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Improvement of loessial soil properties by presoaking and explosive energy of subsurface charges

Amélioration des propriétés des sols de lœss par préhumidification et par énergie d‘explosion des charges profonds

Krivosheev P.
State enterprise «State Scientific Research Institute of Building Constructions», Kyiv, Ukraine

Shokarev V., Marienkov M., Shokarev A., Shapoval V.
State enterprise «State Scientific Research Institute of Building Constructions»,
Kyiv, Zaporizhzhia, Ukraine

Gabibov F.
Azerbaijan Scientific Research Institute of Construction and Architecture, Azerbaijan

ABSTRACT: Compaction of loessial subsiding soil by presoaking and explosive energy of subsurface charges (hydroblasting) makes it possible to eliminate soil subisdential properties and to improve their physical and mechanical characteristics. An experience of up to 30 m thick loess soil compaction in Zaporizhzhia city (Ukraine) in the process of foundation preparation for 9- and 10-storied large-panel residential buildings has been described. The buildings were constructed after replacement of the upper (undercompacted) soil layer by a groundbed. During building installation and the first year of operation 83% of recorded settlements are manifested taking into account installation settlements, and 93% of recorded settlements are manifested during the second year of operation. Nature of separate bays settlement on partially consolidated foundation is a function of settlement stabilization degree under soil net weight, foundation length, rate of load application on the foundation. Provided a foundation compacted by hydroblasting method stress in reinforcement of 10-storied residential building wall panels at 6 points aftershock impact is reduced by 4-7 times; stress in vertical bonds (springs modelling earth foundation) is reduced by 5 times. Seismic stability of a building (taking into account reduction in rigidity of wall panels having suffered damage du to non-uniform deformation of a foundation) has been achieved.

RÉSUMÉ: Compactage des sols de lœss affaissés par préhumidification et par énergie d‘explosion des charges profonds (hydro-explosion) permet de supprimer l‘affaissement des sols et d‘améliorer leurs caractéristiques physiques et mécaniques. L‘expérience de compactage des sols de lœss d‘épaisseur de 30 m dans la ville de Zaporizhzhia (Ukraine) au cours de préparation des fondations pour des bâtiments résidentiels de grands panneaux à 8-9 étages a été décrite. Les bâtiments ont été construits après le remplacement de la couche superficielle (non suffisamment compactée) par un matelas en sol. 83% de tassements enregistrés ont lieu pendant le montage d‘un bâtiment et au cours de la première année d‘exploitation, et 93% de tassements ont lieu au cours de la deuxième année d‘exploitation. La nature de tassement de certains blocs-sections sur une fondation partiellement consolidée est la fonction du degré de stabilisation de tassement par rapport au poids net du sol, à la longueur de la fondation, à la vitesse d‘application de charge et à la qualité de compaction du matelas en sol. Lorsqu‘il y a une fondation compactée par la méthode d‘hydro-explosion, les efforts dans les armatures des panneaux-murs d‘un bâtiment résidentiel à 10 étages déclinent de 4-7 fois sous l‘effet du choc consécutif d‘intensité de 6 point et les efforts dans des raccordements verticaux (des ressorts modulants le sol de fondation) déclinent de 5 fois. Résistance du bâtiment aux séismes est assurée compte tenu de réduction de rigidité des panneaux-murs ayant été détériorés suite aux déformations différées de la fondation.

Keywords: hydroblasting, compaction, settlement, soil consistency

1 FOREWORD

Nearly 80% (483 thous. km^2) of the territory of Ukraine is covered by loessial soils which are caracterized by high original porosity, low moisture content and high percentage of silt. In the area of Middle Dnieper Region with historically contingent large industrial zones and social structures where major construction works are vigorously conducted, expansion of loessial subsiding soils with a thickness of 15-30 m is observed. Loessial layers occur primarily on reddish-brown clay and on crystalline rock and are characterized by well-pronounced alternation of non-homogenous loesses, loessial loams and sandy loams (Zocenko, 2005).

Soaking of loessial soils is accompanied by subsidental deformations up to 1.0 meter and buildings and structures erected on such soils without special foundation preparation are subject to significant differential settlements.

