Investigation of the aggregate state changes of clay soils

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Abstract

For the variety of clay soils there exists a linear functional relation between the moisture, at which the soil state converts from liquid to plastic, and the moisture, at which it converts from plastic to solid (pseudo elastic). In this work the origin of this functional relation is investigated.

It is hypothesized, that the aggregate state of soil changes, if the thickness of water film of soil particles reaches the limit value. Thus, the linear relation between two limit moistures is caused by the fact, that each of them is a linear function of the soil particles surface area per unit volume.

At the result of experiments the information on granulometric composition and physical and mechanical properties of 180 clay soil specimens originating from St. Petersburg is obtained. The calculation method to estimate the soil particles surface area per unit volume is proposed. This method considers irregular forms of soil particles and limited capacities of experimental research. For each clay soil specimen the area of soil particles surface per unit volume is calculated with the accuracy up to a constant multiplier.

By means of averaging the tolerable precision of experimental data is achieved. Using these data, the relationship between the moisture, at which the soil state converts from liquid to plastic, and the area of soil particles surface per unit volume is obtained. The form of obtained dependence is close to linear. The results of this research confirm the validity of the hypothesis.

The water content W_P, at which the clay soil state converts from solid (pseudo elastic) to plastic, and the water content W_L, at which it converts from plastic to liquid, are the important physical and mechanical characteristics of clay soils. Here water content is defined as the ratio of water mass, contained within the soil, to soil solid particles mass.

The numerous experimental research show, that for a wide range of clay soils there is a stable functional relation between the values of W_L and W_P. This kind of the relation is close to linear.

The aim of this paper was to investigate the nature of such correlation. As a working hypothesis it was supposed, that the values of W_L and W_P are proportional to S - the soil particles surface area per unit volume. The aggregate state of soil changes, if the thickness of water film of soil particles reaches the limit value. Thus, the linear relation between W_L and W_P is caused by the fact, that each of them is a linear function of S.

To estimate the correctness of the hypothesis, it was required to discover experimentally the kind of the relation $W_L(S)$ or the relation $W_P(S)$. By means of laboratory research of 180 soil specimens the data on granulometric composition and physical and mechanical properties of Saint Petersburg clay soils were obtained. Geologically these clay specimens belong to Wend (Ediacaran) and Quaternary periods.

The values of W_L and W_P were determined experimentally by standard methods.

The value of S for each soil specimen is calculated according to its granulometric composition. In determining the granulometric composition by areometric method the

Stokes formula [1], connecting the rate of spherical particle sedimentation in a viscous fluid with its radius, is used:

$$U = \frac{2}{9} g R^2 \frac{(\rho_s - \rho_w)}{\eta} \tag{1}$$

where

U - steady sedimentation rate,

g - gravitational acceleration,

R - the radius of spherical particle,

ρ_s - the density of particle,

ρ_w -the density of water,

η - dynamic viscosity of water.

Actually the clay particles have various, often irregular form. So in fact, as a result of the experiment the particles are separated into fractions according to the value of “equivalent” radius. Equivalence implies here as the equal values of sedimentation rate of particles in water. This fact complicates the calculation of S.

For kaolin and illite particles the typical form is hexagonal plate. Acceptable approximation of this form can be considered as a disc. Let us consider the sedimentation of a thin disk of radius R_d and thickness $h = \alpha R_d$ in the water. The plane of the disk is perpendicular to the direction of motion. In the stationary state the disc is affected by a force of resistance F [2]:

$$F = 16 \eta R_d U \tag{2}$$

The motion is stationary, if the resistance force F is equal to the algebraic sum of the gravitational and the Archimedes forces:

$$F = mg - F_A \tag{3}$$

Using (3) sedimentation rate of disc-shaped particles is obtained

$$U = \frac{\pi \alpha}{16} g {R_d}^2 \frac{(\rho_s - \rho_w)}{\eta} \tag{4}$$

From equality of the sedimentation rates of “equivalent” radius spherical particle and disc-shaped particle we obtain the size of disc-shaped particle, expressed in terms of experimentally determined value R:

$$R_d = \frac{4}{3} \sqrt{\frac{2}{\pi \alpha}} R \tag{5}$$

It is supposed, that $\alpha = const$ for all fractions, important for the calculation of S. Weaker condition, when the shape of particles of all fractions retains similarity in the mean, is permissible too.

Let a soil particle have a surface area s'_i and a volume v'_i. The surface area of all such particles, contained in a single soil volume, is equal to

$$S_i = \frac{s'_i k_i \rho_d}{v'_i \rho_s} \times V^{(1)} \tag{6}$$

where

k_i - weight share of such particles in the dry soil,

ρ_d - the density of dry soil,

ρ_s - the density of soil particle,

$V^{(1)}$ - a single soil volume.

