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Confirmation and development of K. Terzaghi’s ideas in the mechanics of structurally unstable clay soils

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ABSTRACT: The scientific contributions of Professor K. Terzaghi continue to attract considerable attention from geotechnical researchers, who rigorously test the hypotheses he proposed and experimentally verify their relevance in contemporary studies. In this context, the authors have developed a novel method and apparatus for more efficient and accurate investigation of the "sensitivity" of swelling clays using a single soil sample. The concept of "sensitivity" for clay soils during swelling was initially introduced in Terzaghi’s seminal works. The findings also highlighted that, in various monomineralic clays, a stable equilibrium hysteresis loop is established by the 4th to 5th test cycles in the compression-swelling regime. Experimental and modeling studies on the shrinkage of clay soils during drying further substantiated the applicability of the capillary theory, originally applied by Terzaghi to clay soils. These studies confirmed that the compressive stresses in clays with different mineralogical compositions are in full agreement with the capillary theory. The temperature-moisture analogy, first proposed by Terzaghi for the analysis of the stressed-deformed state of clay soils, has proven to be highly relevant in contemporary geotechnical research. This analogy has been effectively employed by the authors in their investigations into the stressed-deformed state of swelling clay soils. In the developed method, instead of the traditional temperature potential, an energy source based on the increasing moisture content is used. This energy-active water physically and chemically manifests itself in the unit volume of swelling clay soil over time. Field studies, along with the construction of settlement curves for pit floors and the dependence of soil saturation depth on soaking time, enabled the authors to apply both the swelling prediction method proposed by Terzaghi and their own numerical integration method. The results obtained from both methods differed by only 9%, which underscores the practical effectiveness of Terzaghi’s approach in predicting the behavior of swelling clays.

KEYWORDS: swelling, shrinkage, clay soil, water, method, analogy, load, prediction, K.Terzaghi.

1 INTRODUCTION

The scientific legacy left by K. Terzaghi continues to attract the interest of geotechnical scientists due to the depth and precision of the hypotheses he proposed and the opportunity to experimentally verify their relevance.

Currently, many geotechnical researchers admire K. Terzaghi's comprehensive approach to the study of soil properties. The focus of his theoretical and practical interests encompassed issues in engineering geology, soil mechanics, and hydraulic engineering (Terzaghi K. 1933, 1935, 1958 & 1961).

Professor K. Terzaghi noted that the degree of discrepancy between the behavior of natural soil in field conditions and its theoretical behavior can only be determined through an understanding of nature. A deep knowledge of the physical properties of natural soils under laboratory and field conditions is required for the practical application of theory; otherwise, the engineer is unable to assess the order of magnitude of errors inherent in numerical results.

The methods proposed by K. Terzaghi involves the use of the principles of capillary theory, physico-chemical mechanics of surface phenomena, and soil thermodynamics and have found broad application and practical value in identifying and predicting the stress-strain state of soil masses under various external influences.

2 DEVELOPMENT OF A NEW METHOD AND STUDY OF THE “SENSITIVITY” OF SWELLING CLAY SOILS

The term reflecting the sensitivity of structural bonds ("sensitivity") was first proposed by K. Terzaghi. For differentiating concepts, the following are distinguished here: 1) sensitivity based on compression tests, characterized by the structural strength coefficient; 2) ensitivity based on shear tests.

The disruption of natural structural bonds in clay soils generally leads to an increase in swelling.

The term "sensitivity" of swelling clays was introduced earlier (Schmetmann, 1954) to describe the phenomenon of increased swelling in clays resulting from repeated significant shear deformations during the mechanical remolding of clay soils. The magnitude of this “sensitivity” is expresse as the ratio of the swelling parameters of clay with disturbed $\delta_{H_{\text{пер}}}$ and undisturbed $\delta_{\text{пер}}$ structure.

$$K_c = {\delta_{H_{\text{пер}}}}\Big/{\delta_{\text{H}}} \tag{1}$$

E.A. Snezhkin and R.S. Ziangirov (1987) noted that in certain clays with high internal bond strength, structural disturbance leads to an increase in swelling by 3 to 20 times. Unfortunately, none of the published studies on the “sensitivity” of swelling clays mentions how equality of initial densities between natural and disturbed samples was achieve.