According to design and construction practice, safe operation of buildings and structures erected on loessial subsiding soils is ensured by elimination of subsiding soil properties within the whole soil layer.

One of the prospective methods of foundation preparations for conducting construction works on loessial subsiding soils is pre-soaking with subsequent use of explosive energy of subsurface charges (Litvinov, 1977).

Compaction of loessial subsiding soils by pre-soaking and explosive energy of subsurface charges (hydroblasting) is used during proactive construction site preparation.

This method is widespread in Ukraine due to its simple technology, high degree of soil compaction and low cost of foundation preparation. The total number of foundations having been compacted by hydroblasting method makes 350 (Fig. 1).

Figure 1. Compaction of loessial subsiding soils by hydroblasting method

The essence of the method of loessial sols compaction by pre-soaking and explosive energy of subsurface charges consists in soils structural bonds weakening up to yield point and in explosion blasting of single charges performed at a specified depth and at a scpecified distance from each other. Soils characterized by medium-textured loams and sandy loams with dry density less than 14,5 kN/m^3 are compacted the most effectively.

2 RESEARCH ON BEHAVIOUR OF LOESSIAL SOIL BODIES AT HYDRO-BLASTING COMPACTION.

Researches were conducted on sites situated in residential area 16 of Khortytskiy district of Zaporizhzhia city (Fig. 2).

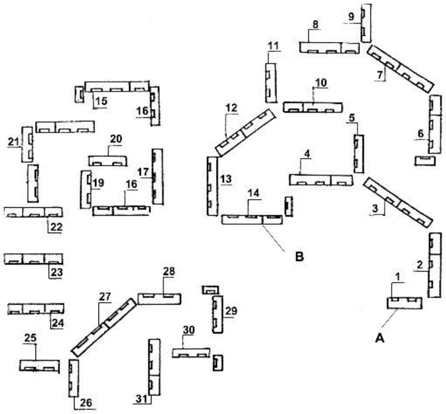

Figure 2. Site for researches on compaction of loessial subsiding soils by hydroblasting method: 1-31 - numbers of residnetial buildings; A - a separate bay; B - settlement joint

In order to prepare foundations of residential buildings No. 1 to 31, drainage holes and drainage-blasting holes of 20 meters deep and 350-400 mm in diameter were drilled on each site at intervals of 5x5 m. 15 m long plastic pipes of 100 mm in diameter were put into the holes for subsequent placement of explosive charges (Fig. 3a). Hole clearances were filled with crushed stone. Soil body was soaked within 40-60 days until humidity degree not less than 0.8 was attained. Water was supplied to holes through trench and piping system.

Water amount (m^3) necessary for soil pre-soaking is calculated as per the following equation:

$$Q = mnV(0.8 - S_r), \tag{1}$$

where m - coefficient that takes into account irregular absorption of water by soil; n, S_r, V - weighed average values of natural texture soil porosity, of humidity degree and of moistened soil volume.

Weight of a single subsurface charge is calculated as per the following formula:

$$q = \left(\frac{H}{\chi}\right)^3 \frac{1}{e}, \tag{2}$$

where H - thickness of a soaked subsiding soil body within which soil structure damage is certain due to explosive energy of subsurface charges; χ - coefficient that depends on dry density of soil and depth of charge laying; e - performance coefficient of an explosive.

Explosive charges are laid at such depth where camouflet explosion conditions are met. Minimum depth is calculated as per the following equation:

$$h = 8.2 k_{\text{в}} k_{\text{гр}} \sqrt[3]{q}, \tag{3}$$

where $k_{\text{в}}$ - coefficient that depends of the explosive type; $k_{\text{гр}}$ - coefficient that depends of the soil type; q - charge weight.

Blasting of explosive charges weighing up to 15 kg provoked severe soil deformations in a radius of soil structural damage zone calculated as per the following formula:

$$R_{\text{н}} = K_{\text{н}} \sqrt[3]{q \cdot e}, \tag{4}$$

where $K_{\text{н}}$ - coefficient that depends on dry density of soil determined by tests.

