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Investigation of hydrogeomechanical parameters of loess massifs in conditions of technogenic underflooding and development of technical recommendations for strengthening of bases of foundations

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Abstract. Based on the analysis of actual data and the results of numerical modeling, dependencies of deformations of the investigated residential complex due to technogenic moistening of a loess massif of soils are investigated. It was established that a dynamics of subsidence of bench marks in time is closely correlated with a moistening mode. In order to form a picture of dynamics of development of moistening phases of the massif

and a quantitative estimation of main factors of their formation, a numerical model of the loess massif was built, based on the finite element approximation of the section of built-up area of the residential complex. Stability of a soil massif was estimated by the character of development of plastic deformation zones. Analysis of a stress-strain state of a rock massif indicated that water-saturated soils are partially in a state of plastic flow in a base. The development of shear deformations is most characteristic within a zone of the main moistening, as well as a boundary of its front. Development of rupture disturbances at the edge of the contour of buildings corresponds with the formation of tear cracks. An intensification of subsidence of buildings with simultaneous frontal and subvertical technogenic moistening of loess soils can be noted. Model estimations of a stress-strain state of the pile foundation, considering the uneven subsidence that occurred along the perimeter of residential buildings, show that the elastic mode of their deformation has not been exhausted. Options of redistribution of loads from residential sections onto an additional pile field, regulated base moistening and grouting of soils are considered as engineering measures to prevent further deformation of the residential complex. Stabilization of a soil base by means of high-pressure cementation is the most acceptable in the present conditions. Technological scheme of cementation of the soil base is recommended, as well as measures after the base stabilization, such as monitoring of further deformations of the complex itself and parking structures, and possibilities of constructing auxiliary drainage.

Keywords: loess massif, deformations, groundwater, hydrogeological conditions

Дослідження гідрогеомеханічних параметрів льосових масивів в умовах техногенного підтоплення та розробка технічних рекомендацій щодо посилення основ фундаментів

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Анотація. На підставі аналізу фактичних даних і результатів чисельного моделювання досліджено закономірності деформацій житлового комплексу внаслідок техногенного зволоження льосового масиву ґрунтів. Встановлено, що динаміка осідання реперів в часі тісно корелює з режимом зволоження. Для формування картини динаміки розвитку фаз зволоження масиву і кількісної оцінки основних факторів їх формування була побудована чисельна модель льосового масиву, на основі кінцево-елементної апроксимації ділянки забудованої території житлового комплексу. Стійкість ґрунтового масиву оцінювалася за характером розвитку зон пластичного деформування. Аналіз напружено-деформованого стану породного масиву показав, що обводнені ґрунти в основі частково знаходяться в стані пластичної течії. Розвиток зсувних деформацій найбільш характерний в межах зони основного зволоження, а також межі її фронту. Розвиток розривних порушень у кромки контуру будівель відповідає формуванню тріщин відриву. Відзначається активізація осадок будівель при одночасному фронтальному і субвертикальному техногенному зволоженні льосових ґрунтів. Модельні оцінки напружено-деформованого

стану свайного фундаменту з урахуванням нерівномірних осадок, які відбулися по периметру житлових будинків показують, що пружний режим їх деформування не вичерпаний. Як інженерні заходи щодо запобігання подальшим деформаціям житлового комплексу розглянуті варіанти перерозподілу навантажень від житлових секцій на додаткове свайне поле, регульоване зволоження основи і тампонажне закріплення ґрунтів. Найбільш прийнятно в умовах, що склалися, зміцнення ґрунтової основи способом високонапірної цементації. Рекомендована технологічна схема цементації ґрунтової основи, а також заходи після зміцнення основи, такі як моніторинг подальших деформацій самого комплексу і конструкцій паркінгу, можливості споруди супутнього дренажу.

