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STRESS-DEFORMED STATE OF THE BOUNDATION OF HYDRAULIC STRUCTURES AT CONTROLLED COMPENSATION DISCHARGE

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Abstract. Numerical simulation of the process of injection of mortar into the thickness of the sandy base during the work on lifting and leveling the structure by the method of compensatory injection is carried out. An author's program has been developed that implements the finite element method (FEM) in a spatial formulation, taking into account the elastic-plastic nature of soil deformation, in which a special element in the form of a spheroid has been developed to describe the expanding area at the location of the injector, which changes its volume during the injection of mortar. During the verification of the program, the results of mathematical modeling were compared with the data of a physical experiment conducted by PhD Luca Masini from the University of La Sapienza (Rome, Italy). Numerical modeling of the stress-strain state of the base of the structure during repair work is considered by the example of lifting the foundation plate of the Zagorskaya PSPP-2. A number of tasks are being solved related to minimizing the number of injection columns, their location, the pitch of the cuffs, the selection of portions of the injected solution, taking into account the requirements for uniform lifting of the foundation plate in order to avoid additional cracking.

Keywords: compensatory injection, sediment leveling, stress-strain state of soil structures and foundations, numerical modeling, finite element method, “energy” soil model.

НАПРЯЖЕННО-ДЕФОРМИРОВАННОЕ СОСТОЯНИЕ ОСНОВАНИЯ ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ ПРИ УПРАВЛЯЕМОМ КОМПЕНСАЦИОННОМ НАГНЕТАНИИ

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Аннотация. Проведено численное моделирование процесса нагнетания строительного раствора в толщу песчаного основания в ходе работ по подъему и выравниванию сооружения методом компенсационного нагнетания (КН). Разработана авторская программа, реализующая метод конечных элементов (МКЭ) в пространственной постановке с учетом упругопластического характера деформирования грунта, в которой для описания расширяющейся области в месте расположения инжектора разработан специальный элемент в виде сфероида, изменяющего свой объем в процессе нагнетания строительного раствора. В ходе верификации программы проведено сопоставление результатов математического моделирования с данными физического эксперимента, поставленного PhD Luca Masini из университета La Sapienza (Рим, Италия). Численное моделирование напряженно-деформированного состояния (НДС) основания сооружения при проведении ремонтных работ рассматривается на примере подъёма фундаментной плиты Загорской ГАЭС-2. Решается ряд задач, связанных с минимизацией количества инъекционных колонн, их местоположением, шагом манжет, подбором порций инъектируемого раствора с учетом требований по равномерному подъему фундаментной плиты во избежание дополнительного трещинообразования.

Ключевые слова: компенсационное нагнетание, выравнивание осадок, напряженно-деформированное состояние грунтовых сооружений и оснований, численное моделирование, метод конечных элементов, «энергетическая» модель грунта.

INTRODUCTION

Non-admission of limit values for uneven precipitation in the foundations of hydraulic structures is one of the main safety criteria and a determining condition in the design of structures according to the second group of limit states. Nevertheless, the inevitable uneven distribution of stresses along the soles of structures, complex geological conditions, interaction with the water environment and filtration flow often cause the collapse of retaining walls, tilting foundations, abnormal settlement of the foundations of hydraulic structures. But the problem of excess settlement of buildings has become most acute in recent decades during the construction of underground transport infrastructure in cities. First of all, to solve these problems associated with tunneling, a method was developed for securing the soil mass using compensation injection technology, in which mortars are injected synchronously with mining operations based on the readings of a system of ground and underground sensors in order to prevent the development of sediments and subsidence of foundations. buildings in excess of the limit values.

The development of compensatory injection ideas related to soil strengthening was the work aimed at obtaining the effect of "lifting" the day surface of the soil, as well as the foundations of buildings and structures by injecting additional volumes of building mixtures into the foundations of structures, which contributes to the subsequent rise of the base, and together with him and structures [1,2].

