Deformation Properties of Bulgarian Loess Soils

Propriétés de Déformation du Loess Bulgare

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SYNOPSIS The main particularity of the Bulgarian loess soils is their relatively large compressibility to subsidence ratio due to a high natural water content. By their subsidential characteristics the Bulgarian loess soils are occupying an intermediate position between the loess soils in the world, with a maximum subsidence of 1.7 meters related to waterworks. Experimental results obtained by different technics in laboratory conditions, as well as in situ, are exposed and two models of the loess deformation are described. Data from measurements of real structure subsidence, loaded plates with different plate diameter, and induced subsidence by means of large area ponding are discussed. More attention is given on the important case of two-layered foundations because about fifty big structures including a nuclear plant are founded on soil-cement cushins in Bulgaria. In situ tests have shown that the loess deformation behaviour is better approached by a model related both to the elastic and Winkler's half-space. A thermodynamical approach, developed recently, is applied for a brief discussion of a large scale blast compaction of loess in situ.

REGIONAL CHARACTERISTICS

As it is well known the indices expressing the deformation properties depend on the loading. This is why, in order to have a comparative value, their regional characteristics must be drawn up from data obtained by tests at the same load. The criterion, proposed by Abelev (1948) for the determination of the subsidence by the value of the relative subsidence at the most often met contact pressure (3 kg/cm^2), although already rejected as an universal index, is quite suitable for comparative and classification purposes and for the determination of the regularity in the regional change of the deformation behaviour of the loess soil at a d d i t i o n a l l o a d. The total value of the s u b s i d e n c e u n d e r n a t u r a l l o a d is also of importance for the comparison and classification. Unfortunately, the scientific literature is still quite poor in c o m p a r a t i v e regional investigations, which, if competently interpreted, may prove to be very useful for the correct determination of the methods for elimination of subsidence of different loess soils and bases.

From the subsidence curve at a load p = = 3 kg/cm^2 (Fig.1), the relative subsidence ($\delta_{np,3}$), the relative settlement before the subsidence ($\Delta h/h$), the modulus of one dimentional compression (M), and the total compression deformation = settlement + subsidence (S_3) are determined.

For Bulgarian loess soils these indices change within large limits and they depend on a number of conditions, first and fore-

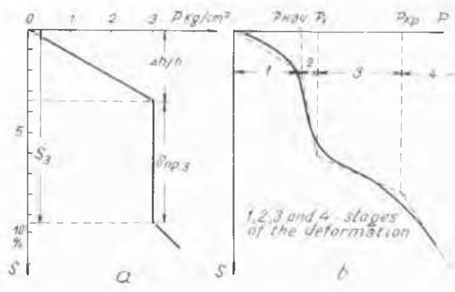

Fig. 1 a) Typical curve of loess subsidence under load of 3 kg/cm^2

b) Typical stress-strain curve for saturated loess under a loaded plate

most on the density, the natural water content, and on the composition of the loess. Table 1 presents the arithmetical mean values of these indices of the basic loess varieties in Bulgaria. They express the change of the deformation properties depending on the composition of the loess and on the structure of a n o r m a l f a c i e s r o w (from the loess sands to the loess clay) characteristic for the loess complex in North Bulgaria. At a gradual change of I_p from 3.6 to 23 the deformation indices change parabolically following the changes

Table 1*

Facies row	Horizon	$\Delta h/h$ %	$\delta_{np,3}$ %	S_3 %	M kg/cm^2	I_p %	n %	γ_d gr/cm^3	w %	S_r %
Loess-like sand	I	5.8	2.0	7.8	135	3.6	46	1.44	9.0	25
Sandy loess	I+II	6.5	4.5	11.0	125	6.4	48	1.42	10.5	30
Typical Loess	I+II	8.3	6.5	14.3	90	10	49	1.39	13.8	45
Clayey loess	I+II	8.5	7.0	15.5	55	17	48	1.47	19.0	55
Loess-like clay	I+II	7.0	2.0	9.0	65	23	43	1.55	22.0	70

