# Geotechnical problems of the Bulgarian loess soils

## Problèmes géotechniques du loess en Bulgarie

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SYNOPSIS Loess covers about 10 percent of Bulgaria's territory and considerable industrial, civil, road and land improvement construction is carried out in loess regions. Extensive engineering geological and soil mechanics studies have been accomplished reflected in numerous publications and maps to different scales. This paper treats problems associated with the defining of the type of loess bases, the utilisation of underground space, construction on slopes, raising the ground waters level and foundation work in loess of great thickness. The first part is devoted to the results obtained from test loading of slabs of big diameter in natural and compacted loess soils. This problem is particularly topical because of the extensive use of dynamic compaction of loess in construction.

## INTRODUCTION

The geographical location, the contact with the Danube and the Black Sea, the varied relief and lithologic composition of Bulgaria's territory have determined the formation of aeolian, diluvial-colluvial, alluvial and mixed loesses and loess-like deposits. Most widespread (about 12,000 sq km) and thickest (up to 100 m) are the loesses in the Danubian region. Identified here has been the lithofacial row with aeolian genesis characteristic of the valleys of many big rivers consisting of loessoidal sand, fine-sand, typical and clayey loess and loessial clays of varying composition, state, structure and building properties. A new region of loess-like sediments of different genesis occurring in an island-like pattern has recently been described. It has been connected with the weathering and redeposition of low cretaceous marl in the northern foothills of the Balkan Range. Such sediments are also common along the Black Sea coast (around Varna, Nessebar) associated with the formation of dunes and in other parts of the country. Some of them spread over wide territories and have highly collapsable properties. The great lithofacial and genetic variety, the complicated stratification and metagenesis and Bulgaria's small territory characterize the country as a convenient test site for various studies of loessial soils.

Unlike the loess regions in semidesert and steppe areas elsewhere, intensive and varied construction is carried out on loess soils in North Bulgaria including: villages, cities with population of up to 150,000, big industrial and power projects (i.g. the Kozlodouy nuclear power complex), multistoried housing and communal buildings, thermo-electric power plants, high TV towers, etc. The areas brought under irrigation are being rapidly expanded, the network of irrigation canals bringing water from the Danube or from ground water sources is being further developed. Therefore during the past 30-35 years loess has been the object of numerous studies in Bulgaria and has become one of the best studied geological formations in the country. The genesis, distribution, conditions of occurence, thickness, morphology, lithological changes, stratification and stratigraphy, composition, state, structure and building properties, terrain patterns classification and zoning, methods and technical means of investigation, conditions for construction, anti-collaps, anti-leakage and anti-seismic preliminary treatment of the loess ground etc. have been the subject matter of three monographs (Stefanoff and Kremakova, 1960; Minkov, 1968; Minkov and Evstatiev, 1975), of a number of studies, more than 150 scientific papers and normative documents. Lithofacial and engineering geological maps to scales 1:500,000 and 1:300,000 have been drawn of the entire loess region along the Danube, and of some territories to scales 1:100,00 and 1:25,000. 1:10,000 and 1:5,000 maps have been drawn of cities like Rousse, Razgrad, Tolbukhin and Silistra,built entirely on loess soils. The greatest achievement has been the establishment of quantitative regularities in the changes in the geologo-geomorphological, lithostratographic and geotechnical elements and properties of the loess formation, of the natural and anthropogenic factors that determine its horizontal and vertical heterogeneity, of the methodology of its investigation, and study of the methods and procedures of preliminary treatment, of conditions for construction, of the classification of the terrain and zoning, of mapping.

The following institutions have been engaged in studying the problems of loess: the Geotechnical Laboratory at the Bulgarian Academy of Sciences and its Experimental Station for Loess Studies in Rousse, the Department of Soil Mechanics, Foundation Work and Engineering Geology of the University of Architecture and Civil Engineering; the Building Research Institute of Civil Engineering at the Ministry of Construction and Architecture and individual specialists of other research institutes and organizations. The wide variety of building properties of the loess soils, the intensification and modernization of construction have raised a number of new problems to be tackled by the Bulgarian scientists interested in loess.