Ключові слова: льосовий масив, деформації, підземні води, гідрогеологічні умови

Introduction. An analysis of engineering and hydrogeological conditions of a territory of the city of Dnipro, a mode of groundwater and a state of their balance indicate the complexity of a mechanism of forming of a process of underflooding within the city. At the present date, underflooding of an urban area is a sufficiently developed phenomenon which is observed practically everywhere, as in areas with a lowered relief and permeable sandy soils (left bank and lower terraces of the right bank), and within the right bank with higher marks of earth surface and loess rocks with low permeability. It is known that loess rocks are practically widespread in Dnipropetrovsk oblast occupying 69.8% of its territory ($22.28 \cdot 10^3 \text{ km}^2$) (Mokritskaya, 2013, Sadovenko, 2012). They demonstrate significant subsidence deformations at additional loads and subside under their own weight during moistening, which is the prevailing factor among the causes of activation of landslide processes in recent years. The dominant influence of a rise of groundwater level on conditions of construction and operation of already built-up territories determines the necessity of performing design and research work on prediction of a state of rock massifs and justification of corresponding protective measures.

That is why prevention of occurrence of underflooding and landslide processes in areas of spreading of loess rocks requires a development of recommendations for a timely detection and elimination of dangerous zones, considering the features of technogenic loading of massifs. Prevention and elimination of these physical and geological phenomena in specific objects enable saving considerable funds at stages of planning, construction and operation of engineering structures located on loess soils.

Materials and methods. *Therefore, the purpose of this paper* is to justify hydrogeomechanical parameters and to develop technical recommendations for works on strengthening the bases of foundations, which allow controlling, predicting and managing processes occurring at a base of a building and a loess massif as a whole in real time. *Methods of research* – systematization of geological and hydrogeological data, factor-range analysis of parameters, numerical modeling of

geomechanical processes, engineering analysis of technical situations.

Geological and hydrogeological characteristic of the object. The investigated residential complex consists of two residential sections and parking. Residential sections (eleven- and fifteen-storey) are built on a wall constructive scheme with cross-bearing walls. Parking is constructed on a framework constructive scheme of monolithic reinforced concrete.

Residential sections are erected on a pile foundation – friction piles with a widened base with length of 20-27 m. The foundations of parking are erected on a dense cushion of thickness of up to 2 m from a blast-furnace slag. The backfilling of cavities of a pit is made with fill-up ground with an inclusion of construction waste. From three sides of the residential complex at a distance of 5.0-15.0 m from the outer walls underground water-bearing communications with a diameter of 100...400 mm (water pipeline, sewage, storm drainage) are located. The residential complex started operation in 2004 with connection to all engineering communications and autonomous heating. Responsibility class of the building is II, safety coefficient for the intended purpose – 0.95.

The territory in terms of engineering-geological conditions relates to the second category of complexity. In a geomorphological aspect, the site is related to the right-bank terraced slope of the valley of the river Dnipro. The natural relief is changed during a construction of the complex. The general slope of the surface is in the south-east direction towards the river.

The geological section to a depth of 43.0 m is represented by a complex of interstratifying loess clay sands and loamy soils, which are underlain by sandy soils and hard rocks. From the day surface, the covering deposits are overlaid with bulk deposits and soil and vegetation grounds with a thickness of 0.7-7.4 m.

Underground waters of a non-pressure water-bearing complex lie at a depth of 31.4-32.0 m from the day surface. The site relates to a category of non-flooded by groundwater in terms of geological and hydrogeological conditions. Presence of a technogenic horizon (perched water table) was noted at a depth of 5.1 m in bulk soils in the soil moistening zone. The chemical composition of

water of a technogenic perched water table indicates that it is a contaminated tap water (Nauchno-tekhnicheskii otchet, 2010).

Surveys revealed and outlined a zone of moistened soils due to leaks of water from underground water-bearing communications. Almost the entire building of a parking lot, a high-rise fifteen-storey section and partially an eleven-storey section were in the boundaries of a moistened zone at the time of surveys (Nauchno-tekhnicheskii otchet, 2010). Stratum is divided into nine engineering-geological elements (EGE).