In world practice, there are a large number of examples of the implementation of compensation injection technology to stabilize sediment or level the position of structures. The most famous examples are: alignment of the building of the hydroelectric power station of the Hessigheim hydroelectric complex on the navigable river Neckar near the city of Hessigheim (Germany), compensation for settlement and tilt of the Elizabeth Tower (Big Ben) of the Palace of Westminster (London, UK) [3], alignment of the building in the city of New Orleans (USA) [4], compensation of the settlement of the Bertelsmann AG office building in Berlin (Germany), etc. The largest values of the compensated settlement for controlled injection today are about 170-200 mm. In our country, studies on leveling the position of the foundation part of the Zagorskaya PSHPP-2 building have been carried out since 2013. Within the framework of these studies, a successful experiment was carried out to raise and set the alignment of the position of a concrete slab on the experimental site near the ZAGPP during controlled compensatory injection, the magnitude of the rise of the day surface of the soil was about 46.8 cm. The experiments carried out are related to the need to substantiate the possibility of leveling the position of the ZAGES-2 station unit after the uneven settlement that occurred in 2013, when the maximum draft was 1.17m. The available data on the compensation injection technology allow us to approach this problem from the side of mathematical modeling, the results of which will help find the best solution in the scheme for supplying mortars to the sandy base of the pumped storage power plant.

Unfortunately, at present there are no known software systems with an interface designed to solve such problems. Different researchers approached the issues of mathematical modeling of the process of injecting a solution into the base of a structure from different positions: assigning the finite elements that simulate the injection zone, the coefficient of additional volumetric deformation or the coefficient of thermal expansion [5].

For the numerical simulation of the solution injection process during compensatory injection, the author's program "JulyS" for a computer, written in the FORTRAN language [6], is used. The program solves the problems of the stress-strain state of the soil by the finite element method in a spatial setting. A tetrahedron is used as a finite element. To create the finite element mesh, the open source Gmsh program version 4.7.1 was used. The same program allows you to visualize the results of numerical calculations, for which the author's interpolation modules have been added to it.

To obtain adequate information about the stress-strain state of the soil medium, two soil models are used: a model of an elastic-ideal-plastic medium with the Mohr-Coulomb strength criterion [7, 10] and a nonlinear "energy" soil model developed by Professor L.N. Rasskazov [8].

In the nonlinear "energy" soil model by LN Rasskazov, the stage-by-stage loading of the computational domain with specified loads is reproduced, and the recalculation of the strength and deformation characteristics of the soil at each stage reflects the effect of material hardening. Due to the lack of experimental data on the magnitude of dilatancy in sandy soils, the model is used in a simplified form, i.e., without taking into account dilatancy, and also without taking into account the development of creeping deformations in time. In this case, the dependence of the stress tensor on deformation according to the "energy" model is written in the form (1):

$$d\sigma_{ij} = \left[\frac{\delta_{ij} E_0 de}{n\left|\sigma_{cp}\right|^{n-1}}\right] + \left[2\left|\sigma_{cp}\right|^{1-n} \cdot \left[f(\nu)\frac{E_0}{n}\exp(B\bar{K}-B) + G_0\bar{K}(1-\exp(B\bar{K}-B)\right]\right]de_{ij} \quad (1)$$

where: $\delta_{ij} = \begin{cases} 1, & for\ i = j \\ 0, & for\ i \neq j \end{cases}$;

E_0 and G_0 are respectively, the initial moduli of volumetric and shear deformation during all-round compression; $f(\nu)$ is a function expressing the relationship between the modulus of volumetric and shear deformation; n is exponent; σ_{cp} is an average soil stresses; B is dimensionless coefficient determined experimentally; $\bar{K}$ is hardening parameter associated with the energy condition of strength [9].

The numerical implementation of the "energy" model in relation to the calculations of earth dams was carried out by LN Rasskazov in the Dampz program. In addition to the elastoplastic nature of the soil deformation, the model took into account the rheological properties of the soil, which appear over time. Currently, the model is successfully used in the calculations of earth dams at the Department of Hydraulics and Hydraulic Engineering of NRU MGSU [12,13]. Also, the "energy" model was used in the calculations of large hydraulic structures in the software packages of the Research Center STADIO [14-50, 15-51, 1616-53].

To implement the "energy model" in the formulation of the finite element method, the dependence of the stress tensor on deformations (1) is written in the form of a matrix of characteristics [17], while the method of initial stresses is used [11]. The solution is made in increments of loads during the iterative process. Testing of the computational program for solving the problem of the stress-strain state of the computational domain in the elastic and elastoplastic formulation was carried out using examples that have an exact analytical solution, when compared with calculations in the Plaxis software package, with calculations using the StatDam program, which implements the "energy" soil model in within the framework of the finite element method in combination with the method of local variations [18].

