Experimental studies of the reinforcement percentage effect on the modulus of soil deformation fixed by cementation

A Yu Prokopov1*, I V Sychev1, A A Revyakin2, O N Soboleva2

1 Don State Technical University, 1, Gagarin sq, Rostov-on-Don, 344010, Russia
2 Rostov State Transport University (RSTU), 2, Rostovskogo Strelkovogo Polka Narodnogo Opolcheniya sq., Rostov-on-Don, 344038, Russia

E-mail: prokopov72@rambler.ru

Abstract. The article presents the experimental studies’ results on the subsidence soils reinforcement percentage influence during cementation on the deformation characteristics of a soil base after fixing. A nonlinear dependence of the fixed soil deformation modulus on the reinforcement percentage and the initial (natural) deformation modulus is established. High convergence of the obtained theoretical and experimental data is proved.

1. Introduction
When designing, constructing and operating buildings and structures on subsiding soils, one of the main problems is ensuring the operational reliability and safety of the facilities during natural and man-made flooding. If the base soils have the subsidence properties, then when a certain humidity is reached, subsidence phenomena occur, which often cause uneven vertical deformations of the foundations and ground bearing structures. This leads to significant violations of the building structures up to the stability loss of a building or a structure. In order to avoid such consequences, modern regulatory documents require the mandatory application of measures to reduce or completely eliminate the subsidence properties of base soils. One of the most effective methods for eliminating the subsidence properties of soils, which are widespread in the Rostov region and other regions of southern Russia, is the method of soil cementation, based on the cement or cement-sand grout injection through the drilled wells [1-4]. The main problem limiting this method’s application is the complexity and lack of accuracy of the existing methods for controlling the soil fixation quality. This article proposes a new method for determining the deformation characteristics of a fixed soil base, and presents the experimental studies’ results of the factors affecting the final results of fixing.

2. Goals and objectives
The main goal of this work is to develop a new method and an experimental bench for monitoring the fixed base quality and study the factors affecting the final deformation characteristics of the soil.

The tasks solved in this paper are:

1. Analysis of the methods for controlling the quality of a soil foundation fixed by cementation, their advantages and disadvantages.

2. Development of an experimental bench and a test method based on it, which allows to control the soil deformation modulus with high accuracy, both during fixing and after its completion.
3. Experimental studies on several objects with a different initial (natural) deformation modulus of the soil reinforcement percentage influence on the total deformation modulus of the fixed soil.

4. Statistical processing of the experimental data and determination of the multiple correlation between the soil reinforcement percentage, the initial and final module.

5. The convergence verification of the results obtained by the theoretical equation and experimental data.

3. Problem statement

When eliminating the subsidence properties of soils by means of the binders’ injection, there is an acute quality monitoring problem, caused by the fact that the work on pumping grouting compositions is classified as hidden and cannot be visually controlled.

All methods of the soil fixation quality monitoring by the injection methods can be divided into the following groups:

1. Methods based on drilling pits in separate sections of the fixed base, and sampling the compacted soil, visual inspection of the cement grout veins distribution and its selection for the laboratory tests. The main controlled parameters of the soil according to the laboratory tests are, as a rule, the dry soil density, the deformation modulus at natural humidity and in the conditions of complete water saturation, less often – the additional strength characteristics of the soil are checked: specific adhesion and the internal friction angle, based on which the calculated soil resistance is determined bases after fixing. The selected samples of the hardened cement grout in the laboratory are tested for uniaxial compressive strength.

The advantages of these methods are the possibility of direct visual control of the fixed area with the physical soil samples’ selection and fixing solution. The disadvantages include the impossibility of drilling pits to the entire depth of the fixed stratum, which can reach 15-17 m or more in the engineering and geological conditions in the Rostov Region. Another drawback of the methods is the selective quality monitoring, which affects the accuracy of the results, as well as the results’ incorrectness when using the average weighted deformation module of the fixed base.

According to the separate territorial building codes adopted in the Russian Federation, in particular TSN-50-306-2005 of the Rostov Region “Foundations and basements of increased bearing capacity”, the deformation modulus of a fixed soil foundation is calculated as the weighted average between the deformation modules of soil and reinforcing elements in the form of veins cement-sand grout, taking into account the grout percentage in the soil.