The first part of this paper (written by Stefanoff, Jellev and Donchev), presents the results of experiments, made with big slabs, of the bearing capacity of natural and compacted loess soils, while the second part (by Minkov, Evstatiev and Donchev) deals with some more general problems of the investigations.

## I

## STRESS AND STRAIN STATE IN COMPACTED LOESS SOILS

The methods of dynamic compaction of loess soils for foundation of residental and industrial building enjoy ever growing application (this refers to the compaction of soil bases by means of 3 to 15 t rammers in layers 1.5 to 4.5 m thick). In some rare cases loess cushions of limited thickness are used. Under severe foundation conditions cement-loess cushions are applied in combination with layers, or loess cushions compacted by heavy rammers. In such cases as well as when the active zone is larger than the thickness of the improved part, we have a multilayer soil base.

Independently of the wide application of these foundation methods, there is no satisfactory calculation method for multilayer soil bases. This demands theoretical and experimental investigations to clarify the stress and strain state of multilayer bases. In connection with this, within the scope of a joint investigation programme between the Laboratory of Geotechnics at the Bulgarian Academy of Sciences and the Department of Soil Mechanics, Foundation Engineering and Engineering Geology at the University of Architecture and Civil Engineering, experiments have been carried out to investigate the stress and strain state of:

(i) homogeneous compacted loess base of a diameter 2.40 m and 2.80 m thickness;

(ii) double-layer base, consisting of a compacted loess layer 40 cm thick and a natural collapsable loess.

The investigations have been conducted in the massif of the I-st loess horizon at the testing site of the Laboratory of Geotechnics at the Bulgarian Academy of Sciences in the industrial area of the town of Rousse. The loess layer is 7-9 m thick and is distinguished by its considerable homogeneity. The basic physical-mechanical characteristics of the loess are given in Table I.

TABLE I

Loess Characteristics

| Grain size in mm | | | $w_L$ | $w_P$ | $\rho_d$ | w | $n_{m,3}$ | $M_{0-2}$ | $\varphi$ | c |
|---|---|---|---|---|---|---|---|---|---|---|
| 2÷ 0.05 | 0.05÷ 0.005 | 0.005 | | | | | | | | |
| % | % | % | % | % | t/m$^3$ | % | % | MPa | ° | kPa |
| 25 | 73 | 2 | 28 | 22 | 1.37<br>1.48 | 11 | 4 | 5.5<br>6.0 | 23 | 2 |

$n_{m,3}$ - macroporosity (Coef. of relative collapse) for q=0.3MPa.

$M_{0-2}$ - modulus of deformation for q=(0÷0.2)MPa

Stresses are measured with soil dynamometers (Jellev, 1980):

(i) Tensoresistor contact dynamometer of a diameter d=40 mm and height h=10 mm, and modulus of deformation $E_c$=500 MPa;

(ii) Dynamometers with a hydraulic transformer of d=70 mm and h=12 mm, and a second type of d=35 mm and h=10 mm, with $E_c$=5000 MPa respectively 1500 MPa;

(iii) Double diaphragm soil dynamometer with d=60 mm, h=10 mm and $E_c$=600 MPa.

The universal tensometric device with a carrier frequency IEMI-N2301, N-2302 with distribution boxes N-2304 made in Romania, and TSA-4 made in Czechoslovakia is used as a secondary equipment.

In measuring the contact stresses and the stresses in the soil base,the method developed by Jellev (1978) and Stefanoff, Jellev (1979) has been used.

The displacements of points of the base have been measured using the following marks (Stefanoff, Jellev, 1981):

(i) string marks,

(ii) surface marks.

Dynamometers and marks are located as per optimal scheme (minimum number, partial repeatability and sufficient initial data) (Fig. 1).

The functions of the measured displacements (vertical w and horizontal $u_r$), the settlements s and the stresses (contact, vertical $\sigma_z$ and horizontal $\sigma_r$, $\sigma_\theta$) have been received by approximation with spline functions of the third exponent (cubical spline). The results permit a full analysis of the stress and strain state of the loess soil.

