Stress-strain state of base strip foundation strengthening with a structure combined with a blind area

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Abstract. The article discusses a modified strengthening construction of the strip foundation, combined with a blind area, which makes it possible to increase the efficiency of this strengthen method. The results of experimental studies to verify the operability of structural protection measures are presented, and also to obtain the basic regularities of the stress-strain state of the foundation construction of a frameless building operated on an unevenly deformable base. The results of numerical studies for two cases are presented: strip foundation without strengthening construction, and strip foundation with strengthening construction. As a result of numerical studies, the dependences of the average vertical movements of the footing of the strengthened and non- strengthened foundation on the load, as well as its full bearing capacity in both cases, were obtained. The most effective application of this strengthening construction is in conditions in which the maximum critical pressures can be reached on certain sections of the strip foundation. For example, with significant uneven settlements along the length of the strip foundation.
Keywords: uneven deformations of the base, strip foundation, strengthening construction, carrier blind area, limit load.

1 Introduction

Deformations of construction (tilt, various forms of bending, skew), as a rule, are the result of uneven deformations of the base. The nature of their occurrence is different and they manifest themselves in different ways, but in all cases their effect on the building is identical. Uneven deformations of the base are the result of force influences on the foundation due to the heterogeneous structure of the soil, different thickness of soil layers, or deformation effects: complex deformation of the earth's surface due to soaking of loess subsidence, saline and swelling soils and mining of coal and ore deposits [1,2,3]. The vast majority of real projects in modern design practice are carried out according to the method

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of permissible settlement or tilts, the use of which does not always avoid the appearance of cracks in the structures of an aboveground structure, the disclosure of which exceeds the permissible limits for the second group of limit states [4, 5]. In particular, the method of permissible settlement gives a large error in relation to buildings whose structures are weakened during long-term exploitation [6,7,8]. In the same cases, when the calculation is carried out taking into account the deformability of the base, it is usually performed in a linear formulation, since in fact the dimensions of the foundations are determined on the basis of the calculated resistance of the soil of the base, which is practically the value limiting the scope of the formulas of the linearly deformable medium. However, the use of linear calculation theory, as a rule, leads to underutilization of the bearing capacity of foundation (exceptions are only weak highly compressible soils), as well as to errors in determining contact stresses redistributed along footing of foundation [9]. Therefore, the development of new optimal technical solutions is relevant, the use of which will ensure the further normal exploitation of structures experiencing the effects of uneven deformations of the base [10, 11, 12, 13, 14]. The reduction of the calculated influence of uneven deformations of the foundation on the building, as a rule, is carried out through the use of constructive measures based on the principle of designing according to a malleable structural system. Constructive measures based on the application of the principle of rigidity include measures aimed at increasing the rigidity and load-bearing capacity of both separate structural elements and the building as a whole [6,7]. The most traditional, although not the most effective way to increase the bearing capacity of foundations is to increase their supporting area by various methods [15,16].

2 Methods

2.1 Construction of strengthening of the strip foundation, combined with the blind area

The article discusses a modified strengthening construction of strip foundation, combined with a blind area, which makes it possible to increase the efficiency of this strengthening method. The effect of using this construction is achieved by transforming the contact stress diagram on the footing the foundation by transferring some part of the load acting on the foundation outside the footing, as well as increasing the rigidity of the foundation structure in the vertical and horizontal directions by analogy with a reinforced concrete belt. The main features of the construction include:

- the transfer of the vertical load from the structure to the strengthening construction is carried out through support spikes pivotally supported on the upper part of the "Г"–shaped structure;
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- the moment arising in the strengthening construction from the distributed pressure by its footing is perceived by a pair of forces - prestressed anchors passing through the foundation body and directly by the foundation wall itself;
- depending on the factor determining the occurrence of uneven deformations of the base, a fundamentally different functional purpose of the strengthening construction is possible;

- in order to eliminate frosty heaving of the soil located under the strengthening construction, instead of a pillow device made of compacted non-porous material, it is possible to use a tongue-and-groove fence located under the edge of the horizontal plate in order to prevent moistening of the base. At the same time, it is recommended to perform the immersion of the tongue-and-groove fence to a depth exceeding the depth of formation of continuous sliding surfaces in case of loss stability of the base.