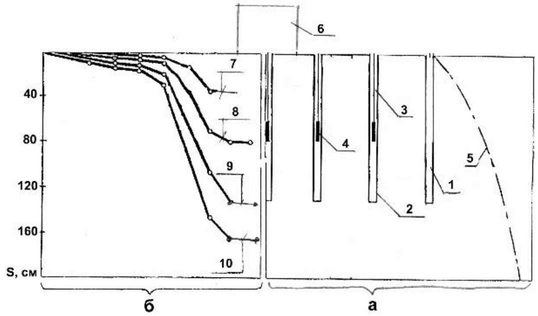

Figure 3. Cross section of the site under research (residential building No. 16). a - layout of foundation perparation by hydroblasting method; b - soil surface deformation curves:

1 - drainage hole; 2 - deainage-blasting hole;3 - plastic pipe; 4 - explosive charge; 5 - outline of moistened soil body; 6 - designed building; 7 – deformations after soil pre-soaking; 8 - 1 day after blasting operations; 9 - in 1 month; 10 - in 3 months.

Dynamic loads on loessial soils lead to disturbance of a balance established in the period of their genesis between porosity on the one part and stress and humidity degree on the other part. Soil compaction taking place during this process (mainly owing to its net weight) shows soil transition to a new balanced condition and is followed by squeezing water out on the soil surface (Table 1).

Table 1. Results of researches on deformation of soils compacted by hydroblasting method

Residential building No.	Subsiding soils		Average soil deformations after subsurface explosions, cm					Average building settlement in the process of installation and after 2 years of operation, cm	Total settlement, cm
	Soil layer thickness, m	Subsidence, cm	Days						
			1	5	20	40	80		
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	26.0	51.0	77.5	88.9	98.8	103.8	108.8	16.0	124.8
2	26.5	56.0	69.2	86.0	100.5	107.9	115.0	26.1	141.1
3	28.0	55.0	54.7	71.2	85.4	92.5	99.6	18.5	118.1
4	29.5	58.1	73.8	93.5	110.5	118.9	127.4	16.2	143.6
5	28.4	58.0	57.2	75.7	91.7	99.6	107.6	7.0	114.6
6	24.9	42.9	83.6	96.2	107.1	112.5	117.9	17.5	135.4
7	26.0	44.0	88.3	109.2	128.7	138.0	147.3	19.9	167.2
8	26.7	44.2	34.1	52.4	68.2	76.1	84.0	22.5	106.5
9	26.7	44.0	46.3	58.3	68.6	73.7	78.8	14.9	93.7
10	27.0	53.5	71.4	91.6	108.3	117.7	126.4	23.3	149.7
11	27.5	53.0	56.9	74.5	89.7	97.3	104.9	20.4	125.3
12	31.4	70.0	42.3	51.9	60.2	64.4	68.5	21.4	89.9
13	30.5	76.6	51.1	64.3	75.7	81.4	87.1	23.6	110.7
14	30.2	75.2	71.7	87.2	100.6	107.3	114.1	22.0	136.1
15	32.3	71.0	58.5	78.4	95.4	104.0	112.5	35.6	148.1
16	32.6	68.6	76.6	100.1	120.4	130.5	140.6	32.2	172.8
17	32.2	65.2	34.2	46.8	57.6	63.0	68.4	24.0	92.4
18	33.1	67.4	69.4	84.7	97.8	104.4	111.0	30.1	141.1
19	31.0	48.5	73.1	88.2	101.2	107.8	114.3	29.2	143.5
20	31.9	57.1	41.6	54.0	64.8	70.1	75.5	37.5	113.0
21	29.3	57.6	86.2	95.3	103.2	107.2	111.1	38.0	149.1
22	29.8	40.2	30.7	49.0	64.8	72.7	80.6	23.5	104.1
23	31.3	60.5	68.6	83.8	96.9	103.4	109.9	23.7	133.6
24	31.3	57.8	88.1	103.6	117.0	123.7	130.4	27.2	157.6
25	24.9	44.9	98.8	105.8	111.8	114.7	117.8	37.4	155.2
26	23.5	49.5	51.8	65.7	77.7	83.7	89.6	42.5	132.1
27	24.8	43.4	35.8	45.6	54.0	58.2	62.3	22.1	84.4
28	25.2	45.3	24.6	42.5	57.9	65.6	73.3	19.0	92.3
29	29.1	53.1	15.4	37.6	56.7	66.2	75.8	34.1	109.9
30	23.7	45.0	43.9	61.1	75.9	83.3	90.7	17.1	107.8
31	21.8	49.8	22.8	38.1	51.2	57.5	64.4	24.3	88.7

To determine vertical deformations of the compacted soil, geodetic observations were carried out on the site No. 31. Observation network covered 2,440 surface geodetic benchmarks at intervals of 5x5 m. Geodetic observations were carried out from the moment of soil pre-soaking and till the beginning of pit digging (Fig. 3b).