Loading of soil has been carried out in stages by means of a rigid circular slab with D=800mm. The values of the measured magnitudes for each stage of loading have been read at given intervals of time until attenuation of the settlement (conditional stabilization 0.1 mm/2h). Fig. 2 shows a general view of one of the experiments.

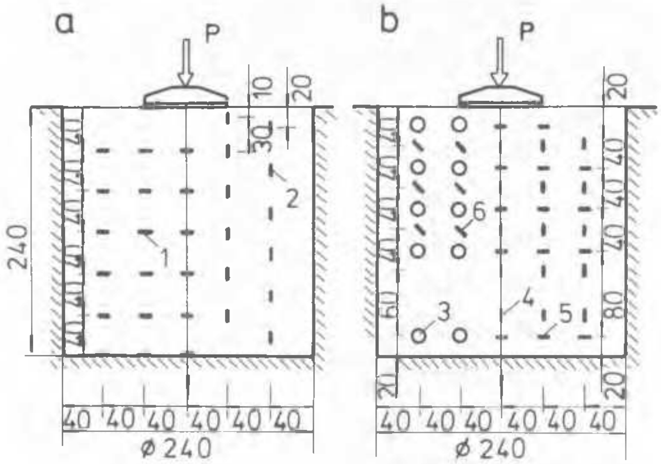

Fig. 1 Scheme of location of marks (a) and of dynamometers (b) in the experiment for testing the stress and strain state of homogeneous compacted loess soil.

1 -marks for measuring vertical displacements w;

2 -marks for measuring horizontal displacements $u_r$;

3 -dynamometers for measuring the horizontal stress $\sigma_\theta$

4 -dynamometers for measuring the horizontal stress $\sigma_r$;

5 - dynamometers for measuring the vertical stresses $\sigma_z$;

6 -dynamometers for measuring the stresses $\sigma_\alpha$ .

The dimensions of the artificially compacted homogeneous loess base are: diameter D=240 cm and total thickness H=280 cm. It is formed in layers 6-10 cm thick, compacted by manual rammers. At optimum water content $w_{opt}$=15% and density $\rho_d$=1.8 t/m$^3$ a density $\rho_d$=1.8 t/m$^3$ with water content w=15.2% has been received.

The loading has been carried out in stages $\Delta q$=0.02 MPa to q=0.48 MPa, and after that the compacted loess base has been unloaded (Fig.3).

A modulus of deformation $E_p$=(14÷3)MPa has been obtained.

Today the most popular methods for testing the stress and strain state of the soil base; legalized in Bulgaria, are based on the theory of elasticity. Therefore a theoretical investigation has been performed of the stress and strain state of the loess base according to Bousinesq and the results have been compared with the results of the experiments.

Fig. 4 shows the distribution of vertical normal stresses along the axis, and Fig. 5 shows the stresses under the slab edge.

