Lecture Notes in Civil Engineering

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Gulchohra Mammadova
Svitlana Sivitska
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Contents

Deformation Monitoring of Silos on the Basement, Reinforced with Soil–Cement Elements, Manufactured According to Boring and Mixing Technology

Serhii Bida, Oleksandr Marusych, Mykola Zotsenko, Anna Pavelieva, and Mykola Biloshytskyy

Abstract The construction of a significant number of new facilities takes place on the territories, where geological-engineering conditions are complicated by the presence of man-made soils or soils with special properties, which makes it necessary to reinforce the basement. This problem becomes particularly topical in construction of such structures as grain storage silos that transfer significant loads to the basement. One of the options for reinforcement is the installation of soil–cement elements, manufactured according to boring and mixing technology. Reinforcement of the basement in this way is quite effective due to the applicability of elements of different diameters and lengths, as well as through adequate choice of distance between them. Variation of these parameters allows to perform reinforcement almost in any geological conditions, taking into account the possibility of consolidation of the bases and foundations below the water table. However, designing and operation of the structures, standing on basements, reinforced in this way, requires intensive study of the stress–strain state of the system "foundation bed–reinforced basement", taking into account operational features of such structures. Proper allowance must be made for different degrees of silos loading and cyclic loading and unloading. Investigative research of the deformability of such systems is possible by applying various models of soils and the finite-element method as a mathematical apparatus.

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When choosing a model, consideration must be given to such factors as the accuracy of behavioral model of foundation soils and the simplicity of identification of parameters, required for performing calculations. Special attention should also be given to monitoring the development of subsidence of the structures, built on the reinforced basement, taking into account the time factor for comparison with the results obtained analytically.

Keywords Soil–cement elements · Man-made grounds · Loose grounds · Basement reinforcement

1 First Section

Due to the development of the agricultural sector of Ukraine, it has recently become necessary to erect facilities which can ensure longterm storage of grain crops. The solution to this problem is possible through the construction of grain storage silos, which are meant for storing tens and sometimes hundreds of thousands of tons of grain. Such structures wield major influence on the foundation soil, which requires serious land development. Another difficulty of erecting such structures is that the territories, provided for construction, can not be used as agricultural lands and have rough engineering and geological conditions (man-made soils or soils with special properties, flooded areas, etc.). Thus, the problem of a weak base had to be solved during the construction of grain storage silos with diameters of 22 m and 30 m, designed for 10 and 15 thousand tons correspondingly, at the construction facility: “Reconstruction of an integral real property portfolio with the construction of manufacturing and service buildings in the city of Nizhyn, Chernihiv region, Ukraine”.

The construction site is located in the southwestern part of Nizhyn. As for geomorphologic characteristics of the territory, this construction site is coordinated with the IV floodplain terrace of the Oster River. Silos foundation is composed of aeolian-deluvial sand clays and argil sand grounds, which are underlain by alluvial clays and sand deposits. In the lot we have discovered one free aquifer, the level of which during the survey (in November of 2017) was recorded at a depth of about 3.0 m below the surface. The aquifer recharge is conducted mainly by influent seepage of atmospheric precipitation. Unloading of the aquifer (water-bearing formation) is carried out into the network of gullies (cloughs) and into the Oster River Valley. However, the larger half the territory is classified as inundated by man-made floods. With multiyear and seasonal fluctuations, the groundwater level (GW level) can rise by 0.5–1 m. Waterproof (impervious) layer up to a depth of 25 m was not detected. It ought to be noted that groundwater level fluctuations, apart from seasonal changes, are subject to years-long cyclicity. Based on long-term observations, the groundwater level (GW level) may not only rise, but also reduce over extended periods, due to natural causes. This process has recently been observed almost on the entire territory of Ukraine. Nonetheless, it remains possible that GW level will rise in future.

