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Geotechnical aspects of construction on loessial soils

Aspects géotechnique de la construction sur loess

N.L. Zocenko, I.V. Matveyev, I.A Rosenfeld & V.S. Shokarev
State research institute of building constructions, Kyiv, Ukraine
E-mail: adm-inst@ndibk.kiev.ua

N.V. Kornienko
National institute of construction and architecture, Kyiv, Ukraine
E-mail: niisk@optima.com.ua

ABSTRACT
The assessment of construction properties of the loessial collapsible soils spread on the most of the territory of Ukraine is given. The classification of difficulty of construction is presented, which is performed on the basis of comparison of possible deformations of soil foundations and values of ultimate deformations of the designed buildings. The main construction methods on loessial soils are described including soil compaction by hydroblast and results of their application in practice. It is recommended to perform monitoring on the most of the buildings constructed on loessial soils.

RÉSUMÉ
Aprés l'évaluation des propriétés constructibles des sols en loess, exposés à l'affaissement, rencontrés sur la plus grande partie du territoire de l'Ukraine, suit une classification des difficultés de construction, basée sur une étude comparative des déformations que peuvent subir les fondations rapportées aux valeurs des déformations limites normatives pour les bâtiments à construire. Sont décrites les principales techniques de construction sur des sols en loess, y compris des sols condensés par hydroexplosion, ainsi que les resultats issus de la recherche appliquée. Pour la plupart des bâtiments construits sur des sols exposés à l'affaissement, il est préconisé d'installer des équipements de système informatique de mesure "Monitoring".

1 FEATURES OF LOESSIAL GROUNDS FOR BUILDING

One of the main factors, which complicates construction in Ukraine, is spreading almost on 70% of its territory of loessial soils, which possess the collapsible properties, i.e. compaction deformation arising at their artificial saturation without changing of stress-strain state at the at the expense of movement of soil particles at radical changing of its structure. Thus in the region of Middle and Low Predneprovie thickness of loessial strata vary within 12…25 meters and near Nikopol reaches 30 meters and more. The value of collapse of such soil strata makes 0.6…1.0 m and near Nikopol is 1.5…2 m. Built-up of these territories by objects of city and industrial infrastructure led to artificial saturation of loessial strata.

At this there is total (as a rule non-uniform) sag of soil surface within 0.1…0.3 m that leads to development of deformations in the buildings and structures, which decrease or disturb their serviceability. Almost 10% of territory of Ukraine has such type of loessial soils.

In other regions of Ukraine where thickness of loessial strata is less or they do not possess collapsibility from dead weight, collapse can occur at artificial saturation of soils under impact of external load, which is transmitted to the soil by foundations of the structures, at this local (as a rule non-uniform) sags of ground base, which cause deformations of structures. Structural strength of loessial soils in addition decreases up to 15…20% at dynamic loads.

The soils collapsible properties are assessed by collapsibility value ε_{sl} and initial collapsible pressure p_{sl}. The soils, for which value of relative collapsibility makes $\varepsilon_{sl} \geq 0.01$, are related to collapsible soils. This limit value ε_{sl} was determined by results of compressive tests. As special tests showed this value ε_{sl} is caused by collapse of soil sample at settlement plates to depth up to 2…3 mm. At this the ultimate value, which characterizes non-collapsibility of soil, depends on its type and state and is varied within ε_{sl}=0.01…0.025. With increasing of pressure the value ε_{sl}, as a rule increases, reaching ε_{sl}=0.10…0.12 for very collapsible soils at pressure p=0.3…0.5 MPa. The value of initial collapsible pressure vary within a wide range p_{sl}=30…300 kPa.