Moistening mode of soils is disturbed. In the moistening zone, the soils have a much higher moisture content than outside of the moistening zone: in clay sands of EGE-3 by 5-13%, in loamy soils of EGE-4 by 3-10%, in clay sands of EGE-5 by 7-10%, in loamy soils of EGE-6 by 5-7%, in clay sands of EGE-7 by 5-9%, in clay sands of EGE-8 by 3-6%. Clay sands transferred into plastic and fluid state, loamy soils into a low-plastic, high-plastic and very soft plastic state.

Moistening of loess soils caused deterioration of physical properties of soils (moisture content, consistency, and density), decrease of deformability characteristics by a factor of 1.68-3.77 (coefficient of compressibility variability) and strength by a factor of 2.6-4.3, subsidence properties of soils manifested.

The total subsidence of soils outside the moistening zone under natural pressure is 54.73 cm, the type of soil conditions in terms of subsidence is the second. The thickness of subsided soils reaches 31.25 m.

Results and discussion. *Modeling of deformation dynamics of the base and the object condition.* Since March 2010, uneven subsidence of foundations of residential buildings and parking with manifestation of rupture strains and tilting was visually and instrumentally recorded. Subsidence values varied from 0 to 192 mm as of 02.25.2011. The highest concentration of subsidence of bench marks is traced within the contour of a zone of technogenic moistening at a conjugation of parking and a fifteen-storey residential section (Fig.1).

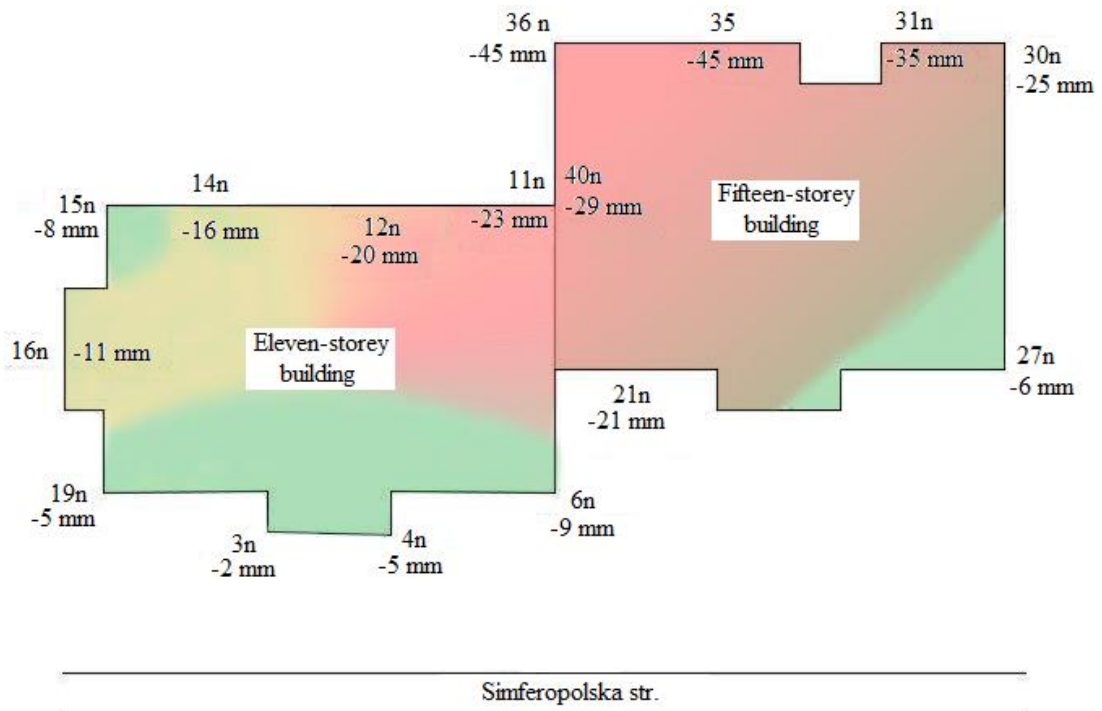


Fig. 1. The plan of installation of bench marks on the residential complex and the subsidence as of 09.17.2018: 3n-37n – the number of bench marks with an instrumental measurement of subsidence (red zones indicate the maximum subsidence of buildings, green – the minimum)

At the first and second levels there is a regular tilt at the ceiling towards the fifteen-storey section of a residential building. The estimated values of the tilt at the ceiling of parking in the zone of maximum deformations are 0.0056 decimal units (parking – fifteen-storey section) and 0.003645 at the ceiling of the fifteen-storey section. The value

of an estimated tilt of the 11-storey section is 0.00323 decimal units.