Geological-engineering cross-section is represented by the following engineering-geological elements (EGE):

EGE-1—loose soils (man-made grounds), which are a mixture of top soil, argil sand grounds, tree roots, with man-made soils–fragments of structures, construction and manufacturing waste. There may also occur macroporous and compressible soils;

EGE-2—yellow-gray, stratified, poor-porous, plastic sand clays with layers of silt sandy loams, which are free-flowing at full saturation with water;

EGE-3—very soft greenish-gray, light-textured, laminated, low-porous argil sand grounds;

EGE-4—greyish-green, stratified, low-porous, ferruginous, plastic sandy loams;

EGE-5—greyish-green and greenish-gray, tight, aqueous quartz sandstones of intermediate size;

IГE-6—EGE-6—green, laminated, low-porous stiff loams.

Geological-engineering conditions here belong to the second category of difficulty. Geological-engineering cross-section is plotted in Fig. 1.

The basement (footing) of grain storage silos consists of bedplates (foundation slabs) with underground galleries, located in the middle. Since the basis is formed of man-made grounds to a depth of 3.5 m, and below fill-up grounds there are collapsible soils, which, when having saturated with water, fall into the category of “loose soils”,

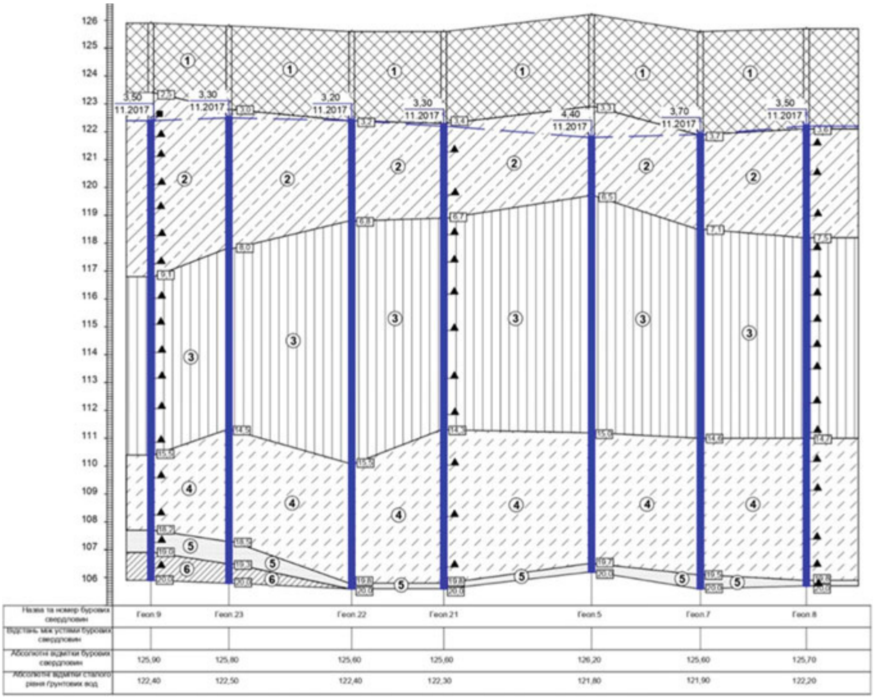

Fig. 1 Geological-engineering cross-section of the construction site

it was decided to perform land development of the site in the form of strengthening the foundation with soil–cement elements (SCE), which are manufactured according to boring and mixing technology [1, 2].