2 METHODS FOR STRUCTURES ERECTION AND THEY MONITORING

The mentioned factors caused the necessity to apply the construction methods, which are adequate to difficulty of soil conditions. In those cases where technical equipment of construction allows and an economical expediency is approved, complete cutting through loessial strata by the piles of different types is applied, that is the most reliable method of foundation of the buildings and structures on such soils. In other cases (at corresponding parameters of loessial strata) methods of reinforcement and fastening of loessial soils can be used. When due to the substantiated reasons it is impossible to apply cutting through of the strata by piles or their fastening (compaction) the construction of buildings and structures of various types is performed in Ukraine applying a complex of protective measures, which includes partial removal of collapsible properties of strata soils in its upper part using heavy tempers or rolling, an increased waterproofing of soils and reinforcement or adjusting of the building (construction) structures to perception of forces and deformations from possible beyond-normative settlements of the base. This construction method is theoretically substantiated, checked in mass construction practice and experiments on field objects, corrected taking into account the analysis of data of long-term monitoring and included into the state standard of Ukraine (DBN B.1.1-5-2000, 2000).

To ensure accident-free construction, reconstruction and operation of the buildings the automated measuring-calculating system

"Monitoring" was developed and is successfully used in the construction practice.

The technical devices in the system "Monitoring" are the following (Fig. 1):

- universal inductive sensors;
- block of information medium and transmittal;
- communication line.

Figure 1. Technical devices of the automated measuring-calculating system "Monitoring". 1 – sensor; 2 – block of information collecting; 3 – communication lines.

After assembling of the sensors the period is programmed on the construction object with which the system switches on, the sensors are interrogated and information is transmitted to any distance to the center of its processing through the Internet to e-mail address or to mobile phone. Off-line operation from uninterrupted power unit is foreseen in the system, which allows to preserve serviceability on the objects with unstable electric network.

Monitoring parameters:

- relative displacement of the object (structure) with accuracy 0.001 mm;
- vector of displacement of the object (structure).

For visualization of the controlled parameters of the object and calculation of the additional ones: angle of inclination and relative settlement, computer program "PENDULUM" was developed. The example of visualization of displacement of the building structure in point i is presented (Fig. 2).

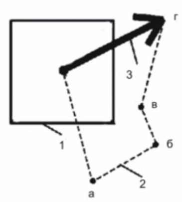

Figure 2. Example of visualization of displacement. 1 – building structure; 2 – way of dislocation (4 cycles of observation); 3 – resultant of displacement of the column.

It shall be noted that in some cases at accident artificial saturation of soils or non-uniform rise of groundwater level beyondnormative tilts of the rigid structures or their separate parts are observed (for example, compartments of multi-storied residential buildings, structures of tower type, etc.). In such cases for liquidation and restoration of normal operation state of such objects different methods of levelling of such objects have been developed and successfully applied using special engineering technologies (for example, using the system of hydraulic jacks; drilling, i.e. partial extraction of soil from the foundation.

3 BUILDING CODES FOR PROJECTING

Unlike (SNiP 2.02.01-83, 1983), in which a conditional geological characteristics is accepted as assessment criteria of difficulty of construction conditions on collapsible soils as a value of collapse from dead weight of the stratum $S_{sl.g}$ = 5 cm, which is not correlated with the anticipated sags and character of deformation of ground surface, in new document of Ukraine (DBN B.1.1-5-2000, 2000) difficulty of construction conditions on collapsible soils is determined and standardized comparing possible (anticipated design) deformations of the base and parameters of distortion of ground surface with values of ultimate deformations for design structure (taking into account presence or absence of engineering preparedness of its base). Proceeding from this the groups of difficulty of construction on collapsible soils are regulated:

- group 1 – on construction site of certain object from load, transmitted to base by its foundations, where group 1-A (difficult conditions) occurs at non-liquidated collapse at upper part of base; group 1-Б (average conditions) – at partially liquidated collapse at upper part of base and group 1-B (easy conditions) – at completely liquidated collapse at upper part of base;
- group 2 – on the whole territory of built-up (in built-up area) depending on values of possible distortion (tilt) and relative deformations of base surface at collapse of stratum soils of from dead weight (taking into account the performed geotechnical measures on liquidation of its collapsible properties within the collapsible stratum). Depending on ratio of value of mutual deformations of the building (structure) with its base in relation to value of ultimate deformations (for this structure) three groups of difficulty of conditions are ascertained: 2-A (difficult conditions), 2-Б (average) and 2-B (easy).