Numerical modeling of the stress-strain state of the soil medium in the field of the introduction of mortars is based on the experience of scientists from the Cambridge, Delft, Ghent universities, who, in cooperation, carried out work aimed at studying compensatory injection in soft soils, the research results were published in the works of A. Bezuijen, AF van Tol, Gafar K., L. Masini et al. [19,20,21]. L. Masini's work "Experimental study of the technique of compensatory injections in sandy loam and loamy soils" describes the experimental setup and experimental conditions. According to the results of the experiments, it was noted that the solution injected into the sandy soil forms not a spherical volume, but a volume of a more complex shape, schematically shown in Figure 1 [21].

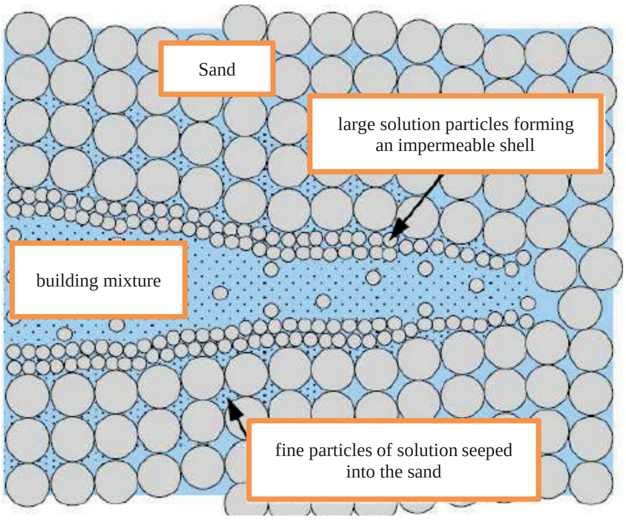

Figure 1. The resulting embedded body. Sectional view

For the numerical simulation of the process of penetration into the soil environment of the mortar, numerical studies were carried out and it was decided to use a spheroid elongated in the horizontal plane with a ratio of the horizontal and vertical semiaxes of 1: 2.5 as a shape for the penetration body. In this case, the equation of the surface of the spheroid takes the form:

$$\left(\frac{10\pi}{3V}\right)^{\frac{1}{3}}\left(\frac{(x-x_0)^2}{2.5}+(y-y_0)^2+\frac{(z-z_0)^2}{2.5}\right)-\left(\frac{3V}{10\pi}\right)^{\frac{2}{3}}=0 \quad (2)$$

where x, y, z are coordinates of a point on the surface of the spheroid; x_0, y_0, z_0 are coordinates of the center of the spheroid; V is discharge volume.

Since the formation of the intrusion body takes place in several stages, when constructing the finite element mesh, it was decided to provide for an "interlayer" of elements, similar to a closed crack, from the edges of which the region will expand, taking the shape of a spheroid. With each additional portion of the injection, the volume of the spheroid increases with the involvement of more and more interlayer nodes in the creation of the embedded volume. In this case, the nodes of the finite element mesh of the "interlayer", which are inside the spheroid, are "pulled" onto the surface of the spheroid along their abscissa (Fig. 2).

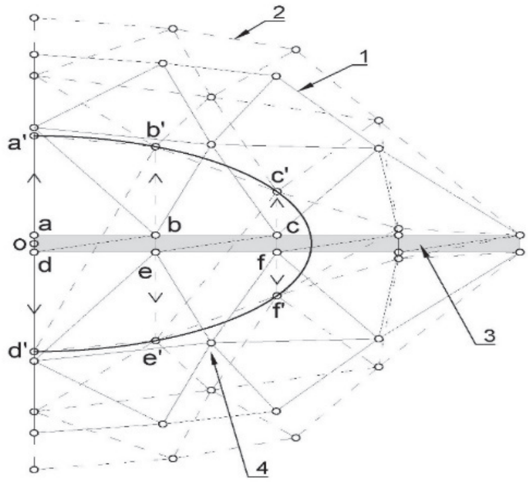

Figure 2. Schematic representation of the process of "pulling" nodes for the elements of the "interlayer" (1 - system mesh before calculation; 2 - system mesh after calculation; 3 - "interlayer" of elements; 4 - boundary of a given spheroid; a, b, c, d , e, f - grid nodes of the system; a ', b', c ', d', e ', f' - given position of grid nodes of the system; o - center of the spheroid)

