The conditions of bulk clay soil compaction

P A Lyashenko*, V V Denisenko, V S Kovalenko, N S Kolomiets
Kuban state agrarian university, 13, Kalinina str., Krasnodar, 350004, Russia

E-mail: lyseich1@yandex.ru

Abstract. Testing of bulk clay soil with static cyclic loading was carried out in order to determine the required number of loading-unloading cycles to achieve a standard soil compaction at a given humidity, as well as to assess the content of bound water. Several samples of different moisture content of the dust loam in the compression device were tested by applying pressure in one stage and unloading with the measurement of deformation of the compaction and expansion of the soil sample. The number of cycles of the test soil samples was limited to the stabilization of the values of the coefficient of the elastic deformation work, the same for all samples of different moisture. Here proposed method of selection of the elastically deformable water and water involved in the inelastic deformation as a phase state of aggregation of the soil. Calculations of the volume content of mineral particles in the soil, elastically deformed water and water involved in inelastic deformation of the sample are made through the coefficient of elastic deformation. It is found that with increasing the density of the soil volume content of mineral particles and the elastically deformable water increases and correlates with the dry density of the soil and the volumetric water content involved in the inelastic deformation of the sample virtually unchanged.

Introduction
Soil compaction is widely used in construction practice. Soil is compacted to the maximum density by static cyclic impact on it by a rink [1]. "As the number of repetitions of the load increases, soil gradually strengthens, i.e. the value of deformation decreases each time" [4]. In laboratory modeling of the compaction process "with multiple compression-decompression, the compression curves approach, the reversible part of the deformation decreases from cycle to cycle, and the curves tend to some stable position" [5]. These regularities are used in laboratory determination of maximum density and optimal moisture by static cyclic loading. The values of these parameters are set for compaction of the soil in the mound, leaving the number of cycles the value derived from these values. Therefore, the test rules in compression devices do not contain reasonable recommendations for determining the number of cycles [5, 8, 11].

In fact, mechanical action during compaction, not only the physical properties of the soil, determines the properties of the embankment, and compaction conditions should include its parameters, such as the pressure on the soil, the mode of its application, the number of compaction cycles.

It is known that soil compaction under three-axial compression "occurs due to changes in the relative content of different phases in the soil" [1]. Usually distinguish a solid (mineral particles), liquid (pore water) and gaseous phase. In the skeleton of clay soil there is always bound water on the surface of mineral particles. Strongly bound water exhibits elasticity at the contacts of adjacent
particles, weakly bound water shows viscosity and plasticity [1−3, 6, 7, 9, 10, 12]. Separating them by physical and mechanical properties both from each other and from free water, they can be considered as separate phases of the aggregate state of matter [2]. They react differently to mechanical action.

The aim of this work is to estimate the ratio of different phases of soil and determine the criterion of compaction at different values of moisture

**Test the soil to cyclic loading**

In our experiments, the static application of cyclic loading on a sample of clay soil was made by applying to it in a compression device a load of 500 kPa in one stage and measuring the settlement $\Delta s_j$, then unloading up to 5 kPa, also in one stage, and measuring the expansion of the sample $\Delta u_{e,j}$, where $j = 1\ldots i$, and $i$ is the number of test cycles of the sample (figure 1). Between the loading and unloading stages, a pause of 5 minutes was maintained, after which the deformation of the sample was measured with the help of motion sensors IH-10 with a division value 0.01 mm.

The experiments were carried out with the same soil at different values of weight moisture and increasing it “until the extrusion of liquefied soil through the form compounds” [9], which is a sign of achieving the moisture condition value. Loading and unloading were carried out in one mode, to the conditional stabilization of the values of the relative increment of the deformation. Soil was crushed silty loam, with particle sizes up to 1.0 mm.

At the end of the test, each sample was weighed, measured its height, determined by the weight moisture drying method. According to these measurements, the density, soil moisture, as well as the density of the skeleton and porosity were calculated.

![Figure 1](image_url)  
**Figure 1.** Scheme of the loading-unloading soil probe to stabilize the deformation work

**Determination of the number of test cycles**

According to the data of load and strain measurements, the mechanical work of the volumetric deformation of the sample $\Delta A_j$, including the elastic $\Delta A_{e,j}$ and inelastic $\Delta A_{pl,j}$ parts, was calculated per unit volume of the soil in the $j$-th cycle:

$$\Delta A_j = \Delta A_{e,j} + \Delta A_{pl,j},$$  

(1)
\[ \Delta A_j = \left( \frac{\Delta s_j}{h_{e,j-1}} + \frac{\Delta u_{e,j}}{h_j} \right) \Delta p . \]  

(2)

The work of elastic deformation was calculated by elastic expansion according to the formula (3):

\[ \Delta A_{e,j} = \frac{\Delta u_{e,j}}{h_j} \Delta p , \]  

(3)

where \( \Delta s_j \) and \( \Delta u_{e,j} \) are settlement and elastic expansion of the sample, \( h_j \) and \( h_{e,j-1} \) are the heights of the soil sample after compaction and elastic expansion in the \( j \)-th loading-unloading cycle, mm (Fig. 1); \( \Delta p \) is the difference between the initial and final pressure values in the loading-unloading cycle, adopted constant for all cycles of all samples of the same soil with different soil moisture.