At the first time in the normative documents the issues are considered and the practical procedure is given of design consideration of possibility of simultaneous occurrence on the construction site of two or a few external impacts (for example, collapse and seismics; collapse and landslide; collapse and underground excavations, etc).

At selecting of optimal ways of preparing of the base and structure of foundations the combination of the following factors is taken into account:

1) physical-mechanical indices of loessial stratum, its thickness, ability to collapse from dead weight (or its absence), value of the anticipated maximal collapse of the base at water saturation of soils of the stratum and others;
2) structural and architectural-planning structure of the design structure, value and character of the loads transmitted to soil, possibility of artificial saturation of base soils (impossible, possible, regular, accident and others);
3) technical possibilities of construction organizations performing construction;
4) character of the surrounding built-up, including basins of rivers or lakes, industrial enterprises, etc.

4 BUILDING PRACTICS

Consideration of the mentioned factors and data of monitoring in Ukraine allowed to develop the methods of construction:

- on loessial strata, which do not have the ability to collapse from dead weight, at thickness more than 10 m - (the most of-

ten) complex of protective measures; arrangement of short piles in rammed in foundation pits; arrangement of posts from fastened soil; at thickness less than 10 m – cutting through by piles of different types, underground stories (complete or incomplete);
- on loessial strata, which have ability to collapse from dead weight, at thickness less than 10m – cutting through by piles of different types, underground stories, complex of protective measures (for light buildings); on strata 20m and more – predominantly complete cutting through by piles, soil compaction by method of preliminary artificial saturation using the energy of blast together with arrangement of compacted soil cushion in the upper zone of the base.

This construction method widely spread both in Ukraine and abroad is applied for liquidation of collapsible strata with thickness more than 8 m with purpose of decreasing of deformation and increasing of soil bearing capacity.

The essence of hydraulic blast method is in weakening of structural connections of loessial soil by the way of its artificial saturation to yield limit and performance of blasts of single charges of the explosive. With this purpose on the construction site by square net (5×5m) there will be drainage-explosive boreholes 0.35…0.4 m in diameter, the plastic pipes 100 mm in diameter are dropped into them, for further location of charges of the explosive. The annular space is filled with crushed stone, the boreholes are connected by trenches and artificial saturation of soil is performed with filling of its pores with water not less than up to 80%. (Fig. 3)

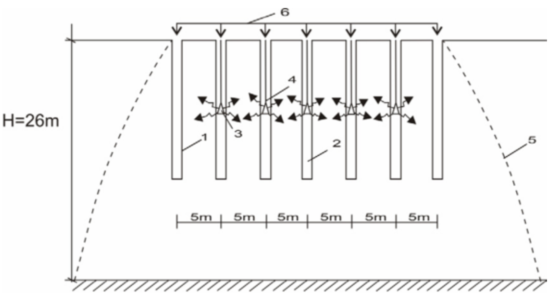

Figure 3. Cutting by the construction site: 1 – drainage borehole; 2 – drainage-explosive borehole; 3 – charge of the explosive (CE) of collapsible stratum; 4 – plastic pipe for supply of CE; 5 – contour of soil moistening; 6 – inventory system for water supply; H – thickness of collapsible soils.

Mass of single deep charge is calculated by the formula:

$$q = (\frac{H}{\chi})^3 \frac{1}{e}, \tag{1}$$

where H – thickness of the watered collapsible stratum, within which the soil structure for sure is damaged by deep charge; χ – coefficient, which depends on soil thickness in dry state and laying depth of the concentrated charge; e – efficiency coefficient of the explosive.

The charges are located in depth, where the condition of camouflet blast is performed.

The blast causes the intensive deformations of soil in the radius of area of soil structure distortion, which is determined by the formula:

$$R_н = \kappa_н \sqrt[3]{qe}, \tag{2}$$

where $\kappa_н$ – coefficient, which depends on soil thickness in dry state and determined experimentally.

Action of dead weight and dynamic load on loessial soils causes the failure equilibrium between porosity from one side and stress and moisture degree from another, which was stated during their genesis. Soil consolidation arising in this condition generally owing to the dead weight reflects its transformation to new equilibrium state and is accompanying with water release and reduction of its filtration capacity. After consolidation the settling equals 10-12% from capability of collapsible strata (Fig. 4).