Soil–cement elements (SCE), which are seated under the construction site, have a diameter of 500 mm, a length of 8.0 m and they are located at the intervals of 1.3 × 1.3 m for silos with a diameter of 22 m and at the intervals of 1.2 × 1.2 m–for silos with a diameter of 30 m. Diameter of the elements was determined taking into account the nonuniformity of the loose soil, occurrence of construction debris in the top part of the basement and the size of bedplates (foundation slabs). The length and expansion step of SCE location was chosen from the value of the weighted-average soil deformation modulus within the compressible width (strata), at which the subsidence of silos will not exceed the standard value Su = 15 cm. In order to avoid the destruction of the upper part of soil–cement elements (SCE), it was decided to arrange a damping layer, represented by a layer of crushed stone with the fraction of 20–40 mm and with a thickness of 500 mm. Thus, thanks to soil–cement elements (SCE), it was possible to strengthen the soil column of EGE-1 man-made grounds, of EGE-2 collapsible (loose) soils and to strengthen partially EGE-3. At the maximum loading of silos, the medium pressure value under the foundation base was 200 kPa.

Thus, the foundations of silos are presented in the form of bed plates (foundation slabs) with underground galleries, which are built on the foundations consisting of soil–cement elements (SCE), reinforced with man-made grounds and collapsible (loose) soils (Fig. 2).

The SCE location was performed on the basis of calculations, carried out in order to determine subsidence, which were performed using a model in the form of a linearly deformed half-subspace with the restriction of compressed width (strata) at the level

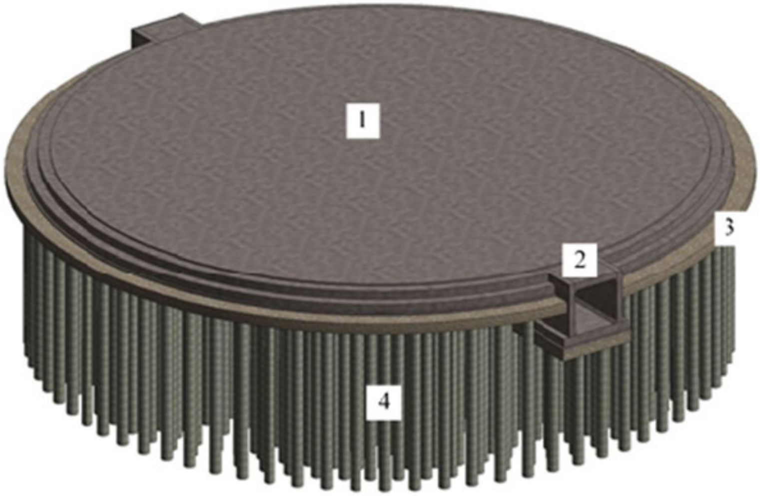

Fig. 2 Structural layout of the foundations of grain storage silos on a reinforced basis: 1–foundation slab; 2–underground gallery; 3–damping layer of crushed stone; 4–soil–cement elements

where the condition σzp = 0,5 σzg was met (where σzp is vertical intensity from external load, and σzg is vertical intensity from the soil's own weight). Enchanced soil was considered as composite material with weighted average characteristics of stiffness and deformability of soils and soil–cement elements.

To assess the change in the stress–strain state of the foundation, consisting of loose soils, which are strengthened with reinforcement by vertical soil–cement elements (SCE), observations of vertical strain (vertical deformations) of grain storage silos were performed throughout their working service. The purpose of monitoring structures is to compare their actual vertical strain (vertical deformations) with the calculated and limit values and to analyze the changes in silos depression/settlement over time depending on their workload, carried out according to the operation practice (cyclic loading–unloading).

Before monitoring, the organization–object owner, handed over to the work performers original reference network points (lubber lines), which corresponded to the II class of measurement accuracy. The location of lubber lines, the type and method of their mounting corresponded to the current regulatory documents. Generally, there were mounted 3 lubber lines.

Deformation control benchmarks for determining vertical displacements were installed on the horizontal faces of the foundations of grain storage silos. These deformation control benchmarks were located taking into account design features of the house footings, dynamic stress availability, the expected values of surface subsidence, the peculiarities of geological-engineering conditions of the object and the most favorable conditions for measuring deformation of structures. The layout chart of deformation control benchmarks is given in Fig. 3.

