Softening and hardening clay soil under loading

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Abstract. The processes of hardening and softening occurring in clay soil under conditions of triaxial loading are described. The reasons causing the improvement or deterioration of the soil mechanical characteristics are given, their mechanism is revealed. The physical mechanism of the effects of hardening and softening of clay soil was explained at the micro level. The main factors affecting the hardening and softening processes are called water migration in the sample, the time and quantity of deviator loading. The results of a cubic-shaped sample in triaxial compression device experimental studies with different exposure times of the deviator loading stage are presented. The tests were carried out on artificially prepared clay soil samples. Data were obtained on changes in the humidity and strength characteristics of clay soil in the characteristic zones of the sample arising during triaxial loading. In this study, the previously made spatial model of clay soil under regime loads proposed by the authors was modified taking into account the influence of water migration in the soil structure during loading and the influence of this factor on the processes of soil softening and hardening.

Keywords: clay soil, shear strength, humidity, hardening, triaxial test.

1 Introduction
Buildings and structures have a developed underground part in the form of deep foundations and are built over several years, and then operated for decades under various loading conditions [1, 2, 3]. In order to increase the reliability of the calculation results, the settlement models of the soil base are being improved [4, 5, 6], including in software systems [7, 8, 9], experimental studies are being conducted [10, 11]. Many authors note the influence of the loading regime [12, 13, 14], including temperature [15], on the change in the characteristics of the base soil. However, when designing foundations and their bases, the influence of time, humidity and loading conditions on the change in the physical and mechanical characteristics of soils is practically not taken into account, which is confirmed by monitoring data [16, 17]. Clay soils acting as bases of foundation are very sensitive to these factors [18, 19, 20]. It does not take into account that the mechanical parameters of the soil obtained during engineering and geological surveys significantly depend on the soil composition [17, 21] and are not constant values and change under the load base. The authors partially covered this problem [22-25], however, the processes of hardening and softening clay soil, as well as their causes are not described in detail.

2 Methods and materials
For testing, triaxial compression devices of a cubic form were used. In order to exclude the foreign inclusions influence in the form of large aggregates and large pores, the samples were made of a clay soil paste. The loading was applied in stages-blocks. The first block is a comprehensive symmetrical compression for 30 minutes or 42 hours, the second block is the deviator loading \( \sigma_1 > \sigma_2 = \sigma_3 \) with different speeds: 10 minutes, 24 hours, 48 hours. To study the changes in soil characteristics in the
sample during the load application, some of the tests were stopped at the stage of deviator loading application, and the rest were brought to fracture according to the "crushing" scheme. After testing, soil was taken from characteristic zones 1 and 4 of the sample (figure 1a) and their density, humidity, specific adhesion $C$ and the angle of internal friction were determined $\varphi$.

![Figure 1](image)

**Figure 1.** a) Different density local zone layout under triaxial test (1 is vertical consolidated pyramids, 2 is fide sides consolidated pyramids, 3 is uniformed deflected state zone, 4 is dilatancy zone); b) The position of the sliding platform in the sample at the loading stages; c) Crack development pattern in the zone of limiting equilibrium.

It was found that after the sample destruction of the first series of tests in zone 1, soil compaction by 5 % relative to the value of the initial density occurred with a maximum possible increase in density in the specified zone by 12 % under prolonged loading, while at the stage of comprehensive compression in 30 minutes the soil in vertical pyramids replenished by 2.5 %, in 42 hours an additional sealing was recorded up to 8 % (figure 2). The obtained results show that at the first stages of loading, soil compaction occurs with the formation of different density zones, while the density growth significantly depends on the rate of the load application. This fact confirms the theory about the mechanism of the sample deformation and fracture [5, 9].

