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# Structural Characteristics of Loess Soils for Evaluating Their Constructional Properties

Caractéristiques structurales des loess pour évaluer leurs propriétés physiques

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## SUMMARY

The constructional properties of loess soils are determined to a great extent by their structure, a concept which includes the interrelation of the solid, liquid, and gaseous parts.

The appearance of subsidence deformations is determined by the action of internal and external factors. Among the latter, the following structural characteristics are the most important: (1) Sand-dust grains are found "floating" in a mass of fine dispersed particles without any contact. (2) The fine dispersed mass is comprised of six types of micro-aggregates having different water resistances. (3) Loess soils are divided into three types according to their structural systems: granular, aggregate, and granular-aggregate. (4) The action of water induces the destruction of the non-water-resistant aggregates. This action is expressed through the water-resistance coefficient  $K_{wat} = W_{un}/(W_{II} - W_{un})$ . (5) The ratio of the volumes of the liquid and gaseous parts of the soil, as expressed by the humidity factor, plays an important part. When its value exceeds 1.1 to 2.2 the soil is not susceptible to subsidence. (6) Interparticle porosity plays the main part in subsidence deformations of loess soils. When the porosity is less than 21 per cent the soil is not susceptible to subsidence.

Thus, the structure of loess soils is determined by the type of its system, by the coefficient of its water resistance, by interparticle porosity, and by the humidity factor.

## SOMMAIRE

Les propriétés physiques des loess sont déterminées principalement par la structure du sol, dont la conception nécessite une idée sur les relations entre les parties solide, liquide et gazeuse.

La naissance des déformations est déterminée par l'influence de phénomènes internes et externes. Parmi ces derniers, les caractéristiques structurales suivantes jouent un rôle de prime importance: (1) Les grains de poussière de sable "flottent" dans une masse de particules à grains fins, sans aucun contact avec ces dernières. (2) La masse de particules à grains fins contient six microagrégats ayant une résistance à l'eau différente. (3) Les loess d'après les systèmes de structure se divisent en trois types: grains, agrégats, grains-agrégats. (4) L'influence de l'eau amène la destruction des agrégats n'ayant pas de résistance à l'eau. La résistance à l'eau est donnée par le coefficient  $K_{wat} = W_{un}/(W_{II} - W_{un})$ . (5) La proportion entre les volumes de liquide et de gaz caractérisée par le facteur d'humidité joue un grand rôle. Si les valeurs trouvées sont supérieures à 1.1 à 2.2, le sol n'est pas sujet à l'effondrement. (6) Le rôle principal dans l'effondrement des loess est tenu par la porosité entre les particules. Quand elle est moins de 21 pour cent, le sol n'est pas sujet à l'effondrement.

Donc, la structure des loess est déterminée par le type de structure, le coefficient de résistance à l'eau, la valeur de la porosité interparticulaire et le facteur d'humidité.

THE SPECIFIC CONSTRUCTIONAL PROPERTIES OF LOESS SOILS, especially their susceptibility to subsidence deformations, are due to some extent to their peculiar structure. In the works of Abelev (1948), Denisov (1946, 1953), Goldshtein and Shugaev (1961), Andrei, *et al.* (1963), Stefanov and Kremakova (1960), and a number of other investigators, some of the structural peculiarities of this type of soil are used to explain their susceptibility to subsidence.

The author's research over many years leads to the conclusion that structure and texture are of paramount importance in the determination of the properties of loess soils. To determine the relation between the physicomaterial properties and the composition of the soil, it is necessary first to define the terms "structure" and "texture." There are no generally accepted definitions of these terms. However, for the solution of problems related to the study of constructional properties, all features of soil composition within the smallest portions should be implied in the term "structure." To give an all-round definition for the structure of loess soils, the following factors must be included in the term "structure": (1) a morphological and quantitative evaluation of the interrelation of the main components: solid, liquid, and gaseous; (2) morphological and quantitative characteristics of each of the components mentioned; (3) characteristics of the bonds between the solid particles, taking into account the

influence of the liquid and solid components. All these features of soil composition are studied within what we call a "structural unit," such a unit varying in size between 10 and 15 mm. A general idea of the structure of a monolith or a given layer may be gained from the investigation of several structural units.