For reliable fastening of deformation control benchmarks on the horizontal plane they were made of a metal plate 100 × 100 × 6 mm in size, which should be attached to the basement surface with a concrete nail/an impact anchor.

After deformation control benchmarks were installed, their elevation numbers were transferred from the nearest state or local points of vertical control survey

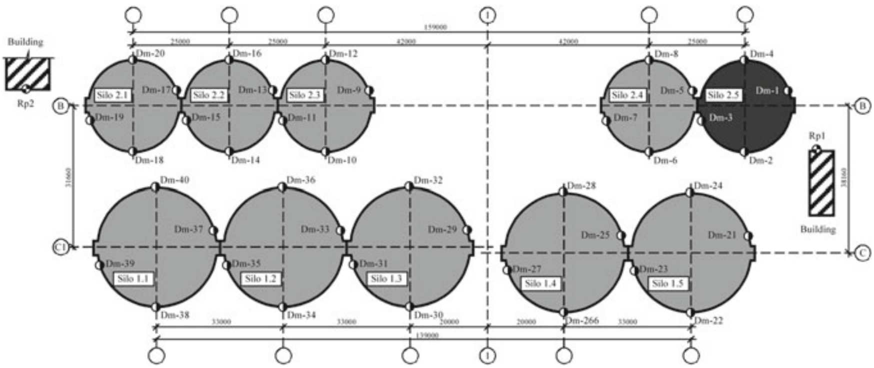

Fig. 3 The layout chart of experimental benchmarks, temporary wall marks and notation conventions

network. As a result of determining precision of measurements, it was found that the permissible error in measuring vertical strain (deformations) during othe running time of structures located on loam soils is 2 mm, with the calculated values of their subsidence up to 50 mm, according to [3–5].

The accuracy class of measuring the movements of structures to be monitored is II.

Vertical displacement of the foundations base of buildings was performed by the method of differential leveling. When carrying out the measurements, we adhered to the measurement tolerances, allowable at differential leveling of the II accuracy class:

- the length of the collimating ray should not exceed 40 m;
- the height of the collimating ray above the hindrance should be not lower than 0.8 m;
- uneven levers (length of sight) at the station should be not more than 0.4 m;
- the accumulation of uneven levers (length of sight) in a closed circuit should not exceed 2.0 m;
- the acceptable misalignment in a closed circuit is (where n is the number of stations); in the absence of the possibility of controlling the uneven levers (length of sight) under the conditions of close-packed arrangement of structures, we have used the short beam method, in which the distance from the station to the leveling boards did not exceed 25 m.

Subsequent to the results of observations, we have constructed dependency diagrams of displacements of deformation control benchmarks depending on loads, and have obtained average deformations of the foundations of grain storage silos (Fig. 4).

The initial readings of all deformation control benchmarks were taken in October 2018. Loading of grain storage silos was begun in 2018. The first cycle of loading the grain storage silo 1.4 began in late November 2018. Thereat the grain storage silo was loaded by 40%, which allowed to avoid the development of significant building tilts. The average subsidence during the first cycle was 16 mm. The maximum difference of vertical displacements of deformation control benchmarks was 20 mm with maximum and minimum displacements of 32 and 12 mm, respectively. The peak load of 100% was in October 2019, which was accompanied by the average subsidence of the silo footing of 41 mm. The estimated value of subsidence was 140 mm.

In order to forecast the value of silos subsidence, we have performed mathematic simulation of the system "foundation bed–reinforced basement" using a discrete model, which allows to obtain more explicit solutions in comparison with other models, as it takes into account the interaction of each individual reinforcement element with the soil. Individual elements of the discrete model under the action of external loading, as in common phenomenological models, are described by the equation of the known model bodies with ideal properties.