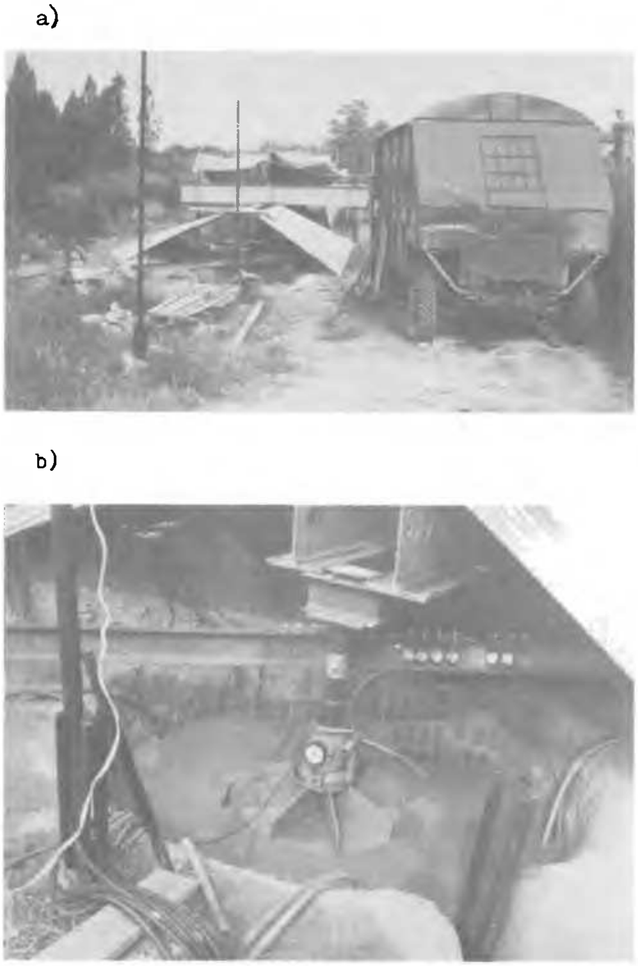

Fig. 2 General view of the experiments

a) General view of the arrangement;
b) View of the experiment for a double layer base.

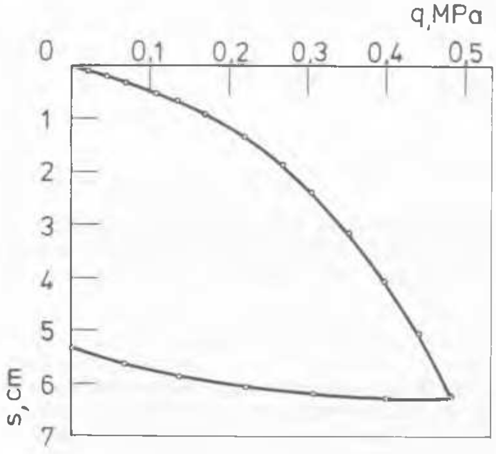

Fig. 3 Diagram of settlement for the homogeneous compacted loess base

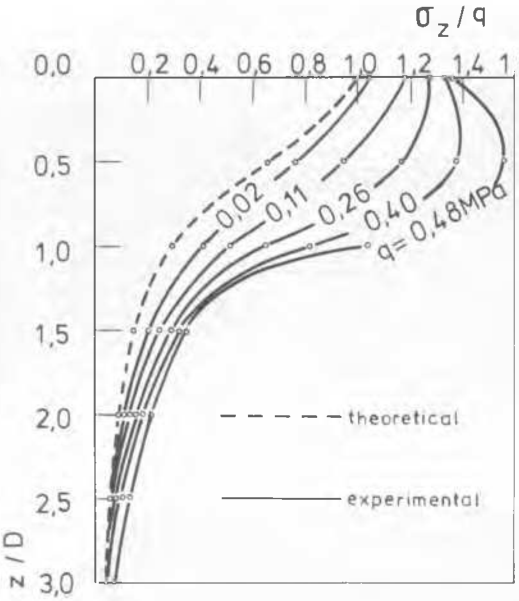

Fig. 4 Distribution of vertical stresses for a load $\sigma_z/q$ along the exis of the slab for different stages of loading.

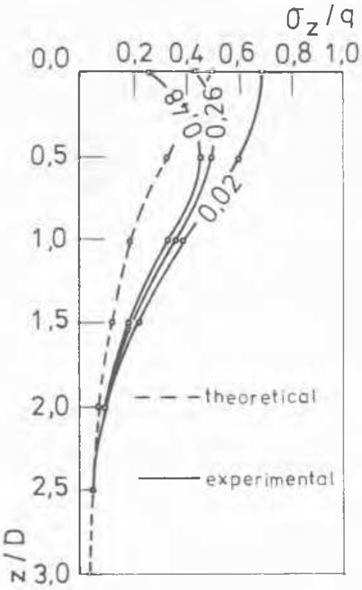

Fig. 5 Distribution of vertical stresses for a load $\sigma_z/q$ under the slab edge for different stages of loading.