Before the introduction of the mortar, the elements of the "interlayer" have the properties of the enclosing soil, and after the introduction of the mortar, they are excluded from the calculation. The elements of the interlayer that fall into the zone of influence of the spheroid are also excluded from the calculation. The zone of influence is taken to be equal to the twice-enlarged surface of the spheroid. Thus, the cross-section of the discharge volume looks as shown in Figure 3.

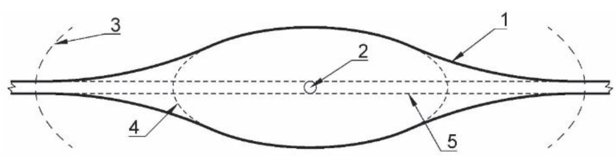

Figure 3. Section of the expansion volume. 1 - resulting surface; 2 - the center of the spheroid; 3 - zone of influence of the spheroid; 4 - a given surface of the spheroid; 5 - the initial position of the interlayer

When using the above assumptions, when calculating the process of injecting tensile stresses around the intrusion body, are not observed. The actual injection volume is calculated as the difference between the pre-injection volume and the post-injection volume.

The verification of the developed numerical model was carried out on the example of a physical experiment described in the works of L. Masini [19]. Figure 4 shows a diagram of the experiment set up. The test chamber has a diameter of 850 mm and a height of 400 mm. At the bottom of the chamber there is a drainage layer of gravel approximately 25 mm thick, covered with a geotextile filter. The drainage system by two pairs of holes on the side surfaces of the chamber is connected to the open cylindrical container with PVC pipes, which determines the conditions for conducting experiments according to the drained scheme. Vertical pressure is applied to the sample through a rubber septum attached circumferentially to a metal cover. The lid has five slots for displacement sensors (LVDTs), each with a through hole to measure vertical displacements directly on the sample surface. The solution is fed into the soil through a horizontal metal tube with external and internal diameters of 15 mm and 12.5 mm, respectively, which is introduced into the chamber at half its length and height so that the solution spreads into the soil in all directions from the open end of the tube located in the center of the camera.

The soil sample was made of medium-sized sand with a particle content of d50 = 0.4mm. The introduced cement slurry with the addition of bentonite had the following characteristics: (W / C) water-cement ratio 1.8, (B / W) bentonite-water ratio 0.08.

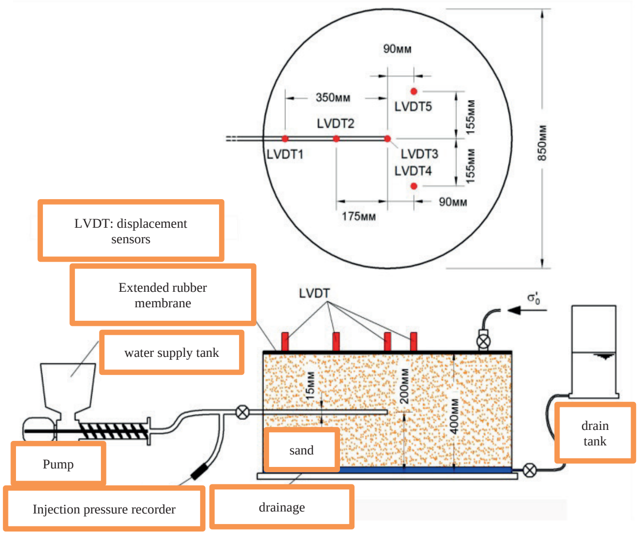

Figure 4. Diagram of the experimental equipment used

Before the injection of the solution into the soil, a pressure of 100 kPa was created on the surface of the sample. In total, 1.11 liters of solution was injected into the ground. As a result of injection, the maximum rise of the sample surface was 4.21 mm, while the volume of the raised surface (useful volume) was about 0.823 L. Thus, the injection efficiency, as the ratio of the useful volume to the volume of the supplied solution, is 74.6%. The results of the experiment are presented graphically in Figure 5.