Main results of researches on deformations of loessial soils compacted by hydroblasting are summarised in Table 1.

Time of relative soil stabilization is calculated as per the following formula:

$$T = \frac{tg\rho}{V}, \tag{5}$$

where V - value of soil stabilization conditions, ρ - proprtionality coefficient determined as per the formula:

$$tg\rho = \frac{S - S_{\text{Н}}}{l_n t / t_n}, \tag{6}$$

where S and $S_{\text{Н}}$ - soil surface settlements at t and t_n.points of time.

Soil surface settlements after two hours of blasting opertions make 20% of design settlements, 50% after 24 hours and up to 70% after 7-40 days (Fig. 4).

Figure 4. Site general view after soil compaction by hydroblasting method

3 SETTLEMENTS OF FRAMELESS BUILDINGS ERECTED ON PARTIALLY CONSOLIDATED FOUNDATIONS

In order to investigate factors afecting deformation of partially consolidated foundations of frameless buildings, field geodetic observations of settlements of a group of buildings constructed on foundations prepared by hydroblasting were carried out. Works were performed in residential areas 15 to 17 of Khortytskiy housing district of Zaporizhzhia city during construction and operation of 9- or 10-storied large panel buildings of 96 series with bays 22.2 m, 25.2 m, 48.7 m, 51.7 m, 76.9 m long and 13.9 m wide. Geodetic observations were carried out on settlement of 46 large panel buildings consisting of a series of typical bays varying from 1 to 5 per one building. Total number of bays in the buildings was 100, where 65 bays were 25.0 long, 34 bays were 50.0 m long and 1 bay was 75.0 m long. According to their operation life the bays were calssified as follows: 7 years and more - 14 bays (including 1 bay of 50 m long); 6 years - 23 bays (-); 4 years - 14 bays (8); 3 years - 27 bays (17); 2 years - 16 bays (10); 1 year - 6 bays (where 2 bays of 50 m long and 1 bay of 75 m long).

Structural diagram of 96 series buildings was as follows: bearing crosswalls (claydit panels with thickenss of 350 mm) with junction of inermediate slabs (160 thick, made of heavy-weight concrete) along the outline; crosswalls pitch was 3.0 and 3.6 m, the span was 5.7 and 5.1 m. Floor height was 2.8 m. Foundations were made as a monolithic reinforced-concrete 1.2 m wide slab which was continuous under all outer and partition walls. The bays were divided by 500 mm wide settlement joints.

All buildings were erected after replacement of undercompacted top soil by gdoundbed with a thickness of 2.0 to 6.6 m made from local clay loams. Routine break period between the date of blasting operations and the start of building installation made 3...13 months, in 60% of cases it made 5...6 months and in 80% cases it made 4...7 months. Average duration of a bay installation was 80 days.

Altogether 662 deformation control benchmarks were arranged on the buildings and 8...19 cycles of geodetic observations were conducted at separate objects. Installed buildings settlements were measured after installation of 1...4 floors throughout the whole construction period. During operation of the buildings observations were carried out 1, 6 and 12 months after installation termination and further once a year.

Certain results of performed geodetic suvreys are listed in Table 1. Average settlements of compacted soil bodies under the weights of the buildings made 70...425 mm. Distribution of average settlements by basic cycles was as follows: settlements accounting for installation - 29...244 mm or 53% of total value; settlements accounting for the 1st year of operation - 30...185 mm (30.6%), the 2nd year operation - 6...40 mm (7.2%), the 3rd year of operation - 4...15 mm (3%), the 4th year of operation - 2...13 mm (2.2%), the 5th year of operation - 2...8 m (1.5%), the 6th year of operation - 2...7 mm (1.3%), the 7th year of operation - 2...3 mm (1.1%).