F.G. Gabibov (2011) developed an improved method for studying the “sensitivity” of swelling clay soils using a specially designed apparatus (Figure 1). The device includes a composite ring 1 with a soil sample 2, a cup 3, into which a permeable tray 4 is placed at the bottom, a stamp-piston 5 with a collar 6 protruding above the upper edge of ring 1, and a dial-type indicator 7. During the swelling test, water 8 is poure into the cup 3.

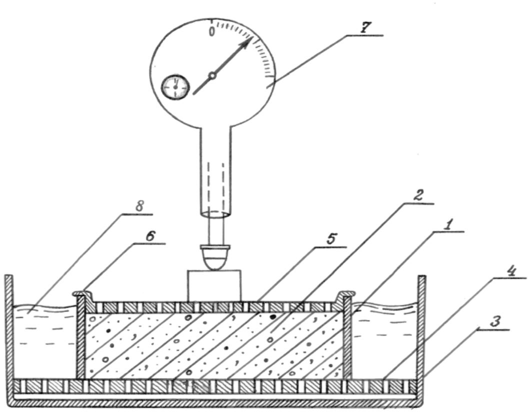

Figure 1. Device for studying the "sensitivity" of swelling clay soils: 1 – composite ring; 2 – soil sample; 3 – cup; 4 – tray; 5 – stamp-piston; 6 – collar; 7 – dial-type indicator; 8 – water.

When collecting a structurally undisturbed sample into the ring, the sample takes on a strictly defined cylindrical shape, determined by the sampling ring size. After testing the structurally undisturbed sample, water is drained from the cup 3, and the indicator 7 and piston 5 are removed from the device. Then, using a special needle, the sample inside ring 1 is loosened. Afterward, the stamp-piston 5 is placed onto the structurally disturbed sample under pressure and is pressed down until its collar 6 rests flush with the upper edge of the ring. In this position, the stamp-piston 5 is temporarily held down on the sample 2 until the dial indicator 7 is reinstalled. Then, water 8 is poured again into the cup 3, the forced holding of the stamp-piston 5 is released, and the swelling of the structurally disturbed clay sample begins.

As shown, this simple device and proposed methodology allow for an easy achievement of the desired initial density of the swelling clay soil. Moreover, the tests in both undisturbed and disturbed states are conducted on the same soil sample that increases the accuracy of the test results for evaluating the “sensitivity” of swelling clay soils.

Studies of the "sensitivity" of swelling soils showed that, in construction practice, it’s recommended to avoid disturbing the natural structural strength of swelling clay masses wherever possible, thereby utilizing the soil’s inherent engineering advantages.

3 USE OF THERMO-MOISTURE ANALOGY IN THE THEORETICAL DESCRIPTION OF DEFORMATION AND SWELLING ENERGY IN CLAY SOILS

The thermo-moisture analogy proposed by K. Terzaghi for studying the stress-strain state of clay soils has proven to be highly relevant.

Figure 2 shows all the compression-swelling cycles in sequence until the system reaches a stable hysteresis loop for hydromica Khvalynsk clay. The clay reached a permanent hysteresis loop in the 4th cycle.

The cycles shown in Figure 2 are describe as follows:

$$Cycle\ 1 - \int_0^A \frac{dW}{P_n} + \int_A^B \frac{dW}{P_{n_0}} \neq 0 \tag{2}$$

$$Cycle\ 2 - \int_B^C \frac{dW}{P_n} + \int_C^D \frac{dW}{P_{n_0}} \neq 0 \tag{3}$$

$$Cycle\ 3\ -\ Closed\ hysteresis\ loop\ - \tag{4}$$

$$\int_D^E \frac{dW}{P_n} + \int_E^K \frac{dW}{P_{n0}} = 0$$

$$Cycle\ 4\ -\ Closed\ stable\ hysteresis\ loop\ - \tag{5}$$

$$\int_K^L \frac{dW}{P_n} + \int_L^M \frac{dW}{P_{n0}} = 0$$

Reaching a closed hysteresis loop makes it possible to apply equilibrium thermodynamics methods to the studied object.