Discrete design diagrams of reinforced foundations are usually modeled by the finite element method. In this case, taking into account the work of soil–cement elements can be ensured by the introduction of variable stiffness ratios or modeling

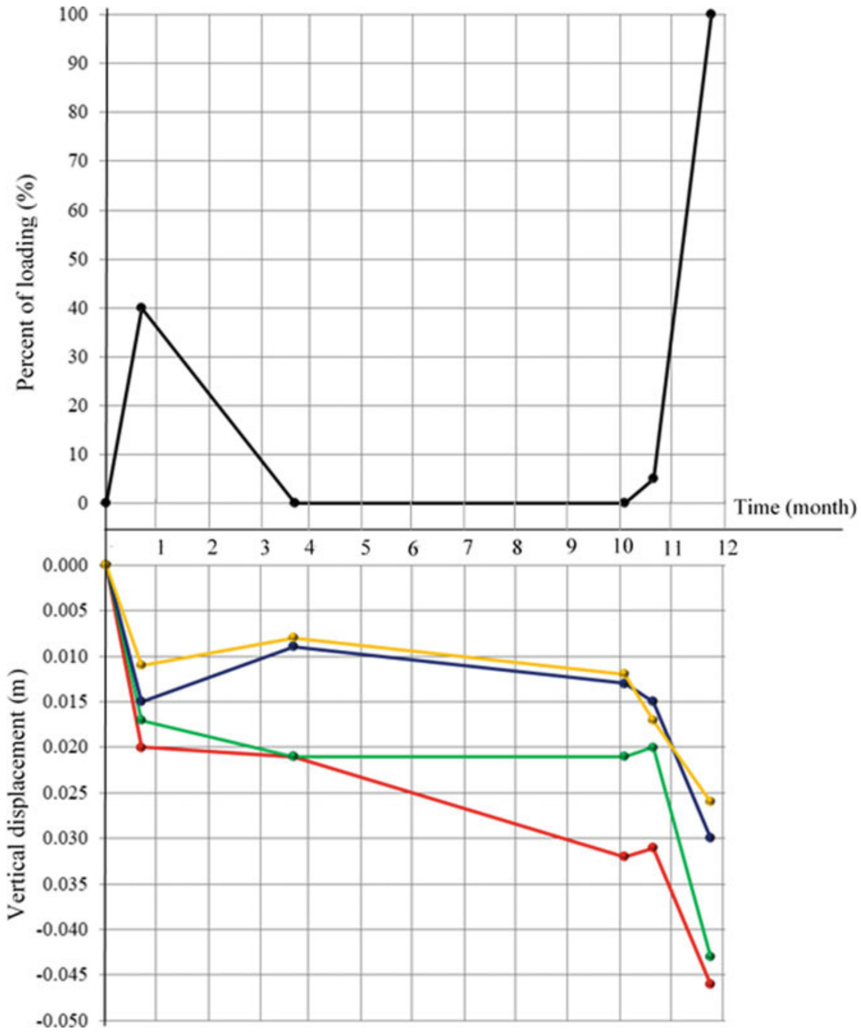

Fig. 4 Dependency diagrams of vertical strain of deformation control benchmarks on loading of a silo 1.4: green color–DCB-25 (deformation control benchmark-25); blue color–DCB-26; orange color–DCB -27; red color–DCB -28

as individual elements of the scheme using rods, plates (plane elastic problem) or solid bodies (three-dimensional problem) [6].

The use of variable bedding values (coefficients of soil reaction) for modeling the reinforced SCE foundation of a bed plate was proposed by V.H. Fedorovskyi. With such numerical calculation, the bedding values (coefficients of soil reaction) determine the stress–strain analysis of the reinforced "cell". This takes into account the nonlinear connection of deformations and stress-strains according to the bilinear