Such an approach, due to the high calculated value of the concrete deformation modulus, often leads to overestimated the deformation modulus values of the fixed soil base, which affects the outflanking calculation results. For example, when designing the fixation of subsidence soil foundation by reinforcing with the elements of increased rigidity by cementation during the apartment building construction in the 2nd quarter of the Leventovsky district in Rostov-on-Don, when calculating the weighted average base deformation modulus, the following design deformation moduli were adopted:

- reinforcing elements \( E_s = 930 \text{ MPa} \);
- soil IGE-1 (medium subsidence loam) \( E_1 = 5.8 \text{ MPa} \),
- module IGE-2 (slightly subsiding loam) \( E_2 = 12.1 \text{ MPa} \).

As a result of applying the TSN-50-306-2005 norms of the Rostov Region with a reinforcement percentage of 10.6%, the weighted average deformation modules of a fixed soil base were obtained: \( E_{av.1} = 25 \text{ MPa} \) and \( E_{av.2} = 30 \text{ MPa} \) respectively for the soils IGE-1 and IGE-2. As a result of this assumption, the estimated foundation outflanking was 9.9 cm, which is permissible in accordance with BC 22.13330.2016 “Foundations of buildings and structures” for the corresponding design of the building under construction.

However, upon the building construction completion, the actual outflanking exceeded 20 cm, which indicates that the calculated deformation moduli at a given percentage of reinforcement were not achieved, and actually amounted to no more than 12-15 MPa.
2. Geophysical methods based on the geo radars and other instruments’ use [5], which determine the qualitative picture before and after fixing the soil mass. The undoubted advantage of the method is the absence of labor-intensive manual work, as when drilling pits, the ability to study the entire thickness of the fixed thickness and determine its conditional boundaries from the characteristic changes in the physical and mechanical properties of the massif due to its filling with more dense bodies consisting of the fixed composition elements. The main disadvantage of the method is the inability to accurately determine the deformation and strength characteristics of soils and grout, as this makes it possible to perform the laboratory testing of the samples taken from pits.

3. The methods of static and dynamic sounding of soils also make it possible to qualitatively compare the strength characteristics of soils before and after fixing, while they can be used at the design stage as basic or additional engineering and geological surveys to detect the local voids or weak zones, which require a larger percentage reinforcement and, accordingly, the grouting components’ consumption. Another important advantage of the method is the ability to control the entire depth of the fixed soil stratum. The disadvantage is the reality of only an indirect assessment of the soil properties’ changes after fixing in relation to the initial state of the array.

4. Test method with standard stamps. This field method is the most accurate in terms of determining the module of the soil general deformation, since it allows to test the soil directly at the future foundation site, at a given depth in real operating conditions. High accuracy of the method when using standard stamps, the area of which, according to GOST 20276-2012 “Soils. Field methods for determining the strength and deformability”, is equal to 600, 2500 or 5000 cm²; it is mainly provided for the homogeneous soil massifs. In cemented arrays, sharp inhomogeneities arise by cementation, which may not be fixed with the stamps of such a small area. So, when the cementing wells pitch is 1-1.5 m and the use of standard stamps, the sole of the latter can fall either on the reinforcing element, thereby showing an overestimated deformation modulus, or, conversely, between these elements and “measure” the deformation modulus of unsecured soil.

In this regard, the authors were tasked to develop and test an experimental bench that allows the field method to determine the weighted average deformation modulus of the fixed soil, while assessing the change in the array properties, both during injection and after the reinforcing elements’ cementation and reinforcement completion.

4. The experimental part
The main objective in the design of the experimental bench was the need to cover a much larger area of the test site than is provided for by GOST 20276-2012 using the standard stamps. The dimensions of the new stamp should cover several injection wells, while being located symmetrically relative to them, thus evenly distributing the load on the fixed array.

Another important task was the possibility of studying the changes in the deformation properties of the massif during the cement grout injection and determining the grout deformation modulus dependence on the reinforcement percentage.

The soil mass reinforcement percentage is understood as the fixing grout volume ratio to the total soil volume. As the practice of fixing soils in the Rostov Region shows, the percentage of reinforcement ranges from 6 to 16%, while the volume of fixing composition and the corresponding decrease in porosity and increase in soil density are enough to partially or completely eliminate the subsidence properties of the massif. With a percentage of reinforcement $A < 6\%$, fixing will be ineffective, reinforcing with $A > 16\%$, as a rule, leads to the solution overuse without a significant increase in the deformation modulus, and also creates the technological difficulties associated with the need to significantly increase the discharge pressure to ensure the design injection of the solution.

