Monitoring the deformation parameters of reinforced soil masses

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Abstract. Ensuring that the strength and deformation parameters of a geotechnical massif are determined reliably is an important task when accepting and assessing the quality of ground reinforcement work carried out. The paper considers the existing approach to controlling deformation characteristics of reinforced ground massifs. A brief analysis of the existing method of assigning and checking the deformation characteristics of reinforced soil by means of reinforcement has been made; problems and drawbacks have been determined. The paper presents the results of a study aimed at improving the approach to control the deformation characteristics of reinforced ground massifs. A numerical model of the reinforced ground massif is offered for the prognosis of the geotechnical massif deformation changes. Method of processing the results of field tests of massifs reinforced with vertical elements when determining their deformation parameters is proposed.

1 Introduction

In the construction practice of buildings and structures the method of reinforcing the foundation soils with vertical elements such as columns, piles, posts, etc. is well known. These elements are often made of concrete, soil concrete, soil cement, compacted soil or other inert materials and are part of the reinforced soil mass, which constitutes the foundation for shallow foundations and does not perform the function of a pile foundation. Nowadays, the design and acceptance phase of this type of foundations must be accompanied by field testing, in which the strength and deformation characteristics of the reinforced masses are clarified or verified. In this regard, it is a very urgent task to ensure the necessary reliability of the strength and deformability characteristics of the reinforced massifs.

When designing reinforcement of soils to reduce the compressibility of the basement for buildings and structures on shallow foundations, the main purpose of reinforcement is to increase the deformation modulus of the massif. In accordance with the provisions of the normative documents, the total modulus of deformation of a reinforced soil mass for the preliminary calculation can be made according to the following formula:

$$E_{mas} = \alpha E_{rein} + (1 - \alpha) E_s \tag{1}$$

where $\alpha = V_{rein}/V_s$ – reinforcement factor;

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V_s – the volume of reinforced soil;

V_{rein} – volume of reinforcement elements;

E_{rein}, E_s – Design values for the modulus of elasticity of the reinforcing elements and the ground deformation modulus.

The calculated value of the deformation modulus according to formula (1) must be verified and checked by field tests. The analysis of the requirements and recommendations of the existing normative documents on the design of soil reinforcement allows us to distinguish the following methods of quality assessment and determination of strength and deformation characteristics of reinforced soil masses (reinforced with vertical soil-cement elements):

- method of testing the reinforcing elements with static load;
- method of test drilling of reinforcing elements with taking cores (samples), followed by laboratory testing;
- method of testing the reinforced massifs with static load by using punches (punching tests).

Also, in some cases, the normative documents provide for the use of geophysical control methods. However, since such methods allow only a qualitative assessment of reinforcement parameters without the possibility of quantitative assessment of strength and deformability characteristics, they are not considered in the present study.

The method of test drilling of soil-cement piles by core sampling is used to determine the physical and mechanical characteristics of the reinforcement material (density, compressive strength, deformation/elastic modulus, etc.). The method of static load testing of reinforcing elements is in fact an analogue of pile testing of soils. As a result of such tests the bearing capacity of the reinforcing element in relation to the ground is established. These quality assessment methods therefore make it possible to determine the strength and deformation characteristics of the reinforcing elements themselves. This approach to assess the quality of reinforcement of soil masses has been investigated in works [1-6] and shows its effectiveness and relevance. However, it only allows the achievement of the required parameters for a part of the reinforced soil mass, without considering the joint operation of the reinforcing element and the surrounding soil in the massif. Thus, to estimate the strength and strain characteristics of reinforced massifs (integral characteristics), it is necessary either to calculate the corresponding weighted averages using formula (1), which carries a number of errors and assumptions, or to perform additional tests, but already for the massif.

In this context, the die test is of great interest and is considered to be the most reliable way of determining the deformation characteristics of soils. For a reinforced soil mass, die testing allows the integral value of the deformation modulus to be determined without intermediate calculations, taking into account the joint operation of the reinforcing elements and the surrounding soil. However, the widespread use of this method is hampered by the lack of a single approved methodology for conducting die tests for reinforced soil masses.