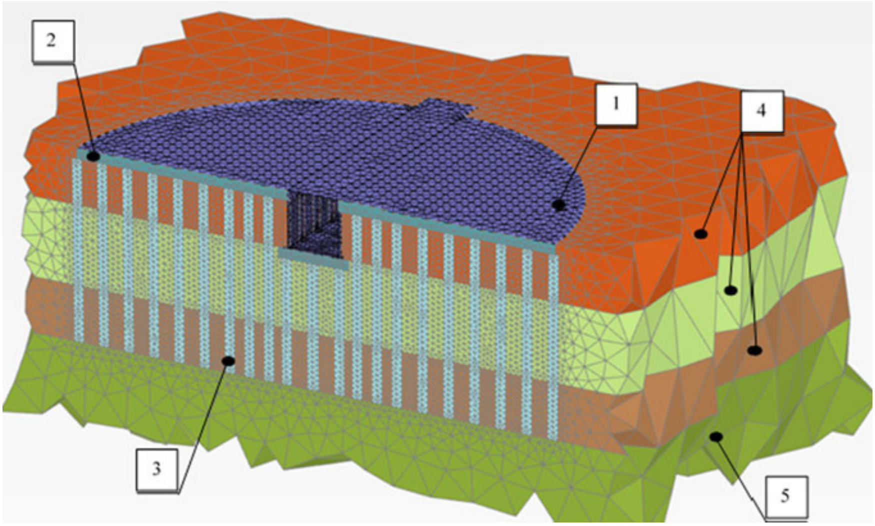

Fig. 5 Modeling of the discrete design model of the reinforced SCE grain storage foundation in the software application "PLAXIS 3D CONNECT Edition V.20": 1–foundation slab of the grain storage; 2–damping layer of crushed stone; 3–soil–cement elements; 4–loose soils to be reinforced, 5–stiff soil

model with reinforcement, displacement of the SCE relating to the soil and extension-type deformation of the surrounding soil.

The combined action of soil–cement elements (SCE) with the soil makes it possible to consider the system "soil-reinforcing elements" as a slab-pile foundation, in which the pile undertakes part of the pressure, and the rest of the pressure is undertaken by the soil. This approach to the calculation of reinforced foundations was proposed by Horikoshi and Randolph in 1999 and improved by the scientists Han in 2009 [7].

The design model of the system is presented in Fig. 5.

To this date, the models of linearly deformed half-subspace (layer-by-layer compaction or banded precipitation) prevail over mathematical method of designing the foundations, reinforced with soil–cement elements. The principle of calculation of house footings on the reinforced foundation by the method of layer-by-layer compaction of foundations provides for the usage of its weight-average mechanical parameters, which, in turn, are determined by the ratio of bank yard and reinforcement material in the total volume of the foundation. The disadvantages of these models are: overestimation of the foundations distribution properties, weak substantiation of the limitation of the bulb of pressure, and for the model of a linearly deformed layer–the necessity for a stiff layer at shallow depths.

The peculiarity of soils is their plastic (rather than elastic) deformation, that is impossibility of the foundation transition into the initial state after its unloading. This is due to the fact that when the limit of proportionality between stresses and strains is reached, the soil becomes plastic. This soil property is taken into account in linearly deformed models by means of increasing the design resistance by 20%. However, the creation of a universal model, that would take into account the simultaneous action of elastic and plastic deformations is complicated by the introduction of a significant number of parameters, because in this case it is impossible to perform analytical calculations.

The most common model, used in the calculations of foundations performed by the finite element method is Mohr–Coulomb (hereinafter MC) model, primarily due to the sufficiency of standard mechanical parameters of soils: Young's modulus E, strength parameters (angle of internal friction φand specific cohesion c), which are determined based on the results of standard laboratory investigations of soils [8, 9]. However, this model does not take into account the strengthening/consolidation of the bases and foundations, and when it is unloaded, the recovery of deformations (the so-called elastic component of strain) significantly exceeds their actual values and etc.