Based on the above-mentioned problems, the design of the test bench [6], presented in Fig. 1, was developed and patented.

The structure for the soil testing with a stamp (Figure 1) includes: a stamp in the form of a reinforced concrete slab with embedded parts - metal pipes with a diameter of 89 mm, with overall
dimensions of $2400 \times 2400 \times 600$ mm, a jack DG200P150 with a pressure gauge MA100VU100, screw metal piles with a length of 10 m; set of deflection meters 6PAO.

The injection of cement-sand grout into the soil was carried out through the metal injectors with a diameter of 70-80 mm installed in the wells.

Figure 1. Diagram of a test bench for determining the deformation modulus of a fixed soil base with a stamp

The working solution was prepared by diluting the reagents in the ratio 1: 2: 1 (cement-sand-water) by weight. The injection of the working solution was carried out using a mud pump at a pressure in the range from 0.2 to 0.9 MPa. When performing the circuit injections at the first stage, an insignificant output of cement-sand grout to the surface was observed, in connection with which a decision on the site to install the packer deeper into the well was made, as a result of which the problem was eliminated.

After the work and the initial set of the cement-sand grout strength, the work to soak the pit with fixing the implementation of subsidence properties of the soil within the pit and nearby buildings and structures was done.

Soaking the pit was carried out in accordance with GOST 20276-2012. Outside the stamps, drainage wells were drilled to the entire depth of the subsidence stratum. The diameter of the drainage wells is assumed to be 300 mm; the borehole is filled with crushed stone of a fraction of 20-40 mm.

According to the clause 5.4.8 of GOST 20276-2012, the subsidence soils soaking at the base of the stamp in the wells was carried out with a dispersed stream to avoid the soil erosion. At the final stage of soaking, the water level was maintained 5-10 cm above the surface of the sand cushion and the water flow was measured. The duration of the soaking process was 4 weeks.

To control soil moisture, the samples were taken to a depth of 17.5 m from the bottom of the stamp. Soil moisture was determined by the weight method, the degree of humidity is $S_r \geq 0.8$.

The test of the fixed array with a stamp is carried out according to GOST 20276-2012 to determine the deformation modulus in a water-saturated state $E_{sat}$.

To study the effect of the reinforcement percentage on the total deformation modulus of fixed soil, the above-mentioned experiment was performed on several objects with different initial soil deformation moduli in a soaked state [7, 8].
5. Processing the experimental results

Based on the tests, the graphs of the fixed soil deformation modulus dependence were constructed $E_R$, MPa, of the percentage of reinforcement $A$, % for various values of the total deformation initial modulus in a water-saturated state (Figure 2).

![Graph of fixed soil deformation modulus dependence](image1)

**Figure 2.** Graphs of the fixed soils deformation modulus dependence reinforcement percentage

To determine the type of multiple correlation and the type of function $E_R = f(E_0; A)$ let us construct the correlation field in the form of a surface (Figure 3).

![Correlation field of fixed soils deformation modulus dependence](image2)

**Figure 3.** The region of points determining the fixed soils deformation modulus dependence on the soil deformation initial modulus and the reinforcement percentage
As follows from the graphs shown in Fig. 2 and 3, there is a non-linear correlation between the studied parameters, while non-linearity is observed with a reinforcement percentage from 8 to 16%, the maximum increment of the soil deformation modulus is observed with an increase in the reinforcement percentage from 8 to 12%, followed by a decrease in the growth rate. This effect is explained by the fact that with an increase in the reinforcement percentage, the number of pores decreases, thereby increasing the deformation modulus, and with a certain saturation of the soil with a solution, the decrease in porosity is much slower, respectively, a slower increase occurs in the deformation modulus.

When the reinforcement percentage $A = 16\%$, the module of the fixed soil $E_R$ reaches from 15 to 22 MPa, depending on the initial deformation modulus, which is sufficient for most buildings and structures designed on strip or slab foundations on an artificial foundation. An increase in the reinforcement percentage $A$ over 16\% is technically and economically impractical. For the structures requiring the calculation of a larger fixed soil deformation modulus under the conditions of limiting the maximum outranking, it is advisable to design on a pile foundation or apply other methods to eliminate subsidence soils and increase their deformation characteristics [9, 10].

By the type of the curved surface (Fig. 3), we can conclude that the dependence $E_R = f (E_0; A)$ can be described by a second-order surface equation of the general form:

$$E_R = aA^2 + bE_0^2 + cAE_0 + dA + eE_0 + f,$$

where $a$, $b$, $c$, $d$, $e$, $f$ are the unknown approximation coefficients.