Currently, the modulus of deformation of the ground using stamps is determined according to the method of National State Standard (GOST) 20276.1. In die testing, the regulated die area ranges from 600 to 5000 cm2 or with corresponding values of diameters from 27.7 to 79.8 cm. The use of standard test methodology and standard die sizes for reinforced massifs can in some cases result in a significant over- or underestimation of the obtained deformation characteristics, since the reinforcing elements can have diameters ranging from a few centimetres to one and a half to two metres. Soil masses reinforced with large-diameter reinforcing elements can be tested using custom-designed dies, but this would require a larger-scale loading system, the size of the die and the interpretation of the test results due to the need to consider the ratio of the cross-sectional areas of the reinforcing element, the die and the soil falling within the influence area of the die. Studies are known in which this problem is partly solved by the use of larger dies, for example, non-standard area

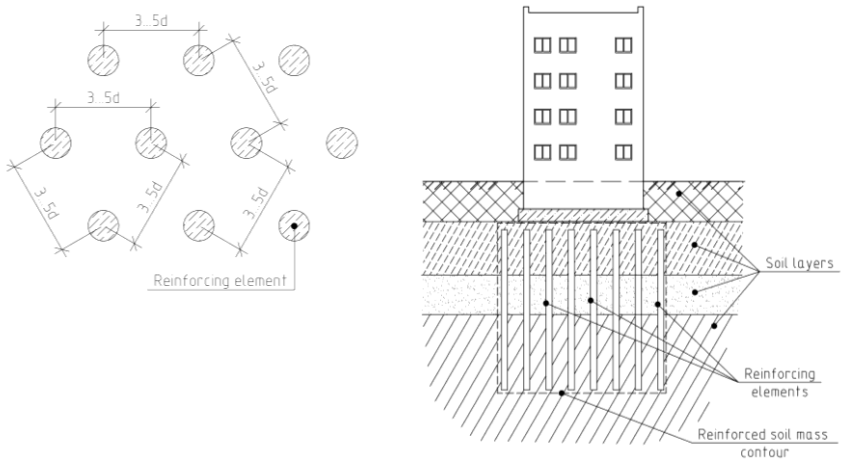
dies are used to determine the modulus of deformation of a foundation reinforced with vertical macadam piles [2, 3]. However, these examples reflect special cases of non-standard tests and there is currently no methodology for conducting and processing the results of die tests that provides the necessary reliability in determining the characteristics of reinforced massifs.

In order to address the above issues, the authors carried out a study of the performance of a soil mass reinforced with vertical soil-cement elements. The study is divided into three stages.

1) Analysis of existing approach to assignment of reinforcement parameters of soil massifs is performed in order to determine criterion for assignment of die size for reliable estimation of deformation characteristics of reinforced massif.
2) A numerical model of vertically reinforced soil massif is developed and justified for the purpose of subsequent modelling of die testing and evaluation of the effectiveness of the defined die sizing criterion.
3) Methodology for processing the results of die tests in controlling the deformation characteristics of vertically reinforced soil-cemented massifs is improved.

1.1 First stage of the study

The existing approach to the design of reinforced soil mass reinforcement is to transform its properties by introducing special elements that provide improved deformation and strength characteristics. The value of the required characteristics is established in the course of iterative calculations of the foundations of the designed objects according to the first and second group of limiting foundations. In order to ensure the required characteristics, the vertical reinforcement elements are placed in the area of the foundation of the structure. The spacing of reinforcing elements, their diameters and material characteristics depend on the required deformation characteristics of the massif, which are to be achieved by reinforcement. Analyzing the authors experience in the reinforcement of soils by vertical elements [6, 7] and examples of implementation of such reinforcement published by other authors [8, 9, 10] and recommendations of regulatory documents one can conclude that when reinforcing clay and sandy soils the reinforcement elements are usually placed in a staggered arrangement with a step of three to five diameters of reinforcement elements (Figure 1).



a) b)

Fig. 1. Layout of reinforcing elements in plan (a) sectional view (b)