The existing geological notion of "texture" should be preserved, meaning the features of the composition of the soil mass: layering, variation of the structure along vertical planes, distribution of large jointings, inclusions, etc.

We studied the peculiarities of the loess soils both by direct investigation of the "structural units" and by an indirect method based on statistical data. From the latter, one obtains such characteristics as granulometric composition and porosity. We managed to establish by experiment the existence of various structural forms of loess soils. The reasons for these various forms can be found for the most part in the geological history of the soil (its origin and subsequent changes). A close connection was found to exist between the chemico-mineralogical composition and the structure of loess soils.

The available data indicate that all the physicomaterial properties are fully determined not by two, but by three factors: (1) chemico-mineralogical composition, (2) structural and textural peculiarities, and (3) the character and

magnitude of the force fields acting on the mass (gravitational field, resulting from the gravitational forces imposed in construction, vibrations, etc.). The result of the combined action of these three factors on the soil is a very complicated problem, but much has already been done to solve it.

#### DEFORMATION PECULIARITIES OF SOILS AND THEIR STRUCTURE

The compressibility of loess soils under a given pressure is a function of their structural peculiarities and moisture content. If a relatively dry loess foundation under a structure is subjected to the action of water, additional settlement is induced. Consolidation of loess also takes place under the action of its own weight (causing subsidence). According to Denisov (1946, 1953) subsidence and additional settlement are the result of underconsolidation of the soil and of the process of peptization of aggregates.

Analyses of the conditions of the final consolidation of loess soils, under the action of humidity, show that its magnitude depends upon both external and inner factors. The external factors are the magnitude of the stresses acting on the mass caused by the weight of overlying structures and its own weight, and the character of wetting (duration, quantity, pressure, and chemical content of the water). The inner factors include the structural and chemicommineralogical peculiarities of the loess soil itself. As soil structure, to some extent, depends upon the mineralogical composition, it becomes the main inner factor determining the tendency of the soil to subside.

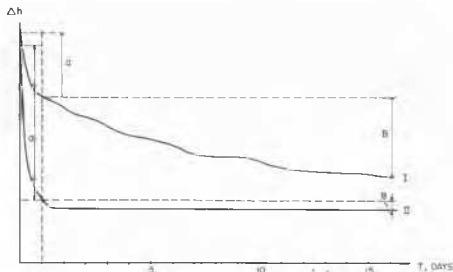


FIG. 1. Typical relationship between the subsidence deformations of a sample of loess soil ( $\Delta h$ ), after wetting under pressure  $P$ , and time ( $T$ ), where: A denotes the collapse part of the subsidence deformation, and B the slow part of the process. Curve I, soil showing the slow type of subsidence development. Curve II, soil showing the collapse type of subsidence development.

A statistical interpretation of over 1,000 laboratory analyses of the character of subsidence was made. In addition, several dozen field observations of additional settlement of structures were done. From this study of subsidence, two time-dependent types of deformation were found: collapse deformations, occurring at the time of soil wetting, and slow deformations which develop over prolonged periods of time. It appears that some types of loess soil structures have a tendency toward collapse deformations, while others lean to slow deformations. Fig. 1 shows the relationship of subsidence deformations and time, as found in the laboratory investigations.