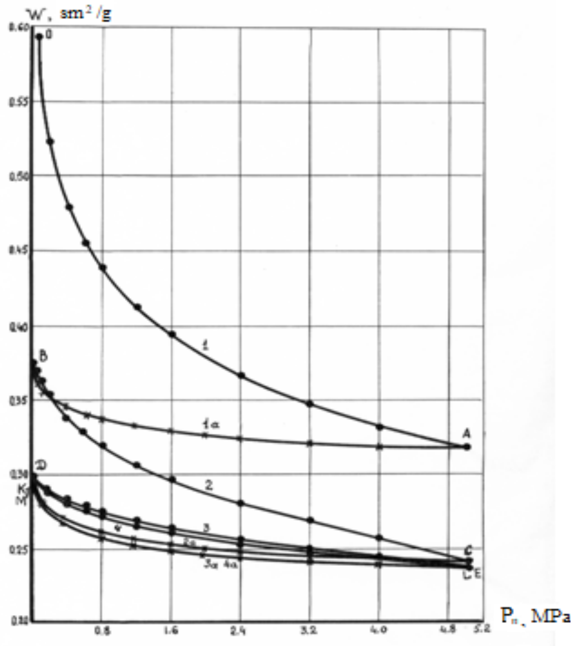

Figure 2. Multicycle compression of Khvalynsk Clay paste to the state of mechanical equilibrium (stable compression–swelling hysteresis loop): 1, 2, 3, 4 – successive compression branches; 1a, 2a, 3a, 4a – successive decompression branches.

Based on the graphs (fig. 2), it will be considered, that q is a state function of the clay soil. Its change depends on the initial and final points and doesn’t depend on the path taken. In that case, an infinitesimal change dq is a total differential with respect to infinitesimal changes in the following parameters: moisture content *(W)*, volume of the clay soil (*V*), density of the clay soil (Δ), mass of the clay soil (*m*), modulus of the difference between external pressure and the swelling pressure of the clay soil *(|P| = Pn – PH).*

$$dq = \frac{dq}{d|P|}d|P| + \frac{dq}{d\Delta}d\Delta + \frac{dq}{dW}dW + \frac{dq}{dV}dV + \frac{dq}{dm}dm \tag{6}$$

since the given diagrams represent closed processes, therefore:

$$\int dq = 0 \tag{7}$$

For the isothermal swelling process of clay soils, in equation (6), the parameters *W, Δ*, and *m* are replaced with the moisture potential, as proposed by [K.L. Bebok, 1966]. Analogous to the chemical potential, it represents the partial derivative of the internal energy of the soil system with respect to the mass of the liquid component.

When formulating the first and second laws of energy-entropy for isotropic moisture-elastic swelling clay soil, instead of the thermal potential, it is proposed to use the specific power -defined as the amount of energy-active water that physically and chemically manifests itself per unit volume of swelling clay soil per unit of time from moisture sources.

Let the swelling clay soil in its initial was undeforme state have a moisture content of W_o- const. It's assumed that the moisture increment W-W_o is such that the pure swelling $\int_{W_0}^{W} adW$ - where α is the true linear swelling coefficient of the clay soil - is of the same order of smallness as ε_{ij}. This assumption doesn't contradict the fundamental principles of linear elasticity theory regarding small deformations and allows to discard the restriction $(W\text{-}W_0)/W_0 << 1$.

4 FORECASTING THE SWELLING OF A CLAY FOUNDATION UNDER SURFACE MOISTENING

Among the known methods for predicting the swelling of clay layers, the most noteworthy is the method developed by [K. Terzaghi, 1961], which is based on the assumption that the filtering thickness of clay formations to a depth H is saturated with water under negative pressure P_1 generating excess pressure.

$$u = -P_1 \cdot \gamma_W, \tag{8}$$

and below, this layer is underlain by impermeable rocks.