By varying the diameter-dependent spacing of the reinforcing elements, the deformability and strength of the reinforced massif can be increased or decreased through the corresponding influence of the material of the reinforcing elements. When designing the reinforcement, it is assumed that the deformation characteristics of the reinforced massif in the foundation of a building are achieved by a certain ratio of the volume of the reinforcing elements to the volume of the whole reinforced massif under the foundation, this volume ratio is expressed as a reinforcement factor ($\alpha = V_{rein}/V_s$). By differentiating the calculation of reinforcement parameters according to the depth of reinforcement, the reinforcement factor can be expressed as the ratio of the cross-sectional area of the reinforcing elements to the area of the massif, which receives the load from the building foundation in the plane perpendicular to the direction of the reinforcement ($\alpha = S_{rein}/S_{mas}$). Thus, the deformation characteristics of a reinforced massif mainly depend on the reinforcement coefficient α (see formula 1). Consequently, when controlling the deformation characteristics of a reinforced mass in the test section, the design value of the reinforcement factor must be ensured for the load application spot (die spot). In other words, the die test in the test section must provide the same operating conditions for the fragment of the massif (within the area bearing the die loads) as for the completely reinforced massif bearing the loads of the whole building.

Consequently, the criterion for assigning a die size when checking deformation characteristics can be formulated as follows: The die area when checking the deformation characteristics of a massif reinforced with vertical soil-cement elements must be directly proportional to the cross-sectional area of the reinforcing element, and the proportionality factor depends on the reinforcement factor α, and can be calculated by the formula:

$$S_d = k_d S_{rein} \tag{2}$$

where S_d – die area, cm2;

k_d – the proportionality factor for assigning the stamp size, calculated as $k_d = \frac{1}{\alpha}$;

S_{rein} – cross-sectional area of the vertical reinforcing element, cm2;

It should be noted that the exact observance of the proposed criterion may in some cases lead to the need to manufacture dies of "inconvenient" dimensions, requiring the organisation of large-scale loading platforms or anchoring systems or requiring high precision to the observance of geometric parameters of the product. For this reason it is advisable to determine:

1) The permissible range of variation of the proportionality factor kd in the manufacture of dies;
2) Correction factor kcor to the die test results required in case of non-compliance with kd during die manufacturing.

The interval of variation of the proportionality factor kd can be determined on the basis of the previously identified recommendations for adhering to a reinforcement pitch of 3...5d (where d is the diameter of the reinforcing element). For this purpose the whole reinforced mass can be divided into identical triangular prisms, at the base of which are regular triangles with a side length l (where l = 3...5d) and whose vertices coincide with the axes of cylindrical reinforcing elements of diameter d.

The ratio of the volume of a part of the reinforcing elements within one prism to the volume of that prism is the reinforcement factor. The coefficient of proportional assignment of die size kd can be expressed through the reinforcement factor α, and the volume of the prism and the fragment of reinforcing element through the product of their cross-sectional areas by the height. Further, by writing down the areas of triangle and semicircle according to the known mathematical formulas, reducing by the height of prism, as well as replacing the length of triangle side by l=n·d (where n is the recommended multiple of diameter in assigning the pitch of reinforcing elements - from 3 to 5), we obtain:

$$k_d = \frac{1}{\alpha} = \frac{S_s H}{S_{rein} H} = \frac{\frac{1}{2} sin60 \cdot l^2}{\frac{\pi d^2}{4}} = \frac{\sqrt{3}(n \cdot d)^2}{\pi \cdot d^2} = \frac{\sqrt{3} n^2}{\pi} \quad (2)$$

By substituting the recommended values of n between 3 and 5 into formula 3, it is possible to calculate the interval of variation of the proportional coefficient kd- between 5 and 15. Thus, when controlling the deformation characteristics of a reinforced massif by means of a die test, the die area must be assigned depending on the cross-sectional area of the reinforcing element and the design value of the reinforcement factor α, but it must be not less than 5 and not more than 15 cross-sectional areas of the reinforcing element.

The calculation of the correction factor kcor to the die test results for interval values of the proportionality factor kd in die manufacturing, as well as the development of the methodology for its application are presented in the following steps of the study.