Fig. 2 shows the result of field observations of different structures. The determination of a soil's type may be derived from an analysis of consolidation curves obtained from tests

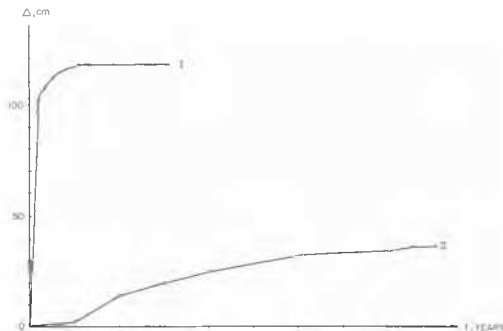


FIG. 2. The results of observations of additional settlement  $\Delta$  of structures, after wetting, from data taken over many years. Curve I, the settlement of an elevator (collapse deformation). Curve II, the settlement of the columns of an industrial building (slow deformation).

in consolidation apparatus. The curves are drawn using rectangular co-ordinates, where the decrease in the height of the sample, during the process of additional settlement, is plotted along the ordinate, and the testing time along the abscissa. The character of the change of settlement with time is established from the magnitude of the consolidation index:  $U_c = \Delta h_1 / (\Delta h_2 K_R)$  where  $\Delta h_1$  is the decrease in the height of the sample in the consolidation apparatus within 24 hours after wetting under pressure,  $\Delta h_2$  is the subsequent decrease in height of the sample during 29 days under the same conditions, and  $K_R$  is a correction factor dependent upon the type of soil and the duration of the test. The value of  $U_c$  varies from 0.1 to 16.0. When  $U_c > 1.0$  the loess soil is one of those liable to collapse deformation; when  $U_c < 1.0$ , it belongs to the group of soils where slow deformation is of considerable importance.

The study of loess soil structure, in connection with the determination of the conditions of the formation of physico-mechanical properties, revealed the following peculiarities.

1. The coarser sand-dust grains never contact each other, as if floating in a fine granular dispersed mass. Because of this state, loess soil strength is determined primarily by the composition and microstructure of the surrounding fine dispersed fraction.

2. Electron microscope studies of the microstructure of the fine dispersed fraction were conducted by the author and S. M. Maslov. These showed that the microstructure is made up of six types of micro-aggregates: tabular-even, tabular-uneven, step-like, egg-shaped, fine-foliated, and irregular (Fig. 3). In respect to composition, they may be divided into monomineral and polymineral. The colloidal particles of the aggregates are distributed either parallel-stratified (tabular-even aggregates) or at different angles to each other (irregular aggregates). The decrease of stability of the fine dispersed fraction is greatly influenced by the accumulation of fine quartz and carbonate grains on the planes of the tabular aggregates. Their amount varies from a few to several dozen particles. These sections should be considered the zones of weakness. It is here that the primary water penetration and consequent cleavage and destruction of the micro-aggregates takes place.