![Figure 2](image)

**Figure 2.** Density change data in characteristic zones of the sample.

Analysis of data on soil humidity in characteristic zones showed that at the comprehensive compression stage in 30 minutes, the humidity in compacted zone 1 decreased by 0.86 % from the
initial value, and in zone 4 it increased by 1.1 % (figure 3), after the sample was destroyed by a short-term static load, humidity in zone 1 was 96.2 %, and in zone 4 – 98 % of the initial value. An increase in the comprehensive compression time led to a humidity change in the vertical densified zone by 1.77 %, and in the decompression zone by 2.6 %. The results obtained show that soil humidity is also not a constant value, since water migrates from the densified zones to the decompression zone, and a decrease in the loading rate promotes the displacement of a larger volume of water into the decompression zone.

Figure 3. Humidity change data in characteristic zones of the sample.

Soil samples were taken from characteristic zones of samples destroyed by deviator loading, from characteristic zones 1 and 4 and strength characteristics were determined: angle of internal friction $\varphi$ and specific adhesion $C$. In the sealed zone 1, an increase in the mechanical characteristics was recorded compared with the initial values of the angle of internal friction $\varphi$ and specific adhesion $C$ by 88 % and 138 %, respectively, and in the local zone 4, a decrease in the angle $\varphi$ was recorded to 45 % and $C$ to 67 % (figure 4).

Figure 4. Strength characteristics change in characteristic zones of the soil sample.

An analysis of the obtained experimental data made it possible to establish that regardless of the sample loading regime (long-term or short-term), a complex stress state forms in the sample, which contributes to the formation of different density and humidity zones. The dimensions of these zones, the density and soil moisture within them are not constant and vary during loading.

2.1 Theoretical researches
Based on the results of theoretical and experimental studies [5, 9, 12], the following scheme of fracture resistance change during triaxial compression can be provided.
Depending on the magnitude, regime and duration of the load in multiphase clay soil, two mutually compensating phenomena occur: hardening due to defects healing and a denser rearrangement of particles, and softening caused by particles reorientation, as well as the formation and development of microcracks and macrocracks. In those cases when softening begins to prevail over hardening, a stage of destruction and progressive creep occurs, and these processes do not cover the entire soil volume, but only the zones of ultimate equilibrium.

Deviator loading and long exposure under load are accompanied by the appearance and development of many shear surfaces and discontinuities in the soil continuity of the sample, the position of which changes with increasing deviator and time, therefore, the negative dilatancy (loosening) of clay soil under regime of triaxial compression is localized within the potential areas of ultimate equilibrium (figure 1 b-c).

Consider the mechanism of hardening clay soil in the triaxial loading process.

Soil hardening depends on the entire loading history and is described by a function characterizing the increase in strength as a result of the restoration of water-colloidal and structural bonds.

The hardening of clay soil during its deformation in time is influenced by the following factors:

a) change in the density of the skeleton;

b) structural changes in the soil, including healing of microdefects, microcracks and wet cavities, changing the particles orientation in time and space.

It should be noted that these two factors are closely interrelated and it is difficult to separate them (to distinguish the share of each of them) and to take them into account separately in time.

Soil hardening begins only at stresses whose values are higher than the level of the lower boundary of microcrack formation. As you know, when loading an array of clay soil around structural defects (microcracks, micropores), a zone of plastically deformed soil is formed (pre-fracture zone). The plastic deformation zone is a damage zone with small microcracks – submicrocracks. Therefore, it is assumed that the hardening process occurs in this zone and it is manifested in an increase in the specific work of soil destruction. Submicrocracks in this plastic zone, formed during regime loading, remain open during the load cycle, facilitating the formation and growth of the fresh product of the restoration of water-colloidal and structural bonds. Therefore, the process of bonds restoration, and consequently, microstructural hardening, can continue without braking during the entire loading period.

In the process of loading, two interconnected processes simultaneously occur in the soil sample: the formation and development of different densities zones and the water migration between these zones. Consider each of the above processes individually.