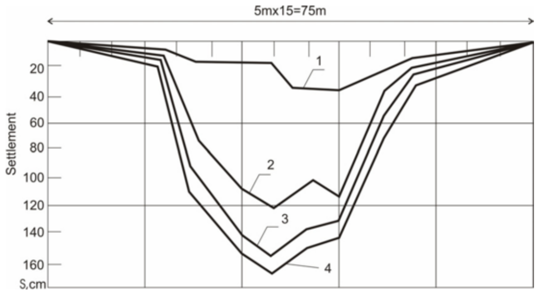

Figure 4. Epure of soil surface settlings, which was consolidated by hydroblast. 1 – after artificial saturation of soil; 2 – after explosions; 3,4 – after 0.5; 1.5 months after explosion.

For the design of structures, which worked together with subsoil, in NIISK (Dr. S.N. Klepikov, 1975-1990) developed multipurpose design (elastic and inelastic) rigidity floating factor model, which considers the soil distributive elastic properties beyond the load applying, and at this inelastic (plastic) deformations are considered non-rehabilitative. This model is characterized like variable factor of rigidity as regards foundation, which allows to consider completely the real properties of subsoil, and gives design results, which provide essential strength and steadiness of erected objects. On basis of this model the electronic computer programs.

For exceeding of determination accuracy of bearing capacity and expected subsoil deformation values in NIISK (Dr A.M. Ryzhov, 1995) developed critical state model and method of determination of potential soil deformations; the procedure of soil strengthening trials taking into account their dilatancy is given and the issues of soil dynamics with reference to soil strata consolidation by preliminary artificial saturation with explosion energy appliance were investigated.

One of the significant construction directions on loessial collapsible soils are the problem of existing building reconstruction (structures), damages or deformations originated on the soils, which have as a result of non-uniform settlings (collapses) of their base. With purpose of stopping of the further deformation progress, and if it is necessary changing of architectural-construction structure of such objects by way of superstructure, dependency and so on, methods of soil fixing (strengthening) by existing foundations are developed and widely applied:
- DSM (deep soil mixing) technology;

- alkalize mortar injection method;
- electrochemical method.

DSM technology are realized by mixing of loessial with cement (5-15%). Small-size equipment allows to fix soils from low basement.

Electrochemical loessial soil fixing method based on the passing of direct electric current between two electrodes. Ground water moves from anode (+) to cathode (-), that realize the soil desiccation (electrokinetic processes). At further current passing owing to electrochemical processes new chemical compounds with participation of electrode metal, which cement soil particles (Trushynskyi, 1993) are created.

Investigation of electrochemical fixing method for water saturated loessial soils was carried out during hospital reconstruction in Poltava city. Strip foundation base is loessial grey silty clay, heavy dusty, soft, with capacity 3,9 m.

Soil fixing was carried out with help of the steel rod-electrode, dipped along the strip foundation edges (Fig. 5), through which the electric current with periodical changing of electrode polarity was passed.

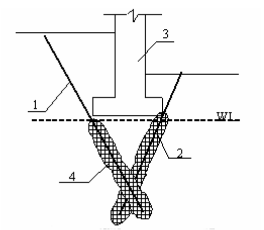

Figure 5. Scheme of base reinforcement by rod-electrodes: 1,2- ∅20 A1 8 mm and 5 m correspondently; 3- foundation body; 4 – fixed area.

Fixing results, viz the increase of bearing capacity of steel rod-electrodes during strengthening, estimated by way of dynamic trials. The clearly determined positive results are received. So, the average settling of non-fixed electrodes from 6 hits of the load equals 20-25 mm, and after passing 100 kW/per hour – 2-4 mm.

Soil fixed area around the electrode was studied by using the penetration method and site measurements after unearthing of fixed elements.