3. The ratio of the coarser sand-dust grains to the fine dispersed fraction changes not only quantitatively, but also

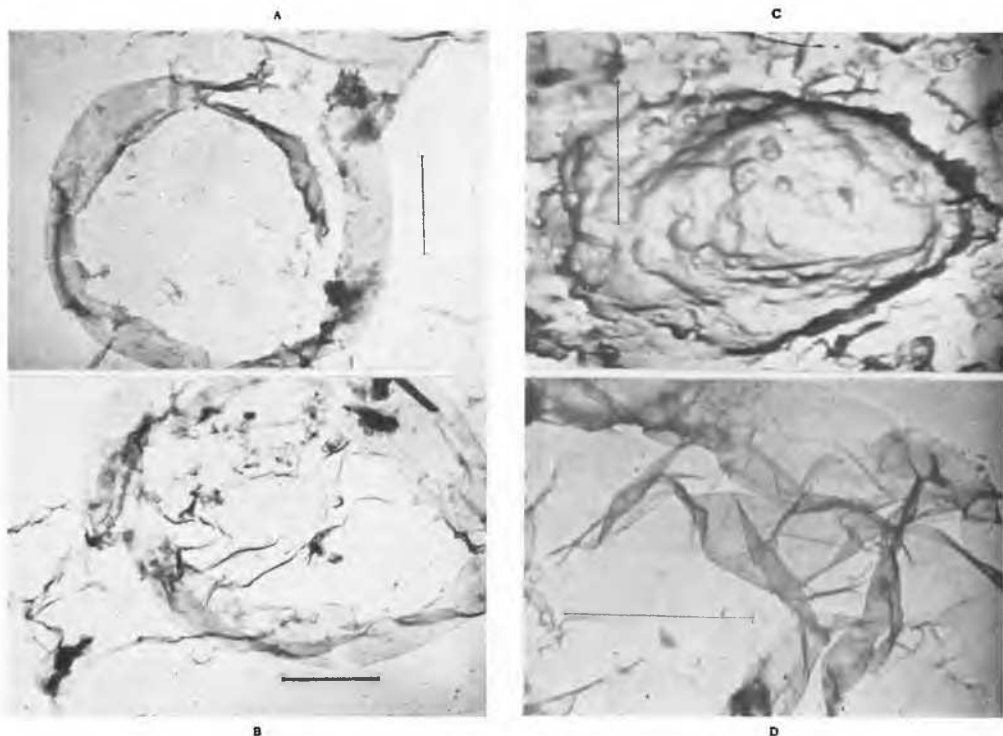


FIG. 3. Copies of photographs micro-aggregates made by the electron microscope: A, tabular-even micro-aggregates. B, step-like micro-aggregates; C, egg-shaped micro-aggregates; D, irregular micro-aggregates.

morphologically. Accordingly, three structural systems can be distinguished in the solid fraction of loess soils (the grain-aggregate ratio in soils): (a) granular, where a filmy distribution of the fine dispersed fraction predominates; (b) aggregate, consisting mainly of aggregates; (c) granular-aggregate, having an intermediate character. Investigations have shown that the changes in the soil properties, when the soil is wetted, depend upon the type of the structural system of the solid part. If all other conditions are equal, granular soils are found to differ from the aggregate ones in that they have less water resistance, lower cohesion, higher permeability, etc. The type of structural system is determined, firstly by visual observation (Larionov, *et al.*, 1959), and then

parts: grains, aggregates, colloidal particles, and soluble salts. The salts and colloidal particles travel freely through the pores and are able to leave the soil, together with the filtering current. Under sufficient external pressure, the grains and aggregates are able to move, redistributing themselves within the nearest pores. The grains, colloidal particles, and the salts are the result of the disintegration of the non-water-resistant parts of the aggregates. Their disintegration is caused both by the peptization of the colloids and the solution of certain salts (Denisov, 1946, 1953). The water-resistant parts of the aggregates remaining after subsection to water action are different in their nature. These are composed of water-resistant aggregates which may be destroyed by the continuous action of water (aggregates having colloidal or condensation type bonds), and those which are fully water resistant. The latter are composed of particles which are either cemented with insoluble compounds, or bound by a complex exchange process.

It has been found that the water resistance of the structure of loess soils and its predisposition to subsidence are determined by the ratio  $K_{\text{wat}} = W_{\text{ln}} / (W_{\text{II}} - W_{\text{ln}})$  where  $K_{\text{wat}}$  = water-resistance coefficient of the soil structure;  $W_{\text{II}}$  = the weight of the monolithic soil sample; and  $W_{\text{ln}}$  = the weight of the same sample after the action of water (the remaining water-resistant aggregates).  $K_{\text{wat}}$  values can range from 0.001 to 50 and more ("rock loess") for different loess

TABLE I. COEFFICIENTS OF WATER RESISTANCE,  $K_{\text{wat}}$

Structural system type	Reaction to drop analysis	Water-resistance coefficient $K_{\text{wat}}$
Granular	T-0, T-1	< 0.1
Granular-aggregate	T-1, T-2	0.1 to 0.4
Aggregate	T-2, T-3	> 0.4

more accurately from the results of "drop analyses" (see Table II) and the magnitude of the water-resistance coefficient of the soil  $K_{\text{wat}}$  (Table I).