The big difference between the experimental and the theoretical vertical stresses is obvious. This difference increases with loading and is considerable for a depth up to z/D=2. A comparison between the theoretical and the experimental strain-tensor and stress-tensor components shows that:

$w_e = (10 - 80)\%\ w_t$

$u_{re} = (10\text{-}140)\%\ u_{rt}$

$\varepsilon_{ze} = (50\text{-}320)\%\ \varepsilon_{zt}$

$\varepsilon_{re} = (20\text{-}250)\%\ \varepsilon_{rt}$

$\varepsilon_{ve} = (40\text{-}240)\%\ \varepsilon_{vt}$

$\gamma_{ie} = (100\text{-}260)\%\ \gamma_{it}$

$\sigma_{ze} = (80\text{-}200)\%\ \sigma_{zt}$

$\sigma_{re} = (100\text{-}400)\%\ \sigma_{rt}$

$\sigma_{\theta e} = (100\text{-}280)\%\ \sigma_{\theta t}$

$\tau_{ie} = (100\text{-}260)\%\ \tau_{it}$

$w$, $u_r$, $\varepsilon_z$, $\varepsilon_r$, $\varepsilon_v$, $\gamma_i$, $\sigma_z$, $\sigma_r$, $\sigma_v$, $\tau_i$, are the respective vertical displacement, horizontal radial displacement, linear vertical strain, linear radial strain, volume strain, intensity of angular strain, normal vertical stress, normal radial stress, normal horizontal stress and intensity of tangential stress. Index "e" means experimental and index "t" means theoretical characteristics.

The diagram of the contact stresses is variable and depends on the degree of loading.

Using the experimental results the homogeneity of the loess base during loading has been checked, and the moduli of volume deformation K and of shear deformation G have been calculated by means of the equations:

$$K = \frac{3p}{v} \ ; \qquad G = \frac{\tau_i}{\gamma_i} \qquad (1)$$

where: 3p - hydrostatic pressure or the first invariant of the stress-tensor.

The values received for K and G show that they vary during loading. The maximum values of K are 2 to 8 times bigger than the minimum values and those of G they are 4 to 6 times bigger. Therefore the compacted loess base is not homogeneous during loading.

Checked is also the isotropy of the compacted base considering the alignment and the similarity between the stress state and the strain state (Jellev, 1984) on the basis of comparing the moduli of linear deformation. The analysis of the moduli obtained shows, that they vary with the increase of the load, i.e. the isotropy increases.

The double layer loess base consists of natural loess (see Table I) and of a compacted loess layer with H=40 cm and D=240 cm, $\rho_n$ = 1.82 t/m$^3$ and $w_n$=11%.

The experiment is carried out in the same way as that for the homogeneous compacted loess base. The necessary values are measured so as to obtain a full picture of the stress and strain state of the compacted loess layer and

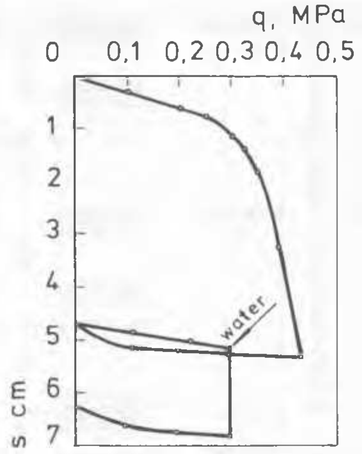

Fig. 6 Diagram of settlement s = f(q) for a double layer loess base.

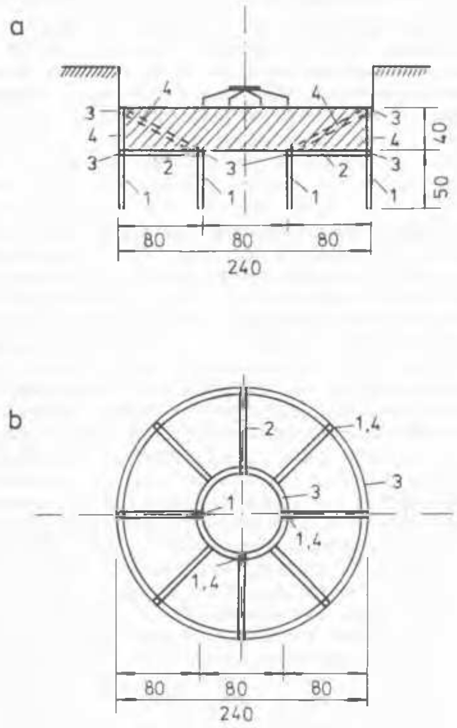

Fig. 7 Scheme of the watering system for the loess base.

a -vertical section; b -scheme of the drains between the compacted loess layer and the natural collapsable loess;

1 -boreholes Ø 40 mm; 2 -radial drains; 3 -circular drains; 4 -hose Ø 18 mm.