Using the least squares method (LSM), we find the following coefficients’ values:

$a = 2,552 \cdot 10^{-3}$, $b = -0,148$, $c = -9,67 \cdot 10^{-4}$, $d = 0,863$, $e = 3,043$, $f = -5,973$.

Taking into account the nullity of the third term, which does not affect the final result, the equation of dependence $E_R = f (E_0; A)$ with sufficient accuracy can be written as:

$$E_R = 2,552 \cdot 10^{-3}A^2 - 0,148E_0^2 + 0,863A + 3,043E_0 - 5,973,$$

where $E_R$ – is the deformation modulus of fixed soil, MPa; $E_0$ – defines the deformation modulus of the initial soil, MPa; $A$ – is the percentage of soil reinforcement with cement (cement-sand) grout, %.

The accuracy evaluation of the obtained equation shows that the average relative deviation between theoretical values and experimental data obtained from 42 test results is 8.5\%, and the correlation ratio is close to 1. This indicates the reliability of the obtained equation.

6. Summary
Based on the research results, the following conclusions are made:

1. Most of the methods used in modern practice for assessing the quality monitoring of fixing subsidence soils have significant drawbacks that do not allow to reliably assess the deformation characteristics of the fixed soil mass, which serves as the building’s foundation.

2. The developed experimental stand with an increased stamp area, commensurate with the sole area of real columnar and strip foundations, allows the most adequate and reliable assessment of the deformation modulus of the soil base after cementing, while the design of the stand makes it possible to study the soil reinforcement percentage effect on the fixed soil deformation modulus.

3. As a result of experimental studies, a nonlinear dependence of the deformation modulus of the fixed soil foundation on the reinforcement percentage and the initial deformation modulus, which is described with high accuracy and reliability by a general-order second-order surface equation, was established. The average relative deviation of theoretical and experimental data is 8.5\%, and the correlation ratio is close to 1.

References
[1] Prikhodchenko O E, Tarzhimanov M A, Tarzhimanov E A, Sychev I V 2014 The experience of applying the cementation method when fixing soft-plastic soils in Rostov-on-Don Scientific...
Review. 9 (3) 746-750.

[2] Prokopov A, Prokopova M, Rubtsova Ya 2017 The experience of strengthening subsidence of the soil under the existing building in the city of Rostov-on-Don MATEC Web of Conferences 106. doi.org/10.1051/matece conf/201710602001.

[3] Prokopov A Yu, Sychev I V 2019 Determination of the deformation characteristics of a soil massif transformed according to the technology of soil reinforcement with cement-sand grout Engineering Herald of the Don 3. Information on ivdon.ru/ru/magazine/archive/N3y2019/5809

[4] Prokopova M V, Prokopov A Yu, Zhur V N 2016 Strengthening subsidence soils under existing buildings in Rostov-on-Don Transactions of Rostov State Transport University 4 79–87.

[5] Fomenko N E, Kapustin V V, Gaponov D A, Fomenko L N 2017 The use of a complex of geophysical methods in the study of pile fields Geotechnics 2 56-64.

[6] Sychev I V, Targimanov M A Patent 160099 of the Russian Federation. A device for testing soils reinforced with cement-sand grout, Publ. 03/10/2016. Bull. №7.

[7] Prokopova M V, Semeshchuk P P, Pilyagina E K, Makarenko A P 2019 Modeling the work of the foundations of foundations, composed of subsiding soils Scientific works collection “Transport: science, education, production”– 23-26 april 2019, Rostov-on-Don: RGUPS 164 – 167.

[8] Reconstruction of MBUZ "City Hospital № 1 named after N.A. Semashko, Rostov-on-Don. Technical report on engineering and geological surveys. № MP84. Rostov-on-Don: Architectural Heritage LLC, 2014.

[9] Black A T 1981 Research and development of effective methods for controlling the quality of silicification of loess soils (dis. Cand. tech. Sciences: 05.23.02. Rostov-on-Don).

[10] Prokopov A, Prokopova M, Hamidullina N 2019 Computer Modeling of Deformation Processes in the Event of Liquidation of a Dip Over a Rock Mine IOP Conference Series: Earth and Environmental Science 272 (2). Information on https://iopscience.iop.org/article/10.1088/1755-1315/272/2/022118