* NOTE: Each value is an arithmetical mean from 500 tests

in the density (n,γ) and the water content (w,S_r). It is characteristic that the settlement dominates strongly over the subsidence and the extreme members, where $\delta_{np,3}$ tends toward zero, the deformation goes off almost entirely as a settlement. The large value of the summary one-dimentional compression deformation at a comparatively small subsidence and an increased settlement is a characteristic sign of loess soils from the moderately damp regions to the damp ones of the moderate climatic belt. They differ by this sing from the loess soils in the arid continental regions, where the subsidence dominates over the settlement (at equal other conditions). This is explained with the difference in the relations between the water content indices and the density ones and it determines the approach to the treatment of the deformation properties.

In Minkov's work (1968) are presented in detail the territorial changes of the deformation indices in areal and vertical direction, the dependence of $\delta_{np,3}$ on the composition and structure, the morphometry of the micro and mesorelief on the water content and density indices, etc. Certain corrections are introduced in some of the existing indices for indirect evaluation of the subsidence, and a number of new criteria for its quantitative and qualitative prognosis are proposed. For instance with the help of the volume of the pores and the water content , the value of $\delta_{np,3}$ may be approximately calculated after the formula: $\delta_{np,3} = K\,(n-40)(30-w)$. The coefficient K shows the influence of the composition of the loess: for loess sand K = 0.02; for sandy loess K = 0.03; for typical loess K = 0.05; for clayey loess K = 0.08 and for loess-like clay K = 0.09. From the obtained value for $\delta_{np,3}$ after the brief G.Stefanoff's method the approximative value of the relative subsidence for each desired load for $n > 40$ per cent may be obtained.

The actual relation between the one-dimentional compression modulus M and the deformation modulus E, obtained by means of loaded plates with large area is of importance for practical purposes. It is accepted in the Bulgarian literature up to now (G. Stefanoff and B. Kremakova, 1960) that E/M is close to 2. The investigations carried out during recent years point out that when $\delta_{np,3} > 1$ per cent, E varies between 180 and 220 kg/cm^2 at E/M near 2.3 to 3.0; when $\delta_{np,3} < 1$ per cent, E varies between 200 and 350 kg/cm^2 at E/M near 2.6 to 3.0. It is evident that in both cases E, which is more representative, is from 2.5 to 3.5 times larger than M. This points out that M must not be used for the calculation of the settlement, if the order of the E/M relation is not established. This relation may be accepted with an accuracy sufficient for practical purposes, as follows: for subsidence soils with $\delta_{np,3} > 1$ per cent, E/M = 2.5; for non-subsidence soils with $\delta_{np,3} < 1$ per cent, E/M = 3.0.

The total value of subsidence under natural load J_γ gives the possibility a classification of the soil base of first and second type to be carried out as well as to estimate the amount of the expected subsidence at the second type base. On the basis of a determination of J_γ according to a large number of tests a map of the thickness of the upper non-subsidence zone, a map of the thickness of the subsidence zone, and a map of the zonation of the loess region in Northern Bulgaria after the value J_γ (J_γ = 0.00 cm; J_γ up to 25 cm; J_γ up to 50 cm; J_γ up to 75 cm and J_γ over 75 cm) on a scale 1 : 500 000 were made up. The first type base soils with J_γ = = 0.00 cm predominate. The base soils with J_γ over 75 cm cover only 4-5 per cent of the loess region. The maximum subsidence, established only in one place under an irrigation -canal, is 170 cm. It is evident that according also to this index Bulgarian loess soils occupy an intermediate place between the "warm" loess soils of the arid regions with J_γ up to 200 - 300 cm and the "cold" periglacial loess soils, where the loess soil bases are usually from the first type.

The zonation of the area according to the J_γ is regulated with a normative document which serves as an appliance for the determination of the subsidence and the type of the loess soil base in the Initial stages of the investigation and planning. In 1976 a new complex zonation of the loess in Bulgaria on a scale 1:200 000 was commenced.