1, 2 and 3 are filled with gravel.

the vertical displacements of the natural loess. Loading is applied in stages from $\Delta q=0.02$ MPa to $q=0.44$ MPa, then the double layer base is unloaded and loaded again with a value approximating the operational load (Fig. 6).

To model the cases of watering of the natural loess base, after attaining a repeated loading with values equal to the operational load, watering of the collapsable loess was conducted (Fig. 6) by means of a specially erected watering system (Fig. 7).

The development of collapsable deformations in the course of time, after watering of the loess, is given in Fig. 8.

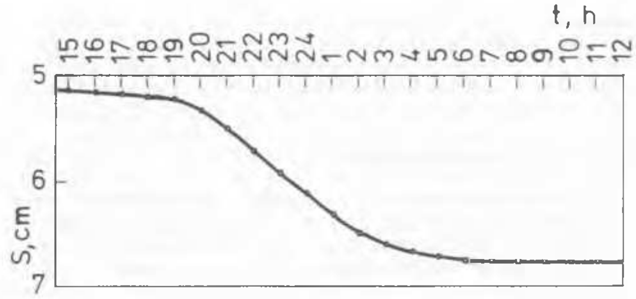

Fig. 8 Development of collapsable deformations in the course of time.

The results from the investigation of the double layer base permit the analysis of the stress and strain state of the compacted layer and the strain behaviour of the base. The analysis shows that until watering the loess double layer base reacts almost as the homogeneous base of compacted loess (negligeably bigger concentration of stresses in the compacted layer), and only after watering the redistribution of stresses begins, wherein the compacted layer manifests itself as a rigid one and participates actively in this redistribution.

## II

## THE MAIN LOESS PROBLEMS

Following below are the most important problems concerning loess which are currently being tackled in Bulgaria.

1. Evolvement of the method best suited to defining the collapsability of the soil type when the horizontal and vertical heterogeneity of the loess deposit is well expressed, thus lending a mosaic and multilayerd character to the soil even within the bounds of a single construction site.

There is a great disparity between the values of collapsability under overburden calculated according to laboratory data and the real total collapse $\Delta_c$. This disparity can be illustrated by two extreme cases (Fig. 9). In the first case (Fig. 9, a) the calculated $\Delta_c$ is about 100 cm while the real total collapse measured under an irrigation canal is 170 cm; in the second case (Fig. 9, b) the calculated value is 70-80 cm and the actual - 0.00 cm. In both cases the thickness of the loess deposit was the same (about 40 m). This result leads to confusion regarding the soil type. To our view the explanation is in the big differences in the dynamics of the infiltration process and the action of the hydrodynamic pressure in radically differing media - of little stratification and of great stratification. There are most varied intermediary states between these two extreme cases. This gees to show that the defining of $\Delta_c$ and of the type of complex stratified base cannot be done proceeding from laboratory data. What is valid is the hydroconsolidation in-situ test or the variant of the "giant sample" of Krutov and Popsuenko (1983), adapting it to different lithostratigraphic conditions. New solutions should be sought applying other in-situ methods for this purpose.

2. Elucidating the temperature-moisture regimen and stress state of the loess deposits in a natural and water-saturated state when underground space is to be used.