As a result of performed investigations the data concerning dimensions and structure of “action area” at electrochemical fixing of water-saturated loessial soil. Near the rod-electrode three areas are picked out: I – area of fixed soil with the size of 5 diameters of the rod, the specific resistance of penetration ($R_п$) in this area is decreasing proportionally of the distance form rod from 36,7 $R_п$ to 10 $R_п$; II – transition area with width equals to the rod diameter, the specific resistance of penetration decreases there from 10$R_п$ up to $R_п$; III –natural soil area with specific resistance of penetration - $R_п$.

In soil grading the amount of dust particles significantly increased, that testified about the generation of new aggregates from clay particles owing to their cementation. Cements are the hydrates of iron oxide, aluminium and calcium. Structural ties between particles, originated with their help, stood the action of 10% mortar of natrium pyrophosphate, 20% of which was added to the distilled water, and further boiling. This testifies about irreversibility of ties, received during the fixing. In the Table 1 the resistance of some values for nature and fixed soil are shown.

Table 1: Basic results of soil fixing by electrochemical method

Soil characteristics	nature	fixed
moisture at the border of yielding, W_L, %	35	29
moisture at the border of rolling, Wp, %	20	19
plasticity index, I_p, %	15	10
soil specific weight γ, kN/m^3	18,6	19,1
angle of soil internal friction, φ^0	16	18
specific cohesion , c, kPa	17	48
deformation modulus, E, MPa	3	10

The decreasing of borders and plasticity amount corresponds to the soil grain composition of fixed soil. Specific cohesion increased owing to the action of electrochemical processes, owing to the generation of the additional insoluble cementing ties; correspondently, the corner of the internal friction and specific weight increased a little bit, the soil deformation module increased significantly.

Owing to the future study of waterlogging territories the laboratory investigations of fixing effectiveness of water saturated loessial soils are carried out by method of alkali mortar injection. Soil samples were selected to the rings with square 40 cm^2 and 3.5 cm in height. For the alkali saturation the rings were placed to the filtration devise, delivered to the soil 20 cm^2 of 5H alkali mortar NaOH and located them in moist desiccators for 7, 14, 21 days.

The fixing effect was estimated with laboratory penetrometer, equipped with steel conical rod end with conicity angle equals 30^o. Loads on the rod end were applied in 8-10 steps. Each step the loads were kept on for 60 s, after that the depth of the deeping to the soil of the rod end up to 0,1 mm.

For each exposure time of fixed soil was placed to the desiccator for 6 rings. Thus, the penetration specific resistance amount for each lot considering penetration from the end face and incisor installed for 12 to the parallel trials. The variation factor for each lot varied within v = 0.07 – 0.09.

Specific resistance of penetration R has the characteristic of invariance. It means, that for homogeneous soil during test carrying out according to the accepted process scheme the diagram of penetration has the form of straight line, which passes near the origin of coordinates. (Fig. 6). All diagrams are differed by the clear invariance of the specific resistance of penetration (experimental points group exactly at averaging straights), that testifies about the homogeneity of soil fixing along the depth of the sample. This is the sufficiently high variance factor during establishment R that testifies about the solidity of soil fixing.

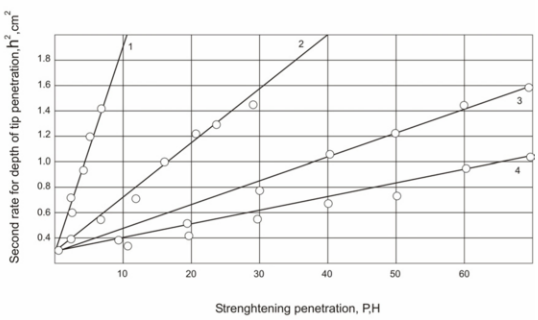

Figure 6. Diagrams of penetration of loessial silty clay, fixed by method of the alkaling: 1 – direct after fixing, R=0,4 MPa; 2 – after 7 days, R=2,1 MPa; 3 – after 14 days, R=4,5 MPa; 4 – after 21 days, R=7,1 MPa.

Taking into account the fact that the specific resistance of the penetration, R, is the generalized characteristic of soil mechanic properties, it is possible to state about the soil strengthening owing to the alkaling in about 18 times.

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