For disc-shaped particles from (6), taking into account (5), we obtain

$$S_i = \beta \frac{k_i \rho_d}{\rho_s} \times \frac{1}{2R_i} \times V^{(1)} \tag{7}$$

where $\beta = 3\,(1+\alpha)\sqrt{\frac{\pi}{2\alpha}}$, R_i is the “equivalent” radius of particle of the considered i-fraction.

The value of $D = 2R$ is defined as the “equivalent” diameter of the particle. The distribution function of granulometric composition traditionally has a form $K = K(D)$. Consider the set of particles, which has $D \in [D_1, D_2]$. The surface area of these particles, contained in a single soil volume, is equal to

$$S_{[D_1,D_2]} = \beta \frac{\rho_d}{\rho_s} V^{(1)} \int\limits_{D_1}^{D_2} \frac{K'(D)}{D} dD \tag{8}$$

In particular, for piecewise linear function $K(D)$ on any interval $[D_1, D_2]$, where $K'(D) = const$, formula (8) becomes

$$S_{[D_1,D_2]} = \beta \frac{\rho_d}{\rho_s} V^{(1)} K'(D) \ln \frac{D_2}{D_1} \tag{9}$$

Larger particles of silt and sand fractions of soil ($D > 0.005mm$) have a shape close to a sphere or a cube. In this case, the formulae (8)-(9) are valid for $\beta = 6$.

In principle, the formulae (8)-(9) allow, according to the particle size distribution, to determine soil particles surface area per unit volume with an accuracy up to a linear transformation. This is sufficient for verification of the offered hypothesis. However, in the practical application of the formulae (8)-(9) the problem arises. Standard methods of experimental research of soil granulometric composition do not allow to determine $\min(D)$ - the significant for the calculation of S soil factions are taken into account.

Directly as a result of the experiment only several “reference” points of distribution function $K = K(D)$ are determined. For the calculation of S piecewise linear approximation of $K(D)$, tied to these points, was used, as the most simple and at the same time stable. As it follows from (9), in this case the condition $\min(D) > 0$ should be fulfilled.

The value of $\min(D)$ was calculated using linear extrapolation of the piecewise linear graph of distribution functions in semilogarithmic coordinate system. Such a representation of particle size distribution data is more visually, that allows to disclose some of their inherent physical regularities (Fig. 1). In particular, the form of group-averaged graph (180 specimen) of distribution function explains the use of linear extrapolation for the approximate calculation of $\min(D)$. In addition, the chosen coordinate system provides non-negativity of sought value $\min(D)$.

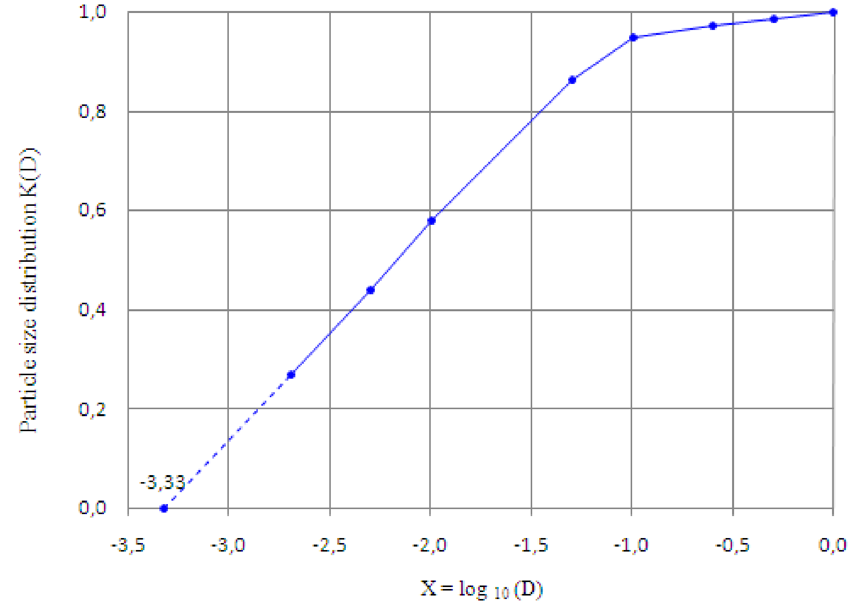

Figure 1. The particle size distribution, averaged for 180 specimens

The character of the dependence $W_L(S)$ was supposed to be determined by the type of graphics. First the graph was formed, every point of which was corresponded to the characteristics of the separate specimen of the soil (Fig. 2). However, such presentation of the results of calculations was non-informative. The reason is that for values of D, close to zero, a small error of $D_1 = \min(D)$ entails significant error of S. The fact that the presence of so significant errors due to the proximity of the singular point, is confirmed by the asymmetric dispersion of data.