With its dead (dispulsive) horizon, stable temperature and moisture, easy superficial and underground excavation and inexpensive sustainment the loess massif is a convenient medium for underground urbanization purposes. No other geological formation can provide such conditions. On the other hand, however, the rapid loss of the strength of loess when moistened requires a good knowledge of the changes of the stress and strain state of the massive in view of the inevitable breakdowns of water supply and sewerage systems, the changes of moisture content around warm underground structures, rising of the ground water level, the formation of water "cupolas", of temporary and constant ground water horizons on top of older fossil soils, during illegal irrigation of adjacent lands, etc. Contributions to the elucidation of this problem are two papers by Hamamdshiev (1981, 1984). Examples of a partial solution of the problem of using underground space in loess soils are the once existing underground houses built in the loess of the Danubian Plain, the numerous loess dwellings in North China, the American practice in the construction of partially underground houses, etc. However, fragmentary experience and the investigations made are not sufficient to start up-to-date urbanization of the underground at greater depths, particularly in view of the rapid changes in the state of the loess soils in North Bulgaria in small horizontal and vertical distances. This requires the evolvement of new methods of prolonged instrumental observations of the temperature and moisture regimen and stress and strain state of the massif under varied conditions which might emerge during the construction of underground buildings, premises and installations in loess soils.

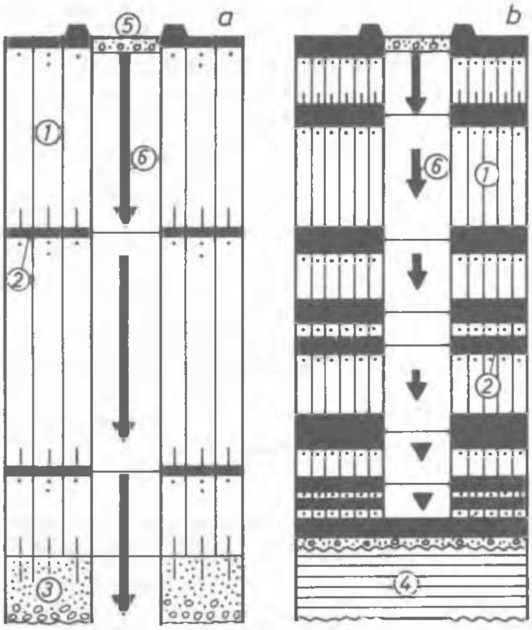

Fig. 9 Differences in the infiltration process depending on stratification a. Western and b. Eastern parts of the loess province; 1-loess horizons, 2-fossil soils, 3-gravel and sand, 4-clay, 5-water basin, 6 -infiltration velocity

3. Establishment of the geotechnical properties of loess soils involved in the formation of the big landslides at the Danube.

In the landslide process, the typical loess of the plateaux undergoes deep changes in composition, degree of saturation, density and strength-deformation properties. This has resulted in formation of: collapsable loess of natural moisture content variously underconsolidated; compacted saturated leached and non-collapsable loess; indurated non-collapsable loess of very high bearing capacity; compacted saturated leached and non-collapsable lacustrine-marshy loessoidal sediments (soft soils) and diluvial-colluvial uncompacted slightly collapsable loess-like sediments. These varieties occur on diverse landslide forms and by their varied properties greatly complicate the conditions for construction. The problem of investigating the loess soils of landslides has come to the fore with great urgency during the past of few years in connection with the assessment of building conditions in a number of towns set up along the Danube on old landslides provoked by hyman activity. The situation has been further aggravated by the high seismic intensity of the region under which landslides are activated while the saturated and uncompacted loess soils step up the destructive effect of earthquakes. The combination of earthquake, landslide and collapsable deformations makes engineering geological forecasts and recommendations considerably more difficult.

4. Forecasting of long-term changes of the

moisture content, density and properties of the loess massif on large territories as a result of urbanization and irrigation.

The first grave consequences of this process have already been noted along three main lines: a) a relative decrease of the collapsability and increase of settlement of the loess massifs including a change in the type of soil base and the building conditions over large territories under irrigated areas and particularly in big cities, due to the slow and lasting increase of the water content of the loess; b) the activation of landslides on slopes around loess plateaux in the course of the slow and lasting increase of the water inflow from irrigated areas and the increase of the hydrostatic and hydrodynamic pressure in the landslide masses; c) raising the level of ground water, the inundation of basements, destruction of foundations and walls of small and not well constructed buildings due to the decrease of the strength and bearing capacity of the base and of the building materials after their saturation with water. From this point of view slow and lasting regional anthropogenic changes in the regimen, state and properties of loess massifs acquire worldwide importance. It is our professional obligation to sound a warning about this tangible danger for two reasons; first, because the process can yet be reversed if suitable measures are taken, and, second, because so far very few specialists have paid serious attention to this danger. This calls for stepping up the investigations of the prolonged environmental-geological changes in the loess complex, setting up of systems for instrument control, the introduction of lithomonitoring of the geological environment in the regions of loess soils, the establishment of geodetic networks and test sites for measuring the deformations of buildings, installations and entire cities built on a loess soil base.