4. Under the action of water loess soil disintegrates into

soil types. In most cases, the  $K_{wat}$  value for typical loess soils does not exceed 0.1 to 0.2 and for loess-like deposits it is 0.2 to 2.0 and more. The greater the value of  $K_{wat}$ , the less the loess soil is predisposed to subsidence. With increasing values of this factor the duration of subsidence deformation increases. The water-resistance coefficient of the soil structure should be considered one of the most important characteristics of loess soils.

5. Volumetric proportions of the dominating soil fractions play a considerable part in the establishment of the physico-mechanical properties of loess soils. The ratio of the water to solid components of the soil may be expressed by the degree of humidity,  $K_w$ . But the humidity factor,  $K_o$ , used in our tests, is more convenient as it gives a greater range of values. It may be derived from the simple volumetric relation  $V_B + V_W + V_S = 1$ , where:  $V_B$  = the part occupied by air,  $V_W$  = the part occupied by water, and  $V_S$  = the part occupied by the solid skeleton. At a temperature of 20 C, and at atmospheric pressure, the following relation may be written:  $V_B = 1 - (V_W + \gamma_s/\gamma)$  where:  $\gamma_s$  = volumetric (dry unit) weight of the skeleton, and  $\gamma$  = specific weight (density) of the soil skeleton. Thus the humidity factor is  $K_o = V_W/V_B = w/[1 - (w + \gamma_s/\gamma)] = w/(M - w)$  where  $w$  = the humidity in fractions of a unit, and  $M = 1 - \gamma_s/\gamma$ .

It was determined by experiment that the magnitude of subsidence deformations depends mainly on the value of the humidity factor. All other conditions being equal, it was found that loess soils having a  $K_o$  value greater than 1.1 to 1.2 are not subject to subsidence, while, with a reduction of the value  $K_o$ , susceptibility to subsidence increases.

6. There are three types of porosity in loess soils: ultramicroscopic porosity (the size being 0.0003 to 2.0 $\mu$ ); interparticle porosity (2.0 $\mu$  to 0.5 mm); macroporosity (Larionov, *et al.*, 1959). Investigations have shown that ultramicroscopic porosity occupies from 2.5 to 10 per cent of the total volume, and this is always filled with moisture under natural conditions. Consequently, it plays little part in deformation processes. Interparticle porosity, which occupies from 13 to 36 per cent of the volume, plays the main part in consolidation processes. Subsidence greatly depends upon its volume. When this type of porosity occupies less than 21 per cent of the volume, the loess soil is not subject to subsidence. In most cases, the macropores consist of small channels the walls of which are consolidated and often calcified. The presence of the latter determines their importance as the most durable part of the loess soil structure. Some varieties of loess soils are found in which the walls of the original macropores are loose. In such cases, the soils are found to deform readily under the action of water and load.

7. Summarizing the results of our investigations of the structure of loess soils, we conclude that their predisposition to subsidence deformations is determined by the type of the structural system of the solid part and the degree of its water resistance  $K_{wat}$ , by the volume occupied by interparticle porosity, and by the ratio of air to liquid in the soil (humidity factor).

#### SOME METHODS OF ESTIMATING THE STRUCTURAL CHARACTERISTICS OF LOESS SOILS

Simple investigations of soil structure at building sites permit the prediction of the predisposition of loess soils to subsidence deformations, permeability, erosion, and other changes. Through our detailed experimental work we developed some methods and ways of estimating the principal structural characteristics.

#### Determination of the Type of Structural System of the Solid Parts of the Soil

An initial idea of the type of loess soil structure can be obtained on the basis of visual signs: from the effort required to break an air-dry specimen; from an examination of the fracture; and from the reaction of an air-dry specimen to slicing with a knife (Larionov, *et al.*, 1959).

One can discover other characteristics by means of drop analyses on the surface of air-dry specimens. This test consists of placing two drops of hydrous blue methylene solution and three drops of a mixture of machine oil and petrol onto the smooth surface of the specimen. The structural type of soil is determined by the reaction of the soil surface to these solutions (Larionov, 1964), the effect being studied by means of binoculars or a magnifying lens (magnification of 15 to 25 times). The determination of the structural system is made according to Table II. (Note: The colour of the soil surface after the action of blue methylene can give some idea of the structure of the fine dispersed minerals.)