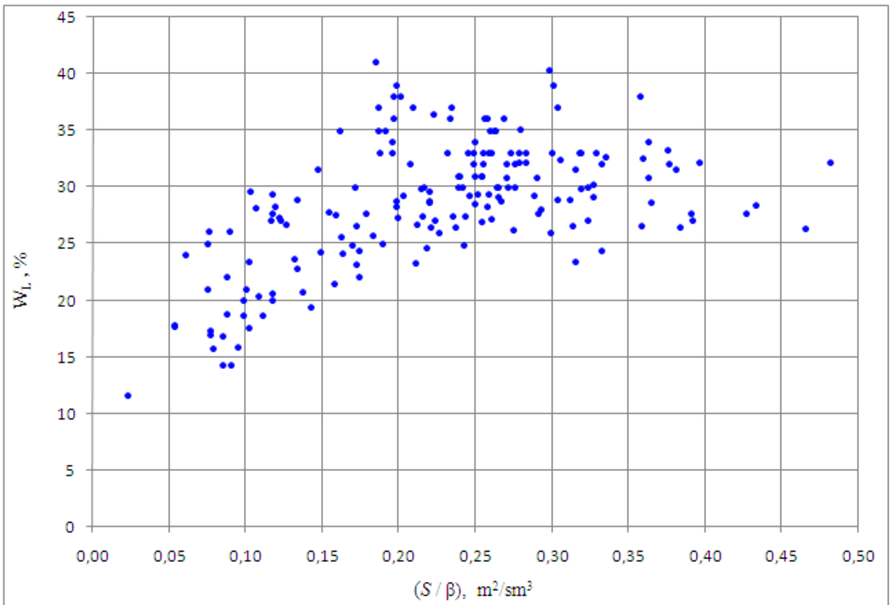

Figure 2. The dependence of W_L on (S/β); mechanical characteristics correspond to separate specimen of the soil

To minimize the error of determination of D, the distribution functions of the soil granulometric composition were averaged. The researched 180 soil specimens were ranked by the values of W_L and grouped into 10 specimens. For each group the averaged distribution function of granulometric composition was calculated as the arithmetic mean of the distribution functions of the single specimens. Similarly other experimental data were averaged, necessary to calculate the S, and the values of W_L.

In consequence of these transformations the error of baseline data, used in the calculation, has decreased about 3 times. As a result, the error of S significantly reduced. For the averaged values (with an accuracy up to a constant multiplier) the graph of $W_L(S)$ was formed. The character of this graph is close to the linear (Fig. 3). Thus, the results of research confirm the validity of the proposed hypothesis.

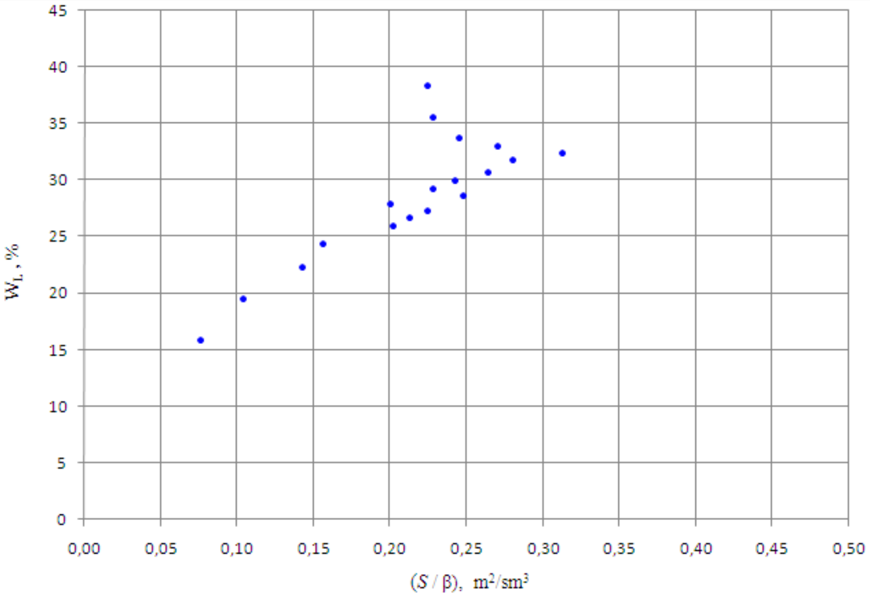

Figure 3. The dependence of W_L on (S/β); averaged mechanical characteristics

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