1.2 Second stage of the study

In the second stage of the study, the task of evaluating the effectiveness of the established criterion for die sizing is solved using numerical modelling. For this purpose, a model of a reinforced foundation with vertical reinforcement is developed and justified.

Since the purpose of soil reinforcement is to provide the required compressibility of the building foundation, the model developed should reflect the result of reinforcing the soil mass to provide the required deformability characteristics. Since the ground mass at the base of the building is to be reinforced, the reinforcement elements should predominantly absorb compressive forces.

Considering the above-mentioned requirements, the authors developed a model of a reinforced foundation with vertical elements, which is shown in Figure 2.

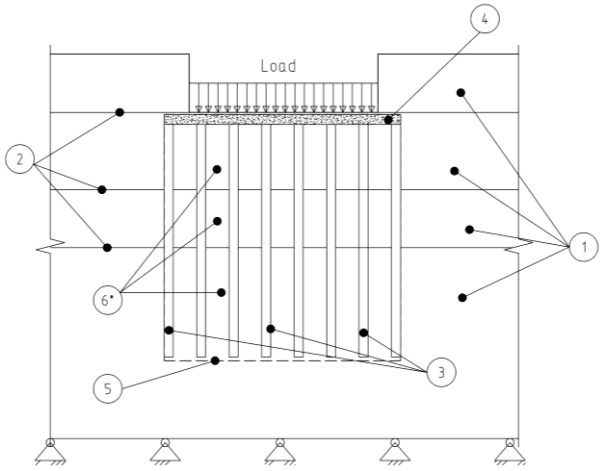


Fig. 2. Model of a reinforced base with vertical reinforcements

The main elements of the model of a reinforced foundation with vertical elements include:

1 - engineering-geological layers in the base of the structure with initial values of physical and mechanical characteristics;

2 - borders of geotechnical layers distribution determined in the course of geotechnical surveys;

3 - vertical reinforcement elements located within the calculated depth ensuring the required compressibility and strength of the structure base.

4 - cushion between reinforcing elements and foundations of the structure ensuring redistribution of stresses between reinforcing elements and the ground;

5 - contours of the massif reinforced with vertical elements, the dimensions of which have been established in the course of the calculations in order to ensure the required compressibility and strength of the structure's foundation;

6* - transformed soils around the reinforcing elements. This element is included in the model as an optional extra, depending on the type of reinforcement. For example, in case of application of the method of wells rolling the soil is compacted during the formation of the reinforcing element body. [7]

The proposed model should be used in FEM-analysis software packages when solving corresponding problems in three-dimensional formulation. Reinforcing elements are placed along the area of the building foundation in a staggered arrangement with an even step of 3...5d, where d is the diameter of the reinforcing element. The spacing of reinforcing elements is dictated by the type of material and diameter of reinforcing elements, which ensures the required strength and compressibility of the reinforced bed. The model design domain is limited by the depth at which the ratio of residual and additional normal stresses is fulfilled, which is equal to $\frac{\sigma_{zp}}{\sigma_{zg}} = 0.5$.

The model requires an input data base containing information about the ground conditions, the parameters of the reinforcing elements, the magnitude of the loads, etc. It is possible to determine some of these parameters from analysis of the input data and design considerations. At the same time, additional experimental investigations are required to obtain specific data, which include parameters of reinforcing elements and, in some cases, transformed soil around reinforcing elements.

In order to confirm the adequacy of the developed model, its verification was carried out by comparing the results of simulation of a fragment of reinforced soil mass according to the proposed model with the results of direct tests.

To verify the model, a construction site in Oktyabrsky district of Novosibirsk was selected where soil reinforcement by reinforcing vertical soil-cement elements manufactured according to the deep mixing technology was implemented (Fig. 3). The diameter of the reinforcing elements is 700 mm and the spacing is 3d (staggered). The depth of the reinforcing elements is 8 m. During fabrication of the reinforcing elements the soils were mixed with cement in the following proportion: cement consumption was 300 kg per 1 m3 of the body of the soil-cement element. Subsequent laboratory testing of samples of ground-cement elements made according to the above formulation showed values of the elastic modulus of the material of 310 MPa.