Horizontal, inclined and vertical cracks in a ground floor part, detachment and local destruction of a building blind area along the entire perimeter of walls, inclined through cracks in joints between the foundation blocks in an underground part of supporting walls, through cracks along the entire

height of the floor in internal self-supporting walls and supporting walls as a result of estimation of a technical condition of building structures of the parking. Separate cracks in horizontal and vertical elements of a framework, cracks in the places of connection of the floor with walls and the place of a local subsidence of a floor of a parking lot, cracks in the places of connection of roof structures with the parapet.

Inconsistencies with the project during the installment of a soil cushion are identified. Based on geological surveys, the soil cushion consists of blast-furnace slag with minor inclusions of bulk soil. There is no soil cushion in the bore hole located 1.0 m from the outer wall of the parking lot.

In order to form a picture of dynamics of development of moistening phases of the massif and a quantitative estimation of main factors of their formation, a numerical model of the loess massif was built, based on the finite element approximation of the section of built-up area of the residential complex. Dimensions of the model are defined with the condition of minimizing the influence of its contours on a stress-strain state of the modeled area and cover an area of 80 m in length and 42 m in

thickness of soil. Soil massif is broken into a network of triangular elements in accordance with the geological and lithological structure of the massif along the section line with the greatest deformations of structures. Zero displacements are also set at the side boundaries of the model and along its lower contour corresponding to the sand bottom. According to the documentation, it is known (Nauchno-tekhicheskiy otchet, 2010) that the residential sections were erected on friction piles of length from 20 to 27 m with a widened base. Based on this, the model was given a one-piece foundation, equivalent in load to the impact of pile foundation. The force interaction between the elements of the model was ensured by the action of gravitational forces caused by the weight of a soil strata and structures.

The numerical model consists of 9 engineering-geological elements, including zones of spreading of technogenic moistening (Fig. 2), which is divided into three phases. Fig. 2 shows the final position of soil moistening phases, which are connected with the period of the most intense leaks during accidents of water-bearing communications.