Soaking of the surface causes occurrence of infiltration, and the pressure u (k, t) begins to decrease, following the law established by the differential equation.

$$\frac{du}{dt} = a^2 \frac{d^2u}{dx^2} \tag{9}$$

where

$$a^2 = \frac{K_\Phi(1-\beta_0)}{\gamma_W a_{VS}} \tag{10}$$

Kp– soil permeability coefficient; β_0 – initial porosity coefficient of the soil; a_{VS} – swelling coefficient of the clay soil; t – time; x – depth; $\gamma_W = 1 g/cm^3$.

After some mathematical operations, K. Terzaghi derives the swelling magnitude at the surface of a soil foundation with thickness H.

$$\Delta V = \int_0^H \Delta\beta dx = \frac{a_{VS}}{1+\beta_0}\left(P_1 H - \int_0^H u dx\right) \tag{11}$$

The authors conducted a prediction of the swelling behavior of a clay foundation studiedunder field conditions along the Samur-Absheron canal route using numerical integration of the consolidation equation (9). The results obtained from calculations using both K. Terzaghi's method and the method developed by the authors showed close agreement and correspond well with the data from field observations.

5 EXPERIMENTAL AND THEORETICAL JUSTIFICATION OF THE CAPILLARY NATURE OF SHRINKAGE STRESS DEVELOPMENT IN CLAY SOILS

The theory explaining the phenomenon of shrinkage in dispersed systems was first introduced by (R. Zsigmondy, 1911) in relation to gels. Later, the theory was applied to soils by [K.Terzaghi, 1933]. Zsigmondy's theory is based on the laws of capillarity and therefore it's referred to as the "capillary" theory.

K. Terzaghi (1933) equated the shrinkage process of clay soils with their compaction under external loading pressure. He believes that "no external force acts on clay drying and shrinking, except for the surface tension of water in the capillary pores - and this (capillary pressure) plays the same role as pressure during mechanical compaction. If there's any difference, it's only that during compression, the loading is applied as we intend, whereas in shrinkage caused by evaporation, a point is reached beyond which the clay volume remains constant."

Based on experimental studies of deformations in two-phase clays under various external influences, and using the model of clay developed by (L.I. Kulchitsky & O.G. Usyarov, 1981), reflecting the crystallochemical specificity of its coagulation structure at the micro-level, we will evaluate the stresses arising during clay shrinkage using the capillary theory.

In the general case, pressure caused by surface curvature of any shape is expressed by the Laplace equation.

$$P_k = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right), \tag{12}$$

where σ - is the surface tension of the liquid, r_1 and r_2 – are the principal radiuses of curvature for the given surface element.

Based on equation (12), the expression for capillary forces is typically derived by considering the compression of a spherical liquid droplet with a sphere radius r and surface tension σ.

$$P_k = \frac{2\sigma}{r} \tag{13}$$

If the liquid surface is cylindrical (which typically occurs when filling plane-parallel gaps), then, according to I.F. Efremov [11]:

$$P_k = \frac{\sigma}{r} \tag{14}$$

Where r – cylindrical radius.

The capillary pressure, arising in the macropores of coagulated clay structures at the limit of their normal shrinkage was estimate using a formula analogous to formula:

$$P_k = \frac{\sigma}{r_m} \tag{15}$$

where σ - is the surface tension of water; r_m – the radius of the macrospores according to the adopted two-phase clay model.

$$r_m = 0{,}5d \tag{16}$$

d – diameter of macropores (figure 3).

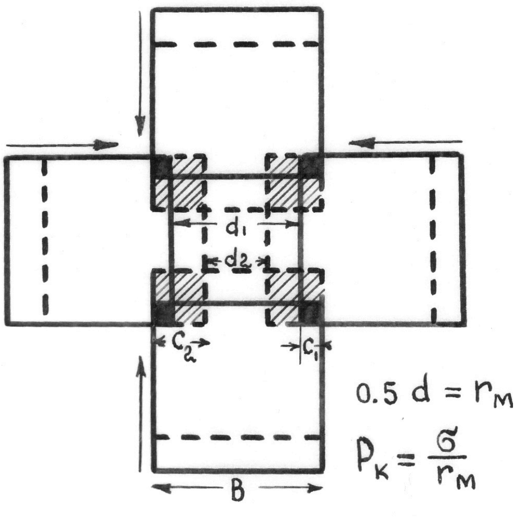

Figure 3. Diagram explaining the geometry of micro- and macropore changes in the XOY plane of the model during the compaction of two-phase clay

According to the diagram shown in Figure 3 explaining the geometry of changes in micro- and macropores in the model during the shrinkage of two-phase clay , the values c were determined from the relationship , where n0 is the total porosity of the clay, as shown in Figure 4 for the values of n0, corresponding to the limit of normal clay shrinkage.