Fig. 3. Manufacturing vertical reinforcements using deep mixing technology

The basement of the test site within the investigated depth is composed of two geotechnical layers:

- Geotechnical unit -1 - technogenic soil. Sandy loam with inclusion of construction debris. The average thickness of the layer is 80 cm.
- Geotechnical unit-2 - sandy loamy plastic non-sagging sandy loam with interlayers of sand. IGE-2 soils have the following physical and mechanical characteristics: density 2.02 g/cm3; humidity 19.4 %; plasticity number 5 %; deformation module 9.8 MPa; specific coupling 12.1 kPa, angle of internal friction 26°. The thickness of the layer is more than 8 m.

The determination of the deformation characteristics at the test site was carried out by means of a die test. The die size was set according to a previously developed criterion and the area of the die was 38,000 cm2. The die size assignment proportionality factor kd was set to 10. A picture of the die is shown in Figure 4.

Fig. 4. A 38,000 cm2 test die for reinforced soil

- The structure of the Reinforced Massive Test Facility consisted of:
- a circular, rigid die with a diameter of 2.2 m;
- a device to create and measure the load on the die (jack, oil station);
- an anchoring device (beam and anchoring reinforcements);
- a device to measure die settlement (deflection gauges, displacement sensors).
- Between the reinforcing elements and the base of the die, a macadam cushion was provided to ensure load redistribution from the die between the reinforcing element and the surrounding soil. A photograph of the installation is shown in Figure 5.

Fig. 5. Setting up a die test

A three-dimensional digital model of the reinforced array was created in the Midas GTS NX software package (Figure 6).

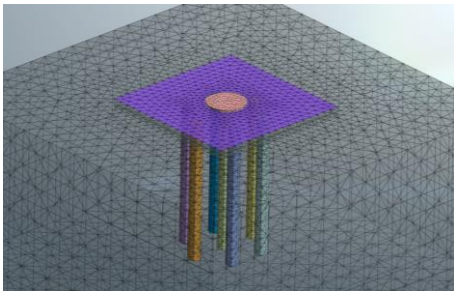


Fig. 6. Digital model of a die-reinforced massif

In the digital model, a circular die with an area of 38,000 cm^2 was used in the same way as in the in-situ study. The load transfer on the die was simulated in steps until the pressure under the die base reached 300 kPa.

The deformation modulus based on the results of the die test (both full-scale and digital) was calculated using the formula:

$$E_d = (1 - v^2)K_1 D \frac{\Delta p}{\Delta S} \quad (3)$$

where v - transverse expansion coefficient (Poisson's coefficient), taken as 0.27;

K_1 - coefficient, taken as 0.79 for a rigid circular die;

D - die diameter, cm;

Δp - pressure increment on the die, MPa, equal to $p_2 - p_1 = 300 - 200 = 100$ kPa;

ΔS - the increment of die settlement corresponding to Δp, cm.

The results of the in-situ and digital tests obtained data on the compressibility of the reinforced soil. The in-situ tests showed a deformation modulus of 28 MPa and the digital simulation showed a deformation modulus of 25 MPa. The graphs of the die settlement are shown in Figure 7.