The main dependence of the above mentioned model is the state-transition diagram of the ideal elastic–plastic body, introduced by Ludwig Prandtl, which is characterized by elastic work to the limit of proportionality of stress to strain, and after its achievement–by infinite increase in plastic deformation at constant stress rate. The total ground distortion is the sum of its elastic and plastic components. In this case, its elastic behavior is described according to Hooke law, while its plastic behavior–according to the associated plastic flow rule. The soil works as an elastic body until the pressure mounts the boundary surface, which should be described by the Mohr–Coulomb failure criterion, and after going beyond the boundary surface, the soil is infinitely deformed at a constant stress value.

For more realistic modeling of soil behavior, it is recommended to use progressive mathematical models. Among such models it is worth noting the models of isotropic hardening "The Hardening Soil", "The Hardening Soil Small" and "Soft Soil" [1, 10–19].

The main difference between the model of isotropic hardening and Mohr–Coulomb elastic–plastic model is strengthening of the foundation soil, which becomes apparent in the change of the boundary surface position in the space of primary stresses.

These models combine two types of hardening: soil shear and soil compaction. The first is caused mainly by the stress deviator, and the second–by compression. These models are suitable for modeling the behavior of different types of soils, including loose soils ("Soft Soil" model). When the load is beyond the soil's elastic behavior, there may develop nonrestorable plastic deformations and the deformation modulus e decreases as well as. Such advanced models use the basics of the plastic collapse theory, not the elasticity theory.

However, the use of progressive models of elastic–plastic behavior of foundations requires the introduction of additional parameters of soil characteristics, which can not always be provided in the technical reports of engineering and geological surveys. In such cases, the calculation data on these models are approximate and not accurate.

The effectiveness of strengthening the foundations of soil–cement elements, manufactured by wet process according to boring and mixing technology is confirmed by the results of field studies of deformations of the silos foundations. All actual subsidence of the foundations did not exceed 30% of the maximum allowable Su = 15 см^2 At the same time, building tilts that were witnessed in the silos were minimal and did not exceed the allowable value of 0.002%.

2 Conclusion

Based on the results of the research, we have arrived at the following conclusions:

1. The results of field studies of deformations of grain storage silos confirm the effectiveness of reinforcement of man-made ground and collapsible soils by their reinforcement with soil–cement elements (SCE), manufactured by wet process according to boring and mixing technology. It should be noted that the actual results of silos subsidence are much lower than expected (calculation) results. The average calculated subsidence value of silo foundations is Sp = 12 cm when using the Linear Elastic model and Sp = 14,5 cm when using the Mohr Coulomb model. The maximum actual silos subsidences were Sф = 4,5 cm
2. In order to more accurately reflect the behavior of the reinforced foundation soil of structures that accept cyclic loading, it is recommended to use advanced mathematical models of soils that take into account isotropic hardening (eg "The Hardening Soil", "The Hardening Soil Small" and, in cases of loose soils–"Soft Soil"). However, the use of advanced models of elastic–plastic behavior of foundations requires the introduction of additional parameters of soil characteristics, which can not always be provided in the technical reports of engineering and geological surveys. In such cases, the calculation data on these models are approximate and not accurate.
3. Designing and construction of house footing on man-made ground requires more detailed engineering and geological surveys. In such a case, it is recommended to coordinate the program of additional technical studies with the design organization that will work out the project of measures for land development.
4. In the absence of data in engineering and geological surveys on the physical and mechanical characteristics of man-made grounds on the construction site, it is recommended to choose the variant of mathematical formulation of soil behavior, which requires a minimum number of initial characteristics. For example, in the analytical calculation by the method of multilayer consolidation using the model of linearly deformed half-subspace with conditional restriction of compressed width (strata), it is necessary to have information on soil density and its deformation modulus. In the case of using finite-element method, the mathematical model Linear Elastic reflects the elastic behavior of the soil and in addition to the deformation modulus of the man-made ground and its density, requires the introduction of the Poisson ratio. To take into account the most unfavorable factors,

the soil density and its deformation modulus of the man-made ground should be chosen as the minimum allowable.

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