TABLE II. DETERMINATION OF STRUCTURAL SYSTEM BY "DROP ANALYSIS"

Type of structural system	Effect of blue methylene solution	Effect of machine-oil and petrol mixture
Granular	No cracks	Completely granular mass. Consolidation appears at the secondary macropores. Interparticle pores can often be noticed.
Granular-aggregate	From single to some cracks not forming a net	Granular and aggregate areas appear
Aggregate	A net of cracks. Surface warping is apparent in specimens of high aggregate content	A prevailing aggregate mass and secondary macropores with consolidated sides appear

The general character of the structure of the solid part, the degree of its homogeneity, soil density, and its change in different directions may be established by the roentgenographic methods worked out by the author jointly with Semyonov (Larionov and Semyonov, 1964). Finally the exact characteristics of the structural type are established from the results of the determination of the value  $K_{wat}$ .

#### Determination of the Value of the Water-Resistance Coefficient of Soil Structure, $K_{wat}$

This determination is carried out by one of the following methods: binocular, heavy liquid, and sieve analysis.

The *binocular method* consists of three operations: (1) The selection of a 0.5-gram sample from an air-dry monolithic specimen. Subsequent destruction of the sample by means of soaking and shaking it in water for 15 minutes. After disintegration of the soil, all particles less than 0.05 mm in size are discarded by decanting. (2) The separation of aggregates from the residual mass. This is carried out by means of binoculars and a steel needle. (3) The drying at 105 C and weighing of the aggregates. The weight obtained is the value of  $W_{ba}$ . In calculating the water-resistance coefficient,  $K_{wat}$ , it is necessary to introduce a correction for the hygroscopic moisture into the weight of the sample.

The *heavy liquid method* permits a more rapid process of separating the aggregates. In using this method (proposed by the author and improved by Galai, 1964), the procedure of preparing the sample is analogous to that discussed for

the air-dry method. Separation of the aggregates is carried out by immersing the obtained mixture of grains and aggregates in a heavy liquid with a specific weight of 2.3. Aggregates with a volumetrical weight (because of the presence of interaggregate pores) less than 2.3 float to the surface. After washing and drying,  $W_{im}$  is obtained.

The sieve method (Larionov, et al., 1964) consists of breaking up the air-dry loess soils on a shaking screen. This is followed by a fifteen-minute water treatment of the residues on the sieves. After drying and weighing them, it is possible to establish the decrease in the content of the fractions resulting from the water treatment. The values obtained determine the content of the non-water-resisting aggregates. To speed up the procedure the determination may be carried out using one sieve with openings 0.06 mm.

#### Determination of the Humidity Factor $K_0$

This factor is determined by establishing the values  $w$ ,  $\gamma_s$ ,  $\gamma$ , and computed by the formula:  $K_0 = w/[1 - (w + \gamma_s/\gamma)] = w/(M - w)$ .

#### Determination of the Interparticle Porosity

This determination is carried out gasometrically according to the author's method (Larionov, et al., 1959). A monolithic air-dry sample (at laboratory humidity) is used for the purpose. It is weighed and covered with a thin film of paraffin, then placed into a gasometer (Larionov's design). Upon slight application of heat, cracks are formed in the paraffin film. By subsequent shaking, complete disintegration of the sample is achieved. The volume of the escaped air is measured, its value being made more exact by introducing corrections for temperature and atmospheric pressure. The volume of the interparticle porosity may be established from the ratio of the corrected volume of the escaped air to the volume of the sample taken. The volume obtained also includes the volume of the macropores, but for practical purposes, this error may be neglected. If necessary, the volume

of the macropores may be calculated separately and subtracted from the total volume obtained.

#### CONCLUSION

Our investigations show that improvements in the methods of evaluating loess soil structure can be made by taking into account new data obtained when studying building sites.

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