2.2 Experimental study of the interaction of the "base – foundation – strengthening construction" system

Despite the existing cases of the use of similar constructive measures when performing construction work to strengthen the foundations of buildings exploitationed on an unevenly deformable base, there is actually no methodology for calculating them that is sufficiently substantiated by experimental data. In this regard, they need to conduct experimental studies that establish the effectiveness of their application and the scope of their possible use, depending on various factors, as well as the features of their interaction with the base and the strengthening construction the bulding.

In addition, studies aimed at improving the methods of calculation, design and diagnostics of foundations and bases of foundations on solving the problem of the interaction of the "bases – foundation – upper structure" system during the formation of local zones of plastic deformations in the base, as well as reducing the rigidity characteristics of building structures as a result of their wear during exploitation, have not lost relevance.

Checking the operability of structural protection measures, as well as obtaining the basic laws of the stress-strain state of the foundation structures of a frameless building exploitation on an unevenly deformable base, is carried out by testing small-scale fragments of a strip foundation of increased bending stiffness (taking into account the influence of an aboveground structure) and a soil base experiencing pressure exceeding its design resistance.

Each experiment is carried out simultaneously for two fragments of a strip foundation, located parallel at a distance of 800 mm between their axes and connected on top by a metal traverse that distributes the load evenly between the foundations and along their length (fig. 1).

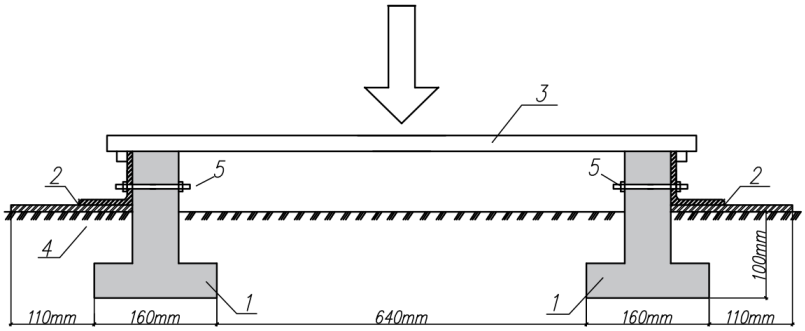

Fig. 1. Layout of the tested fragments: 1 - fragments of strip foundation, 2 - strengthening construction, 3 – traverse, 4 – soil, 5 – kinematic rod system.

The tests are carried out by static loading until the bearing capacity of the base is completely exhausted, the criterion for evaluating which is significant non-stabilizing

precipitation of the tested fragments of the ribbon foundation and the appearance of a visually observable soil stick out.

Loading is carried out by a 25-ton, pre-drilled hydraulic jack. The support for the jack is a metal traverse fixed to the frames in the upper part of the stand.

During the test, a system of stepped loading of the foundation is used. The loading process begins with the removal of zero counts 2 times with a time interval of at least ten minutes. The load is applied in steps equal to 1/15-1/20 of the expected maximum load, determined by the formula (5.32) [4]. After setting the next stage of loading on the foundation, the exposure is carried out under load until the conditional stabilization of the precipitation of 0.01 mm/min., determined by the hour-type indicators, but not less than ten minutes. The readings on the instrumentation are taken twice - at the beginning and end of the interval. In order to reduce the error that occurs due to the fact that the process of taking readings is stretched over time, readings from the instruments are taken twice in the forward and reverse direction, and then their arithmetic mean is determined. The calculation of vertical movements is performed by determining the increments of the hour-type indicator readings as the difference between the countdown at a given time and the initial countdown on the device. For the vertical movement of a fragment of the strip foundation at each stage of loading ⊗S, the arithmetic mean of the increments of the readings of the four hour-type indicators placed on this fragment is taken.