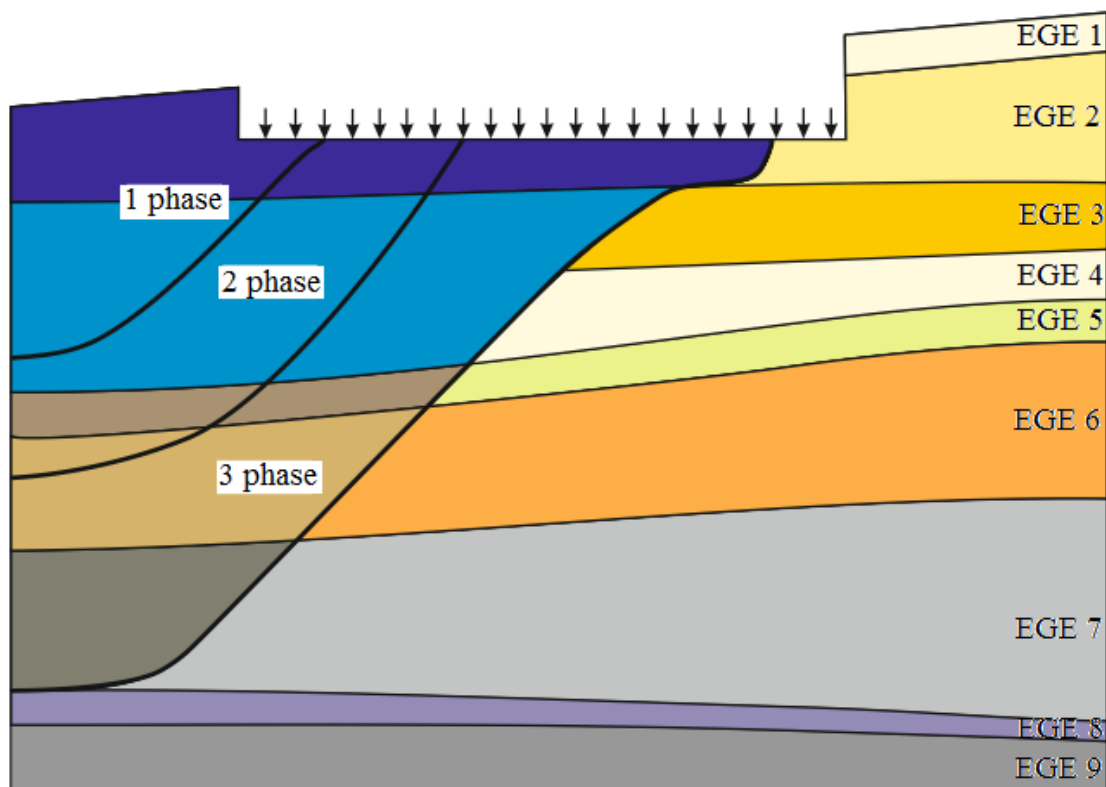


Fig. 2. Geological section with phases of technogenic moistening of the modeled area (I-III – moistening phases): 1 – bulk soil, 2 - 7 – upper quaternary deposits of the loess complex; 8, 9 – lower quaternary alluvial quartz sand

Stability of a soil massif was estimated by the character of development of plastic deformation zones. Analysis of a stress-strain state of a rock massif indicated that water-saturated soils are partially in a state of plastic flow in a base (layers 4-

7). The development of shear deformations is most characteristic within a zone of the main moistening, as well as a boundary of its front. Development of rupture disturbances at the edge of the contour of buildings corresponds with the formation of tear

cracks. An intensification of subsidence of buildings with simultaneous frontal and subvertical technogenic moistening of loess soils can be noted.

Analysis of the actual subsidence data and simulation results showed a direct dependency between subsidence activation and seasonal factors. The deformation bursts are related to the autumn-winter periods – an analysis of weather conditions shows that these periods with precipitation, mainly rain, and active snowmelt, coincided with the activation of deformation processes. The subsidence fading phase corresponds with the period of engineering measures for a renewal of water-bearing communications, but the final stabilization of subsidence does not occur. Increased values of subsidence acceleration were recorded after the pilot stage of injection cementation, which overlapped with a seasonal burst.

When performing cementation works, a significant overuse (about 40-45%) of cement slurry was observed in the experimental area compared to the projected use, while the project pressures were not reached. Sub-vertical and vertical cracks, mainly in EGE 4 and 5 were discovered by subsequent engineering and geological surveys, which apparently led to the absorption of cement slurry. Information about the presence of cracks and

cavities formed in the soil under the action of technogenic filtration and vertical movements under the loading of the slope was confirmed by visual inspection of communication wells in the vicinity of the residential area. At the same time, soil accumulations carried out as a result of suffusion processes were also recorded.

According to the method (Sadovenko, Dereviahina, 2012, 2014), which considers structural connections in loess soils, a field of physical gradients of the vertical section of the soil massif was built (Fig. 3), considering three types of energy – undercompaction of rocks, gravitational position and deformations. Intersections of isolines of deformation gradients and isolines of a total potential energy in a loess massif show the position of critical surfaces inside the soil. Predicted deformation zones in a body of the slope with their quantitative characteristic by the magnitude of activation potentials are highlighted according to the normals. Compared to the classical schemes of estimation of stability of a slope massif (Sadovenko, 2012), this model considers the subsidence of loess rocks in the form of a field of potentials with highlighting of predicted zones of dangerous deformation processes.