For numerical simulation of the physical experiment, the finite element mesh of the test chamber was recreated (Fig. 6). The FEM mesh included 1330 elements and 6359 nodes. It was assumed that the embedded volume is modeled in the form of a spheroid conjugated with a contact element in the form of a flat "closed" layer, as shown in Figure 3. Before the introduction of the injection solution, the volume of the layer was equal to zero.

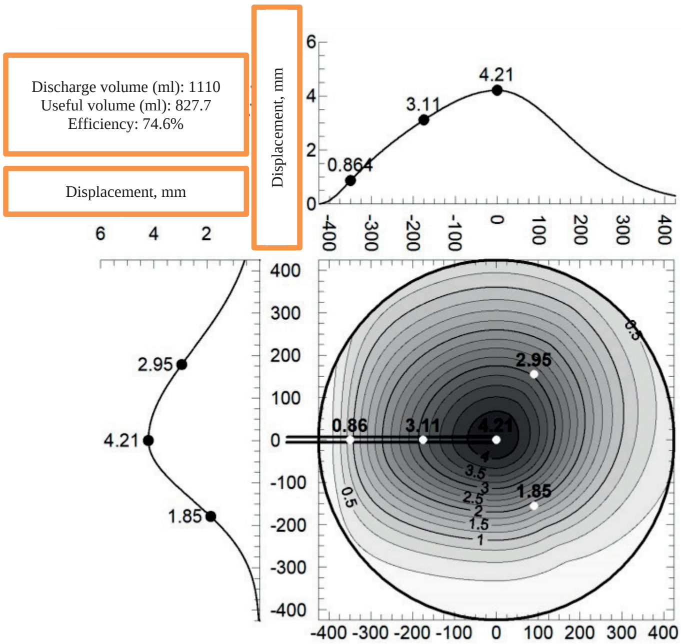

Figure 5. Isolines of the surface displacement at the end of the injection and the profiles of the longitudinal and cross-sectional displacements for the injection point

The calculation consisted of 12 stages. At the first stage, the soil was calculated from its own weight, at the second - the calculation was based on a vertical distributed load equal to 100 kPa. In stages 3–12, the injection of 1.11 liters of solution into the soil in separate portions was simulated. At each stage of injection, the adopted element expands in accordance with the injection volume, and if the nodes of the finite element mesh are inside the spheroid, then they are given such displacements so that they fall on its boundary. The iterative process with one portion of the solution is repeated until a stress-strain state in the computational domain adequate to the specified boundary conditions is obtained. To accelerate the convergence, individual portions of the solution supply are also divided into elementary sub-volumes, the size of which is selected. The accuracy of solving the problem in relative stresses is $1 \cdot 10^{-6}$.

Physical and mechanical characteristics of the soil taken in the calculation: soil deformation modulus E = 30MPa (taken from the manual for the design of the foundations of buildings and structures (to SNiP 2.02.01-83) for medium-sized sand); modulus of elasticity on the unloading branch E_y= 180 MPa; Poisson's ratio ν= 0.3; function value $f(\nu)$ = 1.5; exponent n = 0.8; dimensionless coefficient B = 10; volumetric weight of soil γ = 22kN / m^2.

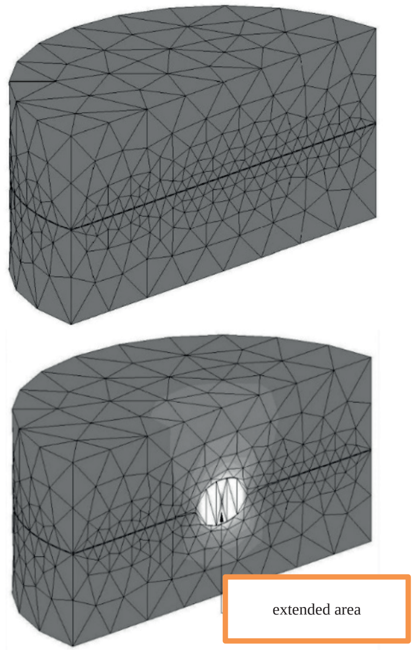

Figure 6. Finite element mesh of half of the test chamber (top - before the start of the experiment, bottom - after injection)

The maximum rise of the sample surface after injection of 1.11 liters of solution was 4.24 mm (in the experiment, 4.21 mm). Isolines of displacements of the sample surface after injection of 1.11 l of solution are shown in Figure 7.