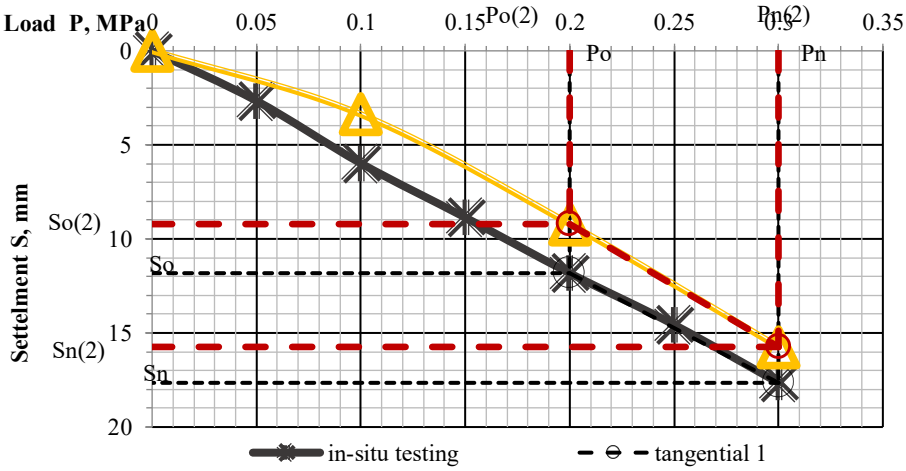


Fig. 7. Die settlement graphs for in-situ testing and digital modelling

Analysing the results of the die test and the numerical simulation, it can be concluded that the convergence of the results is high. Discrepancy in data of determination of compressibility of reinforced soil mass does not exceed 10 %. As a result, it is concluded that the proposed model is adequate.

Using the verified model, further study of the influence of die size on the reliability of determining the deformation characteristics of the reinforced massif was carried out. For this

purpose, 12 test sections of reinforced massif are simulated, the compressibility of which is evaluated by dies of different sizes. The die size assignment proportionality factor ksh was 5, 10 and 15 when assigning die sizes.

In the numerical model, the die load is modelled in two steps from the condition of providing pressures under the die sole p1=200 kPa and p2=300 kPa

A fragment of the deformed view of the model during the digital simulation of the die loading is shown in Figure 8.

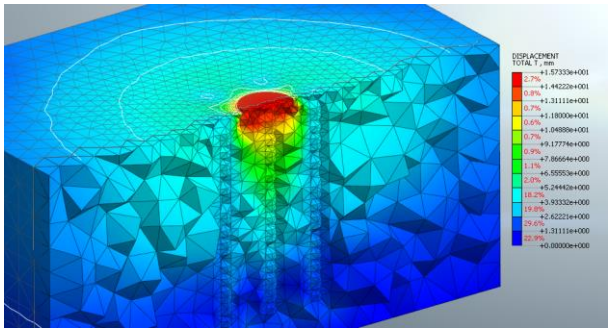


Fig. 8. Fragment of a deformed model view

As a result of modelling 12 sections of reinforced massifs, a database of the compressibility of these massifs under the influence of dies of various sizes was obtained. From the compressibility data, the deformation moduli of the reinforced massifs were calculated.

The study showed that the use of dies that do not provide the designed ratio of the area of reinforcing elements to the area of the whole reinforced massif can significantly overestimate or underestimate the strain modulus values obtained from the test results. The simulation results as a function of the deformation modulus of the reinforced massif and the die proportional ratio kd are shown in Figure 9.

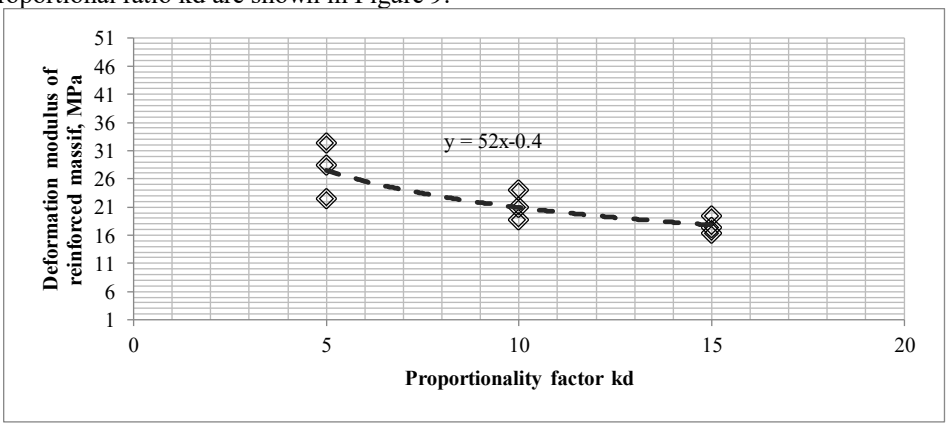


Fig. 9. Functional dependency

Further statistical processing of the simulation results with the determination of the value of the correction factor when the required die size is not observed during testing, as well as the methodology for its application, are carried out in the third stage of the study.