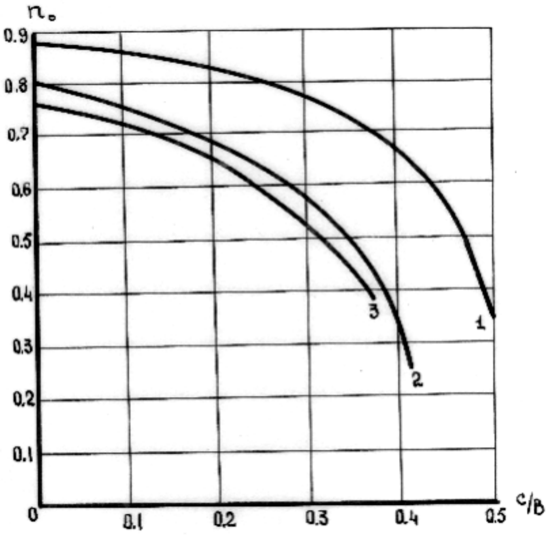

Figure 4. Dependence of the total porosity of monomineralic clay pastes on the overlap index of the outer basal surfaces of microaggregates:
1 – Ca-montmorillonite; 2 – Ca-hydromica;3 – Na-kaolinite

At the limit of normal shrinkage, the values of n_0 for Ca-montmorillonite, Ca-hydromica, and Na-kaolinite were, respectively: 0.45, 0.25, and 0.385. The calculations showed that, accordingly, for Ca-montmorillonite r_m= 15A and, respectively P_k=48.6 MPa, ; for Ca-hydromica r_m= 90A ; P_k= 8 MPa; for Na-kaolinite, r_m= 140A ; P_k= 5.2 Mpa.

The results of the shrinkage study of two-phase reference clays presented above obtained through calculations based on the clay model, practically coincide with the results obtained by (K. Terzaghi, 1933).

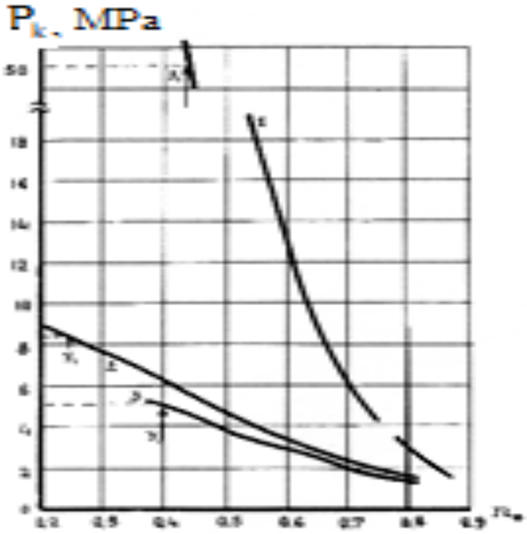

Figure 5. Dependence of shrinkage stress (capillary pressure) arising in the macropores of two-phase clay soils during drying-induced shrinkage on their total porosity:
1 – Ca-montmorillonite; 2 – Ca-hydromica; 3 – Na-kaolinite

6 CONCLUSIONS

1. A new method and device were develope for studying the “sensitivity” of swelling clay soils, allowing this characteristic to be determined through tests conducted on a single sample.
2. Based on the application of the thermo-moisture analogy, an effective method was develope for the description of the deformation and energy characteristics of swelling clay soils.
3. The results obtained by the authors' method for predicting the swelling of clay foundations through numerical integration of the consolidation equation is very close to those obtained using K. Terzaghi’s method and are consistent with field investigation data.
4. The authors’ experimental and theoretical research using the well-known clay model by L.I. Kulchitsky and O.G. Usyarov made it possible to justify the capillary nature of the development of shrinkage stresses in clay soils.

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