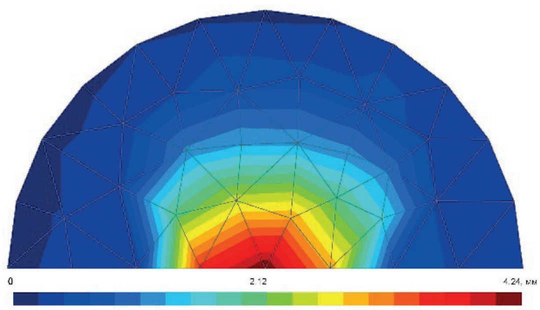

Figure 7. Isolines of displacements of the sample surface after injection of 1.11 l of solution. View from above

The distribution of average stresses in the horizontal section is shown in Figure 9. As can be seen from the solution results, compressive stresses are observed in the entire region. Above and below the expanded area, there is a concentration of large compressive stresses (more than 3000 kN / m^2).

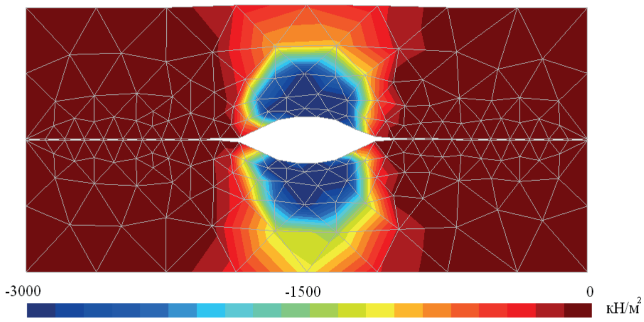

Figure 9. Isolines of average stresses in a horizontal section after injection of 1.11 l of solution

Analyzing the results obtained, it is worth noting that in the experiment, there was probably a loss of part of the volume of the injected solution when water was squeezed into the ground, since the water-cement ratio was large and amounted to W / C = 1.8. Taking this factor into account in the numerical calculation, the volume of expansion of the injection area should be less by the volume of lost "squeezed out" water, which for such mixtures is up to 10% of the injected solution. The obtained results of numerical simulation represent a good accuracy of the description of the physical experiment, the obtained error does not exceed 3%.

A study of grid convergence was carried out for such a formulation of the problem. For the initial finite element mesh, the scheme used in the calculation of the experiment was taken (the level of adaptation of the calculated volume is 3), and 4 meshes were created relative to it, two of which are less often 2 and 1.5 times (the level of adaptation of the calculated volume is 1 and 2, respectively), and the other two are 1.5 and 2 times thicker than the initial one (the level of adaptation of the calculated volume is 4 and 5, respectively).

The value of the maximum rise of the sample was chosen as a control parameter. The characteristics of finite element meshes and the calculation results are shown in Table 1.

Table 1. Results of the study of grid convergence

Adaptation level	Lifting mm	Number of nodes	Number of elements	Counting time, min
1	4.12	352	1455	0.6
2	4.94	623	2818	2.3
3	4.24	1330	6359	6.1
4	4.39	2649	13235	24.9
5	4.34	6012	31276	164.2

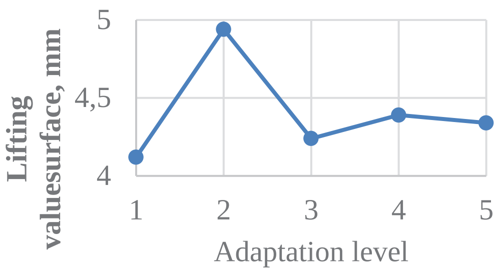

Figure 10. Graph of the dependence of the surface lift value on the level of the calculated volume adaptation

The dependence of the magnitude of the rise of the surface of the sample depending on the level of the calculated adaptation of the grid is shown in the graph (Fig. 10). It should be noted that the automatic mesh generation for each new adaptation level increases the number of finite elements unevenly. The graph shows that thickening the grid by 1.5 times or more of the initially adopted version gives a relatively similar result with an increase in the estimated time by an order of magnitude.