During the first year of operation 83% of recorded settlements are manifested taking into account installation settlements, and 90% of recorded settlements are manifested during the second year of operation. buildings settlements tend to become stable. If the average speed of compacted soil body settlement was 1.88 mm/day or 15.5 mm/floor, then during operation it decreased: during the 1st year - 0.23 mm/day, the 2nd year - 0.055 mm/day, the 3rd year - 0.023 mm/day, the 4th year - 0.018 mm/day, the 5th year - 0.012 mm/day, the 6th year - 0.01 mm/day, the 7th year - 0.0082 mm/day. During the first year of operation settlement speed decreased by 8 times compared to the installation settlement and it decreased by 25...28 times during the next six years.

Dynamics of longitudinal and transversal tilts were examined on the basis of the performed geodetic observations. The following ranges of building tilts were recorded: longitudinal tilt – $0.3\cdot10^{-3}\ldots7.2\cdot10^{-3}$, transversal tilt – $0.7\cdot10^{-3}\ldots10.5\cdot10^{-3}$.

Recorded tilt values for the period of building installation made 3/4 of their maximum values and they reached the maximum during the first year of operation. Tilt buildings didn‘t expand later on and even decreased at certain sites which fact is apparently due to stress redistribution iin the ‚foundation-building‘ system.

Relation between the values of maximum differential settlements (ΔS_{max}) and average settlements ($\bar{S}$) for this class of buildings is linear:

$$\Delta S_{max} = a\bar{S} + в = 0{,}291\bar{S} + 2{,}4. \qquad (7)$$

Visual inspection of settlement joints revealed that in the overall majority of cases their width between separate bays corresponds to the following specification: $a_{ш}=a_{пр}\pm25\%$, where $a_{ш}$, $a_{пр}$ are actaul and design width of a settlement joint.

Nature of separate bays settlement on partially consolidated foundation was a function of quality of soil and groundbed compaction, settlement stabilization degree from soil net weight, foundation length, rate of load application on the foundation etc. Empirical relation between the average building settlement value and the settlement stabilization degree from soil net weight was established. The following was deduced from experiments: 12 months of routine break between the blasting operations and the beginning of building installation instead of 4 months helps to reduce total settlement value by 1.5 times and length extension of bays erected as part of a single building from 25.0 m to 50...75 meters reduces settlement by 1.1...1.2 times; decrease of installation load application rate helps to reduce settlement up to 2 times (Kryvosheyev, 2003).

4 PHYSICAL AND MECHANICAL PROPERTIES OF SOILS COMPACTED BY HYDROBLASTING METHOD

In order to determine degree of soil compaction in depth and to evaluate their physical and mechanical properties, many laboratory tests of soil specimens were performed. Radioactive logging was also used to determine physical properties of soils. Researches were conducted 3…12 months after soil compaction. The following data was recorded during the tests: increase of dry density of soil from 14.1...15.8 kN/m^3 to 15.2...16.2 kN/m^3, decrease of porosity from 47.5...41.4% to 43.4...39.2% and decrease of relative subsidence below the value of 0.01.

It is recommended to use the following parameters as design characteristics of loessial soils compacted by hydrolbasting at the stage of conventional stabilisation: deformation modulus - 10 MPa; internal friction angle - 16... 18°; bond - 0.005 MPa.

In 2017 engineering and geodetic surveys were conducted at the site where soil compaction by hydroblasting method had been performed in 1993, however the designed building hadn‘t been constructed.

According to the results of engineering and geodetic surveys, geotechnical structure of the construction site from the daylight surface to the explored depth of 35.0 m was made up of early and late quaternary sandy-loam loessial soils superposing sandy-clayey Neogene soils (Fig.5).

For the period of field works, groundwaters from the daylight surface to the depth of 35.0 m were not exposed.

Based on the data obtained concerning determination of dry soil density of all the soil layers detected at the construction site and following a comparative analysis using overall average density values of dry soils at the construction site location the following can be noted:

- soil layers No. 3-7 experienced maximum compaction; dry density in these layers changed from 13.49…14.81 kN/m^3 to 14.96…17.31 kN/m^3;
- increase in dry density of soil layers No. 8-11 from 16.19…16.97 kN/m^3 to 16.43…18.30 kN/m^3 was observed;
- soil compaction of layer No. 2 was insignificant, these soils being completely in undercompacted zone (Fig. 5).

