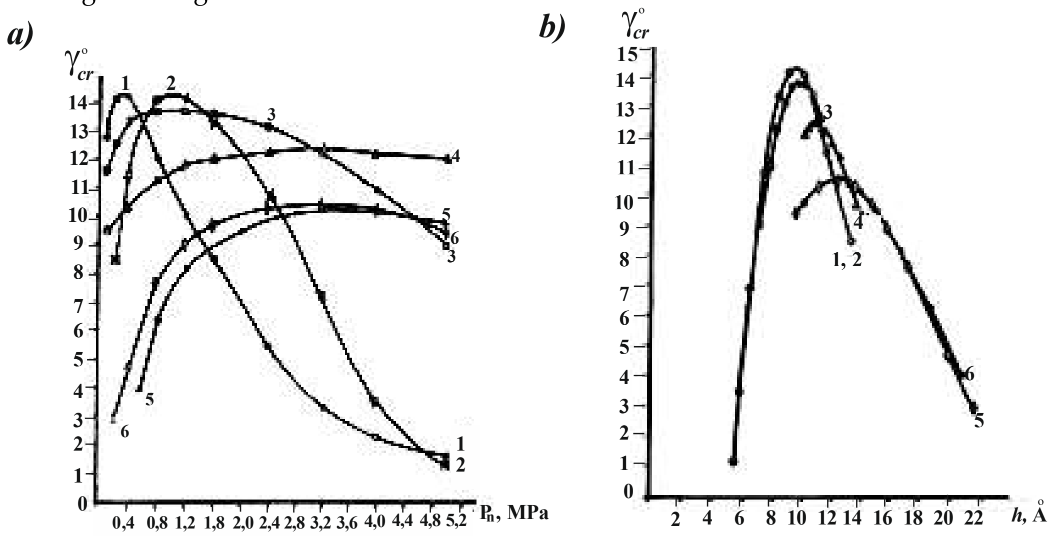

Figure 4: *Dependence of the critical shear angle of two-phase clays on preconsolidation pressure (a) and the thickness of water films at microaggregate contacts (b): 1 – Ca - kaolinite; 2 – Na- kaolinite; 3 – Ca-illite; 4 – Ca- montmorillonite; 5 – Na-illite; 6 – Na- montmorillonite.*

The authors have established that, under natural conditions, during landslide formation in isotropic clay slopes, the deformation zone develops as a deep-seated direct shear zone with a thickness not exceeding 1.0 m. Within this zone, clay microaggregates begin to orient themselves parallel to the forming slip surface manifesting in the simple shear zone.

This provides a time window for the planning and implementation of preventive engineering protection measures, which can significantly reduce the risks of hazardous and catastrophic landslide events in unstable clay slopes, particularly within urbanized areas.

IV. Conclusion

1. In simple shear, when only one pair of shear stresses is applied, the resulting moment—required to prevent rotation of the considered element—must be balanced by a moment generated from non-uniformly distributed normal stresses acting on the top and bottom of the soil specimen. Unlike direct shear tests, simple shear or "shearing" tests allow for the study of soil resistance to shape distortion.
2. For the purpose of determining the critical shear angle of clay soils under simple shear, the authors developed a special attachment for the standard shear apparatus VSV–25.
3. Taking into account data on the interaction of elementary microaggregates of clays with different mineral types and their mutual sliding during shear, the authors believe that the critical deformation of two-phase clays is governed by the adhesive strength of the contacts and the rheological properties of the fluid in the interparticle gaps and, consequently, by the coefficient of friction.
4. The authors have established that under natural conditions, during landslide formation in isotropic clay slopes, the deformation zone develops as a deep-seated direct shear zone with a thickness of no more than 1.0 m. Within this zone, clay microaggregates begin to align parallel to the developing slip surface, which is manifested in the simple shear zone.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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