To solve the problem of eliminating the excess settlement of the foundation slab of the Zagorskaya PSHPP-2 using the compensatory injection method, it was necessary to conduct a numerical study of the influence of various technological factors on the amount of surface rise in order to establish a functional relationship between them. As the main factors affecting the amount of lift, one can single out: the volume of injection of the solution into one cuff, the depth of the cuff at the base and the number of cuffs on one vertical.

A study was carried out on the influence of the depth of the collar on the amount of rise of the day surface under the foundation slab. It is assumed that the foundation slab creates a distributed pressure on the base surface of 0.4 MPa [22], and the surface is lifted along the axis of the vertical arrangement of the collars, while up to 10 collars, which are tiers of collar columns, can be located on one axis.

The volume of cement slurry injection into each collar was selected based on the condition of the interstitial bodies closing together, thus, the resulting shape of the intrusion bodies located on the same vertical axis is similar to the structure of a hardened soil pile in a sandy base [23], which in the above studies is called a pillar injection.

To obtain a functional relationship between the magnitude of the rise of the day surface and the volume of the solution injected into the cuff, as well as the depth of the cuffs and their number in one injection column, 10 series of calculations were carried out with different numbers of cuffs on the vertical. In the last calculation, the injection was simulated with ten cuffs located in a single injection column. In this case, the total rise of the surface was 1.17m, while in total, in all 10 cuffs, the injection of 66700l (66.7 m3) of cement slurry was simulated. The useful volume of the raised surface was 37,900 liters or 37.9 m3. For the last calculation, Figure 11 shows the pattern of displacement isofields in the computational domain, and Figure 12 shows the pattern of the isofields of principal stresses.

The generalized results of the calculations performed for all injection columns with different numbers of cuffs are shown in the graph in Figure 13.

The resulting graph of cumulative lift versus the number of cuffs in the column is shown in this upper envelope graph. The upper envelope is the dependence of the lift of the foundation slab on the discharge volume, and the discharge volume determines the layout of the collars in the discharge column.

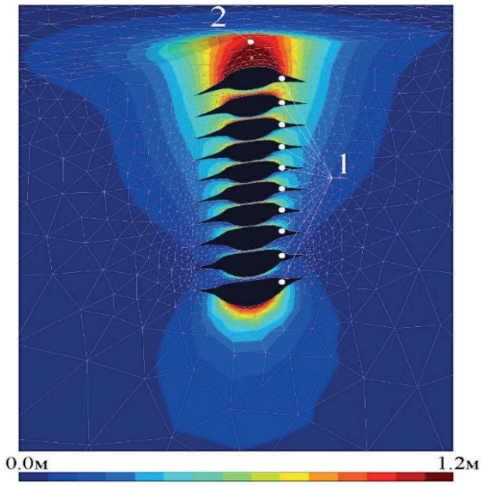

Figure 11. Picture of isofields of displacements in the computational domain when simulating the injection of a solution in ten cuffs

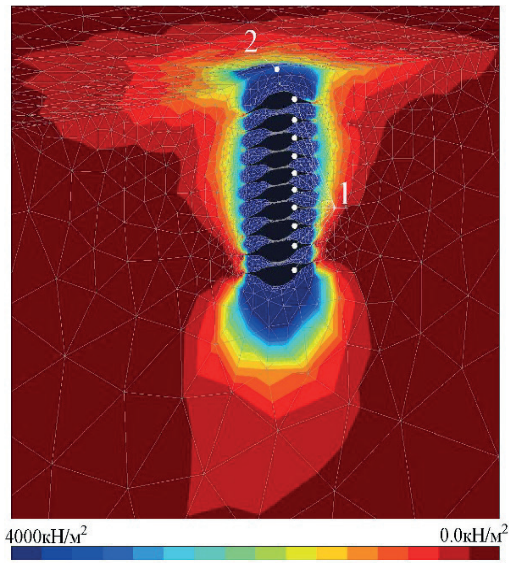

Figure 12. Picture of the isofields of the principal stresses in the computational domain when simulating the injection of a solution into ten cuffs in one injection column