By means of comparative investigations it was established that the estimated values of J_γ, obtained in laboratory, are larger than the real ones, obtained by continued saturation with water of the loess massive in large area pits. The coefficient of discrepancy K in the expression $J'_\gamma = J_\gamma / K$ is the greatest at the bases of the slightly expressed second type with J_γ up to 25 cm. Here K varies from 0.70 to 7.oo with a mean value of about 3 (for 15 tests). Toward the stronger subsidence soil bases the discrepancy decreases and if J_γ is greater than 75 cm, K varies in narrow limits and its mean value is about 1.0 to 1.2. This fact is of great importance for the making up of prognosis maps. The estimation on the basis of laboratory data is possible only after a preliminary determination of the amount of discrepancy.

ANISOTROPY OF LOESS BASES

Anisotropy is a characteristic feature of the structure and texture of Bulgarian loess soils and bases.

The structural anisotropy influences the deformation behaviour of the loess samples and consists of: a) a vertical position of the long axes of the larger part of the macropores, which is characteristic mainly for the typical and the clayey losses, and more specially for the fossil pedocomplexes; b) an irregular distribution and a different extent of incrustation of the pores and macropores in the carbonate horizons of the fossil pedocomplex and capillary zones of paleoaquifers, and c) horizontal position of the long axes and the flat walls of a large part of the minus 0.005 mm particles in loess sands and non-macroporous sandy loess.

The textural anisotropy influences the deformation behaviour of the loesss massive as a soil base and is expres--sed in the presence of: a) fossil pedocomplexes from 1 to 7, b) strongly compacted zones on the place of the paleoaquifers over the older pedocomplexes; c) over-moistened zones in the places of constant or temporal water bearing horizons; d) numerous negative forms of the loess micro and mesorelief; h) compacted, over-moistened and structurally worked over sites in the places of former structures; i) numerous places with a greatly reduced water content in places of perennials with a large transpiration capacity (alfalfa, acacia etc).

Beca-use of its great textural anisotropy, the horizontal section of the soil base bears a resemblance to a motley "mosaic" of sectors dissimilar in form and size with different deformation properties - from a water-saturated, greatly compacted (n about 36 to 38 per cent, γ_d about 1.70 to 1.75 gr/cm^3) and a non subsident at great loads loess soil to a greatly subsident one, whose deformation modulus differs from 3 to 5 times. Such differences have been established many times even in the foundations of a middle-size building. This circumstance necessitates the elaboration of a new detailed typification, which includes in its three types, 8 sub-types and 12 classes - the whole variety of the loess soil bases in Bulgaria (M.Minkov and D. Evstatiev,1975).

Owing to the great textural anisotropy the vertical section of the soil base represents a two-layer or a multi-layer system from two up to a dozen of layers, with a different deformation behaviour. This fact simulates our experiments on the deformation behaviour of naturally or artificially formed two-layer ground bases with an upper stronger layer. A typical two-layer soil base with an upper stronger and water-tight layer is created in a case of foundation with a soil-cement cushion (Minkov and Evstatiev, 1975). At a suitable thickness and hardness it redistributes the contact stresses to safe values at the limit of the natural loess. Thus over 50 buildings and equipments of nuclear and power plants, high television towers, industrial equipments, 8 to 18 storey residential buildings, hotels etc. have been built. The average thickness of the cushion is 1.0 to 1.5 m. and under the heaviest equipment it is up to 3.0 meters. For cement quantities from 2 to 6 per cent the deformation modulus of the cushion is 1000 to 1200 kg/cm^2.

From the existing tests on two-layer systems of this type it was determined that: a) the settlement with buildings on a soil-cement cushion at a first type loess base is max 2 - 3 cm, while the stresses on the cushion are from 3 to 5 kg/cm^2; b) the deformation modulus - according to data from geodetic measurements and from plate loadings - is larger than the calculated equivalent deformation modulus for a two-layer base; c) the stresses, at which the destruction of the cushion occurs, are 1.5 to 2 times greater than those after which the "stress-settlement" dependence ceases to be linear; d) before the destruction the bending of the cushion increases sharply; radial fissures appear, and under the plate a rupture surface in the shape of a frustrum of a cone is formed, whose generant is inclined toward the axis of loading at an angle of 40 degrees.