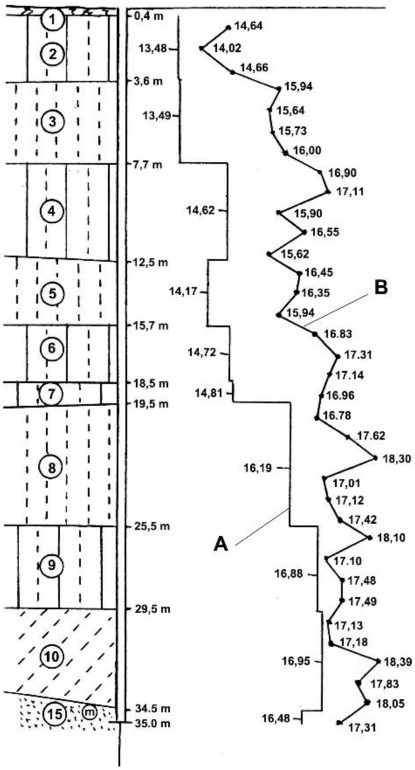

Figure 5. Diagram of dry soil density variations at depth (kN/m^3). A - prior to soil compaction; B – after soil compaction by hydroblasting method (24 years later):

1 - chernozemic soils; 2 - solid yellow-brown loessial loams; 3 - solid yellow-brown sandy loams; 4 - solid brown and yellow-brown loessial loams; 5 - semi-solid yellow-brown loessial sandy loams; 6 - semi-solid rust-coloured loessial loams; 7 - solid grey bottom loessial loams; 8 - semi-solid brown and yellow-brown loessial loams; 9 - solid brown, reddish-brown loessial sandy loams; 10 - solid reddish-brown loessial loams; 11 - solid yellow-grey, yellow-brown and reddish-brown sandy loams; 12 - grey and yellow fine sand

During the period of surveys in 1991, loessial soils of the construction site had subsidential properties when soaked. Thickness of subsiding soil column at the construction site was 29.0…32.4 m, overall soil subsidence under soils net weight when soaked was 96.4…118.5 cm.

Residual overall soil subsidence could be 9.03…10.84 cm, i.e. foundation soil subsidence under soil net weight decreased more than tenfold.

5 NUMERICAL STUDIES OF NON-LINEAR STATIC MODEL OF A 10-STORIED RESIDENTIAL LARGE-PANEL BUILDING FOR 6 POINTS AFTERSHOCK IMPACT

Standard intensity of seismic impact of the territory of Zaporizhzhia city is 5 point on MSK-64 scale.

A building is designed on shallow foundation. A compacted groundbed with the following parameters is a base surface: deformation modulus - 20.40 MPa, density - 17 kN/m^3, porosity coefficient - 0.55, liquidity index - 0.09. Stress-related characteristics of loessial soils compacted by hydroblasting method were adopted according to engineering and geodetic surveys conducted in 2017 (chapter 4).

The following dynamic linear simulation models were studied:

- a simulation model with deformation modulus of class C20/25 concrete E_{ck} = 26000 MPa in bearing structures (panels and slabs) without taking into account cracks provoked by seismic impact (aftershock woth 6 points of intensity);

- a simulation model with deformation modulus of class C20/25 concrete E_{cd}= 12600 MPa in bearing structures taking into account cracks provoked by seismic impact.

Seismic impacts were applied to a building crosswise. When designing a non-linear model of a 10-storied large-panel residential building on a foundation compacted by hydroblasting in order to study aftershock impact of 6 points intensity (seismic loads should be determined by spectral method), maximum values of storey drifts made 0.007. Maximum design values of a bay top displacement during 6 point aftershock impact made 18 mm. Width of an aseismic joint between contiguous bays of a residential building should not be less than 40 mm (deformation width as per the project was 500 mm). Analysis of the listed estimated data confirmed that provided a compacted foundation stress in reinforcement of a 10-storied residential building wall panels at 6 points aftershock impact is reduced by 4-7 times; stress in vertical bonds (springs modelling earth foundation) is reduced by 5 times (Marienkov 2018).

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