With each subsequent loading stage, the cycle repeats. With the appearance of progressive, non-stabilizing sediment fragments of the strip foundation, as well as visually observed signs of loss of stability of the base, the time and level of load at which the loss of the bearing capacity of the base occurred is recorded.

Partial adjustment of the loading time and stages is allowed during the experiment.

Characteristics of the soil massif, which is used as the base of the tested fragments of the strip foundation during the experiment: internal friction angle, $\varphi = 32°$; specific cohesion, $c = 16$ kPa; modulus of deformation, $E_0 = 40$ MPa; Poisson 's ratio $\nu = 0{,}27$, unit weight of the soil of natural humidity, $\gamma = 19{,}875 \pm 0{,}15$ kN/m^3.

As the tested foundation , small-scale fragments of a rigid reinforced concrete strip foundation of a T- shaped shape with the following geometric parameters are used:

- length 500 mm;
- width footing 160 mm;
- width of the foundation wall 60 mm;
- height of the distribution cushion – 60 mm;
- full height 185 mm;
- depth of laying 100 mm;
- total area of the footing – 0,16 m^2.

The construction of the "carrier blind area" is made of welded metal Г-shaped elements (fig. 1) and is attached to the foundations using a kinematic rod system that allows determining the bending moment at the attachment point. A feature of the strengthening construction under test is its malleable coupling with the foundation structure with a one-way connection in the vertical direction. Fastening of the structure of the "carrier blind area" to the foundation body in each section is carried out in two hinged nodes with a preliminary stress created by tension the bar on the foundation concrete.

2.3 Numerical research methodology

The design model for numerical studies is a two-dimensional rectangular array with dimensions in terms of 1000x500 mm and a thickness of 1000 mm, operating under conditions of plane deformation. The dimensions of the array are taken based on the following considerations:

- half of the length of the soil tray is taken as the length of the array, due to the symmetry of the working conditions of the soil array within its limits;

- the height of the array is taken in such a way as to provide a depth sufficient for the formation of zones of plastic deformations under the footing of the simulated foundation. By [17] the maximum depth of development of plastic zones can be determined by the formula

$$z_{\max} = b \cdot \frac{\phi + \sin}{\phi \cdot \cos} \quad (1)$$

where b – the width of the footing of the foundation; φ - the angle of internal friction of the soil under the footing.

Characteristics of the strip foundation fragment modeled in this study: the depth of laying the strip foundation 100 mm; width footing 160 mm; width of the foundation wall 60 mm; modulus of deformation of the material E = 21000 MPa; Poisson 's ratio ν = 0,16.

The strengthening construction was adopted with an extension of 160 mm and a thickness of 20 mm. Modulus of deformation of the strengthening construction material - 210000 MPa, Poisson 's ratio - 0,16.

At the first stage of loading, a uniformly distributed load of 375 kN/m is applied to the continuous triangular elements modeling the top of the cross-section of the foundation, which corresponds to the average pressure along the sole of the foundation of $P_{average}$ = 187.5 kPa and the load on the foundation of 30 kN.

At each loading step, the average settlement of the foundation sole was determined as the arithmetic mean of the settlement of the middle and its extreme points, as well as the total vertical load acting on the foundation at a given time was determined.

The calculation was performed for two cases:

- strip foundation without strengthening construction;

- strip foundation with strengthening construction.

The end of the calculation was considered a complete loss of the bearing capacity of the base.

The calculation was performed in the Plaxis 2D software package for plane deformation conditions [18, 19, 20].

3 Results

As a result of numerical studies, the dependences of the average vertical movements of the footing of the strengthening and non- strengthening foundation on the load of Fig. 2, as well as its full bearing capacity in both cases, were obtained.