ON THE CHARACTERISTICS OF THE DEFORMATION AND CALCULATION METHODS

It is proved by Kroutov and Bojko (1972) that the subsidence (stage 2 in Fig. 1b) is not a destruction, but is a compaction of the soil base, after which the deformation curve gets the characteristics habitual for other soils (stages 3 and 4 in Fig. 1b). This interpretation of the development of the deformation is of great practical importance. It consists in the possibility to determine the initial load of loess subsidence P (stage 1) and in the necessity of a considerable increase of the loading and duration of the test after stage 2, as well as in the proof that stage 3 is a normal settlement at quite great loadings (3 - 4 kg/cm^2), from where the conclusion is drawn that if the subsidence (stage 2) is eliminated beforehand, the loess soil base may be treated as an ordinary soil base.

This conclusion is of great importance for those investigators, who distrust the properties of soils whose subsidence is eliminated, for instance by soil compaction with a preliminary moistening and energy of deep explosion (I. M. Litvinov's method). As a result of the dynamic character of the compaction, the density of the soil base at depth of 4 to 5 meters corresponds to that one at a complete subsidence under load $p = 2.5 \div 3.0$ kg/cm^2. In the process of dissipation of the water pressure a tyxotropic consolidation of the structure takes place and the newly obtained soil base may be loaded with 2.5 to 3.0 kg/cm^2, like an ordinary soil base. On such a base an 18 storey build-ing was built on a common foundation slab at $P_{нopм}$ = 3.0 kg/cm^2 and a thickness of the subsidence zone before the compaction of about 20 meters.

In the normative documents of many countries the settlement of the loess soil base is prognosticated on the base of the hypothesis for the isotropic elasic semi-infinite space in spite that the real deformations differ considerably from the prognosis. To the date on this problem found by other authors we shall add the following ones: a) the real settlement of a number of many-storey buildings is from 3 cm to 5 cm, and the calculated one - from 12 cm to 20 cm; b) the deformations to one side of the foundations are distributed to several smaller distances from those obtained after the adopted calculation methods. During experimental loadings with a circular plate this distance is hardly 3 to 5 cm close to the external edge of the plate. On reconstructing the city of Russe, which is built on a loess soil base with a thickness of 12 to 40 meters, a practically important interaction of the foundations of 4-5 and 12-13 storey buildings adjoining each other was established nowhere.

These data give us grounds to join the opinions set forth in the special literature, that loess soil bases may be treated as Winkler's foundations (N. A. Tsytovich and I. I. Cherkassov, 1970), or better as a combined Winkler's - Elastic semi-space, which has the particularities of both, because, even though at small distances, settlements around the plate still exist.

Certain facts, for instance the convex shape of the deformation curves in the beginning of the loading (obtained from 15 experimental loadings with a plate of 0.80 m dia.) make us think that also some of the recently developed theoretical analyses, which treat the earth's crust as a non-linear-deforming body, could be applied to the loess soil base problems.

An essential reason for the search for new, more suitable calculation methods is presented also by the availability of a clearly expressed vertical textural anisotropy of the loess soil bases. Quite often, especially for the first type loess bases, the difference in the modulus of the general deformation of the loess soil directly under the foundation and at the lowest part of the section reaches 500 per cent. If a soil compaction by preliminary moistening and energy of deep explosions is applied in order to improve the foundation, the modulus would increase from 100 kg/cm^2 at a depth of 3 m up to 800 kg/cm^2 at a depth of 15-16 meters. These differences are quite big, so it will be not correct to consider as a homogeneous elastic semi-infinite space bases of this type (especially at large foundations with a deep spreading of the deformation zone). In such cases more complicated models, as for instance Klein's one, applicable to the foundations, whose deformation properties increase in a power function from the depth must be used.

It is evident, that because of the complicated structural and textural variety of the loess soil bases, one must get out of the frames of the ideal homogeneous elastic semi-infinite space and look for new, more suitable for the real conditions calculation models and schemes.

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