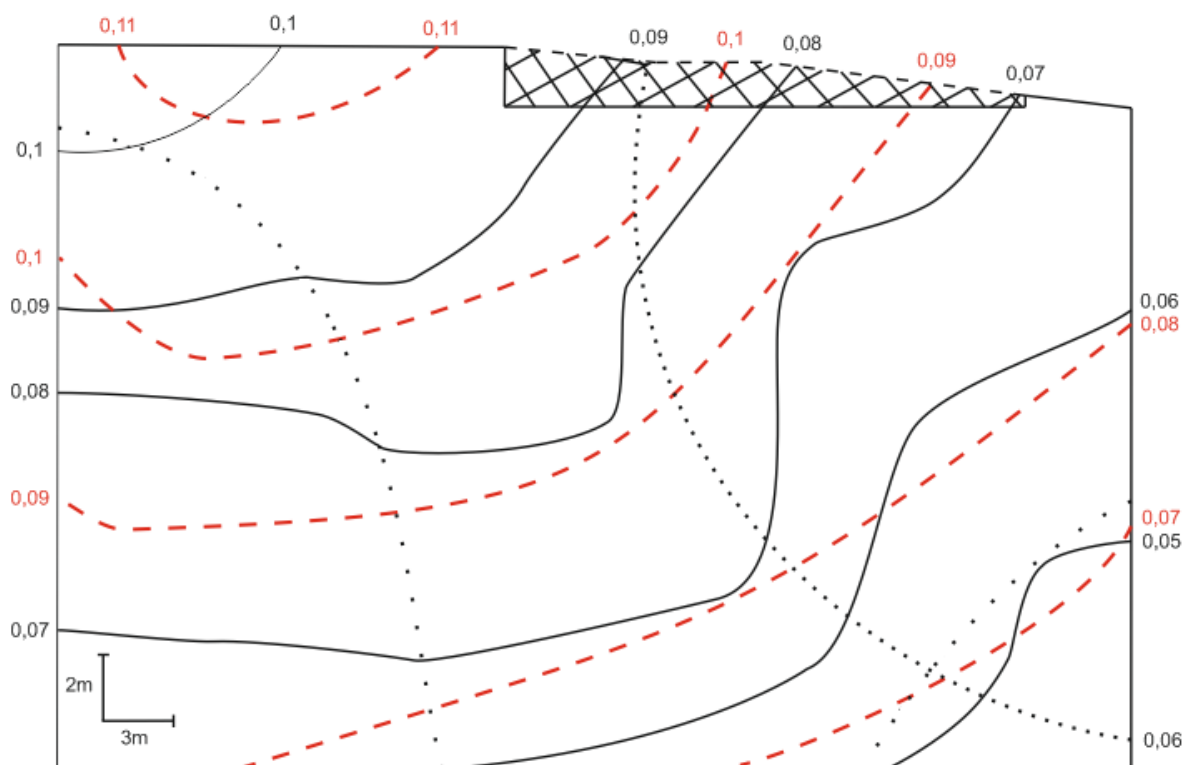


Fig. 3. Isolines: 1- of gradients of energy of a loess slope; 2 --- slope activation potential;- predicted sliding surface; - boundary of technogenic moistening

Presence of cracks and cavities in the massif, formed in a soil under the influence of technogenic filtration and vertical deformations of the slope,

were defined as zones with corresponding values of the rock strength properties. The most dangerous zones are located within EGE 4 and locally within

EGE 5 and 6. Activation potential of the slope in these zones varies within 0.07-0.08. Isolines of energy gradients of the massif have visible extremes in zones of greatest deformations. The boundary value of a gradient of activation potential for a range of potentials of 0.08-0.09 is 0.00125. At this value, processes of deep erosion are activated in the loess massif with the subsequent stage of the flow landslide (Sadovenko, 2014).