Then we introduce the coefficient of elastic deformation of the soil:

\[ k_{e,j} = \frac{\Delta A_{e,j}}{\Delta A_j} , \]  

(4)

Experiments have shown that the coefficient of elastic deformation increases with the number of loading-unloading cycles, striving for a limit value \( k_{e,i} \) (Figure 2), where \( i \) is the total number of cycles for certain soil moisture.

Stabilization \( k_{e,j} \) indicates that the maximum density of the soil at a given soil moisture after several cycles of loading and unloading. The total number of cycles \( i \) may vary with different soil moisture values, but it must meet their common compaction criterion. The sample compaction was evaluated by the coefficient of variation of the values \( k_{e,j} \) in the last 6 cycles: from \( k_{e,i-5} \) to \( k_{e,i} \).

The condition for sufficient soil compaction may be a limitation of the coefficient of variation in the last six cycles, for example, a value of 15%:

\[ \text{var} \left\{ k_{e,i-5}...k_{e,i} \right\} = 0,15 . \]  

(5)

![Figure 2](image-url)  

Figure 2. Change in the coefficient of elastic deformation work with an increase in the number of loading-unloading cycles of sample 1.

Calculations of the volume content of soil phases

Imagine the volume of the mineral part of the soil sample as the sum of the volumes:

\[ V(1-n) = V_{ss} + V_{e} + V_{pl} , \]  

(6)
where $V$, $V_{ss}$, $V_e$, and $V_{pl}$ are the volume of the sample, the volumes of mineral particles without water shells, shells of elastically deformed water, water involved in inelastic deformation, respectively. $n$ is the porosity of the soil calculated after drying the sample.

Suppose that the volume of elastically deformed water is proportional to the volume of mineral particles (7), and the volume of water involved in inelastic deformation is proportional to the sum of the volumes of mineral particles and elastically deformed water (8):

$$V_e = k_e V_{ss}, \quad (7)$$
$$V_{pl} = (1 - k_e)(V_{ss} + V_e). \quad (8)$$

From equations (6)–(8) it is possible to calculate the volume content of mineral particles in the soil without water shells $q_{ss}$, elastically deformed water $q_e$ and water involved in inelastic deformation $q_{pl}$:

$$q_{ss} = \frac{1 - n}{2 + k_e - k_e^2}, \quad (9)$$
$$q_e = \frac{k_e (1 - n)}{2 + k_e - k_e^2}, \quad (10)$$
$$q_{pl} = \frac{(1 - k_e^2)(1 - n)}{2 + k_e - k_e^2}, \quad (11)$$

also the volumetric content of free water $q_g$:

$$q_g = \frac{W \cdot \rho_s (1 - n)}{\rho_w}, \quad (12)$$

where $W$ is the moisture content of the soil samples after the $i$-th cycle of loading-unloading; $\rho_w$ is the density of water; $\rho_s$ is the density of mineral particles coated with a shells of bound water.

With standard compaction, the density of the skeleton of the soil increases with increasing soil moisture, the volume content of mineral particles without water shells and free water increase respectively (Figure 3). The volume content of elastically deformed water also increases (Figure 4), according to the assumption (7). The volume content of water involved in inelastic deformation remains unchanged, as it reflects the phenomenon of mutually counteracting trends: reducing the width of micropores and increasing their total area [7, 10].
Summary

If soil compaction static cyclic loading, the relative increment of the work of elastic deformation increases with increasing number of cycles, and asymptotically tends to the limiting value. The condition of approximation to the asymptote is an objective indicator that can serve as a criterion for sufficient compaction of the soil and the required number of cycles of standard exposure to the sample.

The limit value of the relative increment of the elastic deformation is used to calculate the phases of the aggregate state of the soil. The phases of mineral particles, elastically deformed water, water participating in inelastic deformation, and free water are distinguished. By the example of compaction of crushed silty loam, it is obtained that the volume content of mineral particles, elastic deforming
water and free water increases with increasing values of soil moisture, and the volume content of water participating in inelastic deformation does not change. Thus, the relationship of the deformation of the soil sample with the deformation of elastic deforming water and water involved in inelastic deformation is determined, and a method for assessing their volume content is proposed.

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