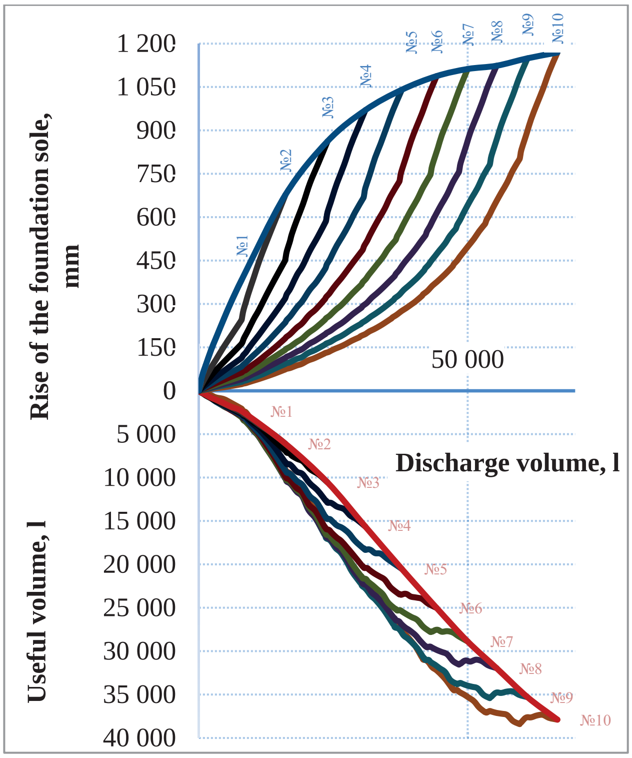

Figure 13. Graphs of the dependence of the rise of the base of the foundation and the useful volume on the volume of injection of the solution (the numbers indicate the dependence curves for individual design cases)

Using the obtained dependencies, it is possible to calculate the total volume that needs to be pumped into the cuffs located on the vertical to lift the base of the foundation by a given value in the range from 0.0 to 1.17m. The volume obtained can be used to calculate the useful volume. According to the calculated total volume, the required number of cuffs in the post can be determined. At the same time, the order of injection is established starting from the lower cuff, discrepancies in the delivery volumes are compensated by the lower cuff.

Based on the data obtained, calculations were made to lift the ZAGES-2 foundation slab. A scheme was developed for feeding the solution into the collar columns using the compensatory injection method, in which the required volume of the injected solution was 9240.8 m3, the arrangement of the collar columns in the plan and along the tiers of the subgrade was developed, the total number of collar injectors was 74 pcs.

CONCLUSIONS

1. Numerical studies to simulate an expanding area in the thickness of soil material led to the development of a computing program JulyS, which allows to recreate the conditions and repeat the result of a physical experiment on the introduction of cement slurry into a sandy base with the goal of obtaining a response in the form of a rise in the day surface. The error of the obtained result is no more than 3%.
2. Within the framework of the finite element method, a special element has been developed that simulates the injection body in the area of injection and volume expansion around the injection pipe (cuff). The shape of the element is taken in the form of a flattened ellipsoid with an axis ratio of 1: 2.5, which grows and expands on the basis of the "interlayer" elements previously built into the grid.
3. The length of each group of elements of the "interlayer" should be selected according to the maximum volume of the total injection in the area of this "interlayer".
4. The effectiveness of the numerical experiment is controlled by the absence of tensile stresses when the nodes are "pulled" to the boundary of the sphere and can be adjusted to the individual task in the course of refining the shape of the spheroid.
5. It has been proven that the most effective way to lift the foundation slab is to create, due to the adopted layout of the collars, injection pillars, in which injection is carried out in the direction from bottom to top.
6. The functional dependences of the height of the foundation slab lift on the depth of the collars in the soil layer, their quantity in the injection column have been obtained, which makes it possible to find the volume of solution injection and the layout of the collar columns for a given lift value.

7. According to the results of numerical modeling of the lifting of the Zagorskaya PSHPP-2 foundation slab by the compensatory injection method, the required volume of the injected solution is 9240.8 m3, while the number of collar columns distributed over the base area is 74 pcs. and the axial distance of the collar holes in the collar columns is 3.5m.
8. In the developed method of modeling the process of compensatory injection using the example of the Zagorskaya PSHPP-2, the injection efficiency is about 38.8%, which correlates with the data of field experiments [1].

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