Measures to stabilize the deformations of the residential complex. According to the simulation results, it was established that the main cause of deformations of residential sections and parking is the simultaneous frontal and subvertical technogenic moistening of a loess complex of soils, which are of the second type by subsidence. Moistening dynamics is caused by sources of moisture from water-bearing communications that are heterogeneous in intensity and location in space.

The absolute values of deformations are not critical, but the range of their changes led to the occurrence of cracks in bearing elements and the occurrence of tilting of ceilings. At the same time, the state of the structures of residential sections and parking is estimated as satisfactory according to the current standards.

The dynamics of subsidence of bench marks over time are closely correlated with the moistening mode. Subsidence fading phase corresponds to the period of engineering measures for the renewal of water-bearing communications with some delay. In this regard, the final stabilization of subsidence is not expected. This is confirmed by expert calculations (Nauchno-tehnicheskiiy otchet, 2010) of summing up the negative friction forces on the surface of a pile foundation and the occurrence of a concentrated pressure in the base of piles of more than $1.4 \cdot 10^3$ kPa, which can lead to loss of connection of the pile with a widened base.

According to the estimation of modeling of a stress-strain state of the pile foundation, considering the uneven subsidence that occurred along the perimeter of residential buildings, it was shown that the elastic mode of their deformation has not been exhausted.

As engineering measures to prevent further deformations of the residential complex, options for redistribution of loads from residential sections to an additional pile field, regulated moistening of a base and grouting of soils are considered. In the current conditions, stabilization of a soil foundation by the method of high-pressure cementation is the most acceptable (Golovko, 2010, DBN B/1/1-5-2000, Sadovenko, 2002). It was selected that the first stage of stabilization occurs directly under the pile cap, where the greatest subsidence is observed. Considerable experience of such works showed that

in this case there is a moderate increase in a modulus of soil deformation near the piles of up to 2 times and a decrease in porosity of up to 20%, while eliminating subsidence and the effect of negative friction on the side surface of piles. These factors were major in observed processes of deformation of buildings.

The technological scheme of cementation of the soil base was approved to be by intervals from top to bottom (due to unsatisfactory backfilling) and the distribution of injection wells under the pile cap from the most subsided areas to the smallest ones. The discharge pressure is selected in a mode of transition from filtration injection to controlled hydraulic fracturing, which is controlled by the pressure drop and increase in a grouting mix.

The final phase of grouting is a phase of stabilization of the flow and pressure after the hydraulic fracturing, which provides cementing stabilization of zones containing pressed-out water. After performing the cementing stabilization of soil base of residential sections, it is recommended to continue the monitoring of their deformations and parking structures, in order to finally resolve the issue of stabilization of soils under the entire complex.

To ensure reliable operation of the residential complex, the reconstruction of the main water supply system on Simferopolska str. was performed, as well as a drainage well with automatic pumping of water into storm drainage was constructed.

Conclusions

1. The main reason for the occurrence of deformations of residential sections and parking is simultaneous frontal and sub-vertical technogenic moistening of the loess complex of soils, which are of the second type by subsidence. Moistening dynamics is caused by sources of moisture from water-bearing communications that are heterogeneous in intensity and location in space.

2. The dynamics of subsidence of bench marks over time are closely correlated with the moistening mode. Subsidence fading phase corresponds to the period of engineering measures for the renewal of water-bearing communications with some delay. In this regard, the final stabilization of subsidence is not expected. This is confirmed by expert calculations of adverse summing up of negative friction forces on the surface of a pile foundation and the occurrence of a concentrated pressure in the base of piles of more than $1.4 \cdot 10^3$ kPa, which can lead to loss of connection of the pile with a widened base.

3. Model estimations of a stress-strain state of the pile foundation, considering the uneven subsidence that occurred along the perimeter of

residential buildings, show that the elastic mode of their deformation has not been exhausted.

4. Options of redistribution of loads from residential sections onto an additional pile field, regulated base moistening and grouting of soils are considered as engineering measures to prevent further deformation of the residential complex. Stabilization of a soil base by means of high-pressure cementation is the most acceptable in the present conditions.