1.3 Third stage of the study

Statistical processing of the deformation modulus values obtained in the course of modelling makes it possible to obtain a functional dependence allowing to determine the value of the correction factor to the results of die tests depending on the die size applied.

The influence of the die size, described through the proportionality factor kd, on the value of the strain modulus of the reinforced massif, is described by the following equation:

$$E_{\text{y}} = \frac{\text{C}}{\sqrt[2.5]{k_d}} \tag{4}$$

where C is a constant coefficient determined from the statistical treatment of the simulation results (C=52);

Calculation of the correction factor to the die test results in the event that the proportionality factor kd for the assigned die does not correspond to the reinforcement factor for the entire reinforced mass is as follows:

$$K_{cor} = \frac{\text{C}\sqrt[2.5]{\alpha}}{\frac{\text{C}}{\sqrt[2.5]{k_{df}}}} = \sqrt[2.5]{\alpha \cdot k_{df}} \tag{5}$$

where α is the design value of the reinforcement factor for the entire reinforced base, the deformation modulus of which is verified by the die test;

k_{df} – the actual value of the proportionality factor for the die used in determining the deformation modulus of the reinforced massif, and calculated using the formula (2).

A reliable deformation modulus value of the reinforced massif E_{frein}, determined from the results of the die tests, can be calculated as

$$E_{f\ rein} = K_{corp} E_d \tag{6}$$

where K_{corp} – correction factor, determined according to the formula (6);

Ed – deformation modulus value of the reinforced massif obtained from a die test using a die with a proportionality factor k_{df} (calculated from formula (2)) ranging from 5 to 15.

2 Conclusion

1. A criterion for assignment of die size for reliable assessment of deformation characteristics of reinforced massif by direct die tests is defined;
2. A model of reinforced base by reinforcement with vertical elements is developed, justified and verified;
3. A functional dependence has been obtained which makes it possible to determine the value of a correction factor to the results of die tests depending on the size of the die applied.
4. The procedure of calculating the deformation characteristics of reinforced ground massifs by means of applying a correcting coefficient to the results of die tests which takes into account the size of the die assigned to the test is improved.

References

1. I.O. Grebennikov, Bulletin of Siberian Transport University **2(61),** 123-130 (2022) https://doi.org/10.52170/1815-9265_2022_61_123
2. Z.G. Ter-Martirosyan, A.Z. Ter-Martirosyan, V.V. Sidorov, MSCU Bulletin **13(3)(114),** 271-281 (2018) https://doi.org/10.22227/1997-0935.2018.3.271-281

3. R. Lukpanov, S. Enkebayev, Д. Tsygulev, Engineering Journal of Satbayev University, **143(2),** 252–260 (2021) https://doi.org/10.51301/vest.su.2021.i2.33
4. V.V. Semkin, A.V. Shaposhnikov, M.N. Ibragimov, Methods of quality control of artificial foundations made of consolidated soils (2020)
5. V.V. Semkin, A.V. Shaposhnikov, M.N. Ibragimov, Methodological guide for strengthening soils by methods of jet grouting, deep mixing, injection with microcement based solutions, collar injection in hydrofracture mode (2020)
6. A. Lanis, D. Razuvaev, P. Lomov, MATEC Web of Conferences **216,** 01006 (2018) https://doi.org/10.1051/matecconf/201821601006.
7. P. Lomov, A. Lanis, D. Razuvaev, M. Kavardakov, Sciences in Cold and Arid Regions 13(5), 357-365 (2021) https://doi.org/10.3724/SP.J.1226.2021.21040
8. A.L. Lanis, A.M. Popov, P.O. Lomov, Proceedings of higher educational institutions. Construction **7(703),** 29-38 (2017)
9. O. Makovetskiy, S. Zuev, Procedia Engineering **165,** 504-509 (2016) https://doi.org/10.1016/j.proeng.2016.11.726
10. N.G. Seregin, et al, Forestry bulletin **24(5),** 104-108 (2020)
11. F. Zekhniev, D. A., Korpach, Bulletin of Perm National Research Polytechnic University. Construction and architecture **8(4),** 116-125 (2017) https://doi.org/10.15593/2224-9826/2017.4.12