The formation of compacted zones begins at the stage of comprehensive compression and their initial dimensions and density depend on the average normal stresses and the duration of the load application phase (figure 1b). The increase in the densified zones size depends on the inclination angle of the limit equilibrium area, in the plane of which the formation of microcracks begins, depending on the prevailing process: either combining microcracks into a macrocrack and forming a shear site and, as a result, destruction of the soil, or healing by restoring colloidal bonds and collapse microcracks and, as a result, soil hardening in the considered plane and rotation of the ultimate equilibrium area under further loading, the growth of compacted ones and its further movement as a rigid body inside the sample [5, 9].

Water migration from the compaction zone to the softening zone with a density decreasing due to the formation of microcracks (dilatancy zone) occurs during the entire loading process. At the same time, in the dilatancy zone (zone 4, figure 1), in which microcracks form and, accordingly, the soil density of the sample is minimal, moisture is squeezed out from the compaction zones, the soil density in the decompressed zone during long-term tests is 67.7 % of initial value, and humidity increases by 3 %. The specified free water in microcracks is included in the self-healing processes of the soil, that is, the formation of colloidal bonds between particles. Thus, the microcrack is filled with a colloidal solution, the stress concentration at the crack tip decreases and the fracture process damps until a new loading stage of the sample causes an increase in stress at this point. It should be noted that at the same time this water acts as a lubricant between the soil particles on the sliding surface, reduces the friction
force and specific adhesion between them, and contributes to the shift of one part of the soil in the sample relative to another.

3 Results
The conducted experimental studies have established that the duration of the loading stage significantly affects the transported water volume. During short-term tests, not all free water is displaced from the pores and the rate of water movement is less than during long-term tests, that is, moisture does not have time to fully move to zone 4, damaged by microcracks. In this case, the destruction processes prevail over the self-healing processes due to the lack of water to restore colloidal bonds, in addition, the water part that has moved to zone 4 acts as a sliding layer between the soil particles and accelerates shear processes. This fact is confirmed by a significant decrease in the specific adhesion and the internal friction angle in the dilatancy zone in the sample (figure 4).

The soil hardening and softening process is described by the equation of change in specific adhesion:

\[
C_0(t, \tau_1) = C_0(\tau_1) \cdot m(t, \tau_1) \cdot \lambda(t, \tau_1) \times \frac{K(\tau_1)}{K(t)} \times \frac{1}{\left( 1 + \frac{K(t)}{K(\tau_1)} \right) \cdot C(t, \tau_1)}, \tag{1}
\]

where \( C(t, \tau_1) \) is measure of soil volumetric creep; \( C_0(\tau_1) \) is initial value of specific soil adhesion during short-term loading; \( m(t, \tau_1) \) is soil hardening function due to restoration of water-colloidal bonds; \( \lambda(t, \tau_1) \) is hardening function due to restoration of soil structural bonds, taking into account the combination of various blocks in the loading process.

The delayed development effects of micro and macrocracks and the effects of self-hardening and self-healing of clay soil due to the restoration of structural and coagulation bonds take into account the functions \( m(t, \tau_1) \) and \( \lambda(t, \tau_1) \). These functions are determined indirectly on the basis of experimental data.

4 Discussions
The hardening of clay soil during its deformation in time is influenced by the following factors: changes in skeleton density and structural changes in the soil, including healing of microdefects, microcracks and microcavities, change in particle orientation both in time and in space. It should be noted that these two factors are closely interconnected and it is difficult to separate them (to distinguish the share of each of them) and to take them into account separately in time. The main reason for “healing” is the water migration from the compaction zone to the softening zone and its reaction with clay particles, resulting in new structural water-colloidal bonds.

These self-hardening processes are confirmed by an increase in the specific adhesion of the soil and the compacted zones growth. The presence of a dilatancy zone shows that softening processes are also present in the soil sample under triaxial loading both at the stage of comprehensive compression and at the stage of deviator loading.

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