5. It is recommended that the first stage of cementation is performed directly under the pile cap, where the greatest subsidence is observed. Considerable experience of such works showed that in this case there is a moderate increase in a modulus of soil deformation near the piles of up to 2 times and a decrease in porosity of up to 20%, while eliminating subsidence and the effect of negative friction on the side surface of piles.

6. The technological scheme of cementation of the soil base should be approved to be by intervals from top to bottom (due to unsatisfactory backfilling) and the distribution of injection wells under the pile cap from the most subsided areas to the smallest ones. The discharge pressure is selected in a mode of transition from filtration injection to controlled hydraulic fracturing, which is controlled by the pressure drop and increase in a grouting mix. The final phase of grouting should be a phase of stabilization of the flow and pressure after the hydraulic fracturing, which provides cementing stabilization of zones containing pressed-out water.

7. After performing the cementing stabilization of soil base of residential sections, it is recommended to continue the monitoring of their deformations and parking structures.

8. To ensure reliable operation of the residential complex, it is necessary to consider the possibility of constructing an auxiliary drainage, in order to intercept leaks from the main water supply system on Simferopolska str. In this case, it is possible to construct drainage well with automatic pumping of water into the storm drainage.

References

- DBN B.1.1-5-2000. Budynky i sporudy na pidroblyuvanykh terytoriyakh i prosidayuchykh gruntakh [Buildings and structures in forged territories and subsidence soils] (in Ukrainian)
- Golovko S.I. 2010. Teoriya i praktika usileniya gruntovykh osnovaniy metodom vysokonapornoy tsementatsii [Theory and practice of reinforcement of soil bases by the method of high-pressure grouting]. Porogi, Dnepropetrovsk (in Russian)
- Mokritskaya T.P., Bogachenko L.D. 2013. Osobennosti formirovaniya erozionno-opolznevykh protsessov na primere basseyna b. Tunnel'naya [Features of the formation of erosion-landslide processes on the example of the pool b. Tunnel]. Journ. Geol. Geograph. Geoecology. - Vol. 21 (15), 84-90 (in Ukrainian)
- Nauchno-tehnicheskii otchet ob inzhenerno-geologicheskikh izyskatel'skikh rabotakh (bureniye dvukh skvazhin) dlya opredeleniya perechnya vozmozhnykh meropriyatiy po likvidatsii deformatsiy, prosadochnosti i povrezhdeniy konstruktivnykh zdaniya po ul. Simferopol'skoy, 11 v g.Dnepropetrovske, obyekt № 8103/83, vypolnennyy gosudarstvennym predpriyatiyem «UKRNIINTIZ» v 2010 g. 118 (in Russian)
- Nauchno-tehnicheskii otchet po monitoringu dvukh sektsiy zhilogo doma po ulitse Simferopol'skoy, 11, v gorode Dnepropetrovske, vypolnennyy OOO «RemBud» v 2010 g. [Scientific and technical report on the monitoring of two sections of a residential building on Simferopol St., 11, in the city of Dnepropetrovsk]. 45 (in Russian)
- Sadovenko I.A., Vlasov SF, Maksimova-Gulyaeva N.A. 2002. Obosnovaniye vozmozhnosti ispol'zovaniya struynoy tekhnologii zakrepleniya gruntovykh sklonov na osnove analiza protivopolznevnykh meropriyatiy [Substantiation of the possibility of using inkjet technology for fixing soil slopes based on the analysis of anti-landslide measures]. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5, 31-33 (in Russian)
- Sadovenko I.O., Derevyagina N.I. 2012. O potentsiale aktivatsii opolzneвого lessovogo massiva [About activation potential of loess landslide massif]. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2, 80-84. (in Russian)
- Sadovenko I., Derevyagina N. 2014. Phenomena of filtration inversion and depth erosion of technogenic loaded loess slopes. Visnyk Kremenchuts'koho natsional'noho universytetu im. Mykhayla Ostrohrads'koho, 1 (84), 150-153.