5. Evolvement of suitable methods for the anti-collapsable treatment of the loess soils at the Danube whose collapsable zone is 35-40 m thick.

So far construction in North Bulgaria has been chiefly carried out on river terraces with comparatively thin superficial loess layer. Greater urbanization and irrigation on the older relief forms - high terraces and loess plateaux (80-100 m thick loess) exhaust the possibility of effectively applying the traditional methods (heavy and over-heavy tamping, compacted soil and soil-cement cushions, pile foundation,etc.), while the methods of strengthening in depth are either economically inexpedient (e.g. injection of silicate and aerated silicate grouts, thermal stabilization, etc.) or technically inapplicable in urban conditions (e.g. compaction by moistening and deep explosions). There are three options in resolving this problem: a) treatment of the entire collapsable zone (for instance soil-cement piles made in boreholes widened by means of explosions of deep linear blast cartridges) with buildings and installations of first-rate importance; b) treatment only of the upper part of the collapsable zone applying some of the traditional methods for conventional buildings and structures used for dry technological processes and erected on a reinforced concrete slab where the risk of moistening of the uncompacted part of the base is very small; in such a case the rising of the ground water level, the formation of water cupolas or temporaly ground water horizons could not do much damage to the structures either because of the great thickness of the layer between the moistened part and the stabilized layer, or because of the strengthening action of the system of stabilized base and a common reinforced concrete slab; c) treatment of the collapsable zone of land improvement constructions by compaction with moistening and deep explosions at different levels where the risk of damaging neighbouring installations is small. This calls for the introduction of the category of "collaps risk" which is to be applied in assessing the anti-collaps methods depending on the class and function of the building or installation.

6. Further improvement of the methods of stabilization and compaction depending on the thickness, type and properties of the loess soil.

This can be done by continuing the studies on the mechanism of stabilization and its regulation (Evstatiev, 1984); on improving the effect of the methods so far used for dynamic compaction with tamping or explosion (Minkov, Donchev, 1984; Minkov, Evstatiev, Donchev, 1977); on the wider introduction of the other methods of stabilization in depth; on the search for methods and technologies of stabilization and compaction new in principle; on observations of the state of house and installations built on stabilized foundation, etc. The most suitable method should be selected on the basis of a comparative technical and economic appraisal.

7. Expansion of in-situ tests by using rapid methods in conditions of accelerated construction, quick technogenic changes in the state of the base, high cost and insufficient reliability of laboratory tests, the technical complexity, long duration and limited depth covered by the traditional collapsability tests.

The in-situ instrumental investigations can include numerous large-scale installations built on loess soils, when the soil base has been treated in different ways. The bases of these installations are gigantic slabs providing reliable information about the correspondence between the measured real settlement and the values obtained through different methods of calculation. The analysis of this information regarding installations of different structure where different methods of treatment have been applied and the properties of the natural base are different, would represent a very important contribution to the real stress-settlement relation which is of international interest. Such an attempt has already been made through measuring the deformations of high television towers and other buildings in Rousse in which novel methods of preliminary treatment of the base have been applied (Milev, 1984, Evstatiev et al., 1985).

8. Improving the methods of making engineering seismogeological characteristic of the

ground and seismic micro-zoning of the loess terrains with higher seismic intensity, the existence of an interdependence between landslide, settlement and earthquake deformations.

The first attempt of making a seismogeological characteristic of loess terrains in Bulgaria is being currently conducted for the purposes of building a new residential suburb in Rousse where the seismic intensity is of the 7th, 8th degree and the city is entirely built on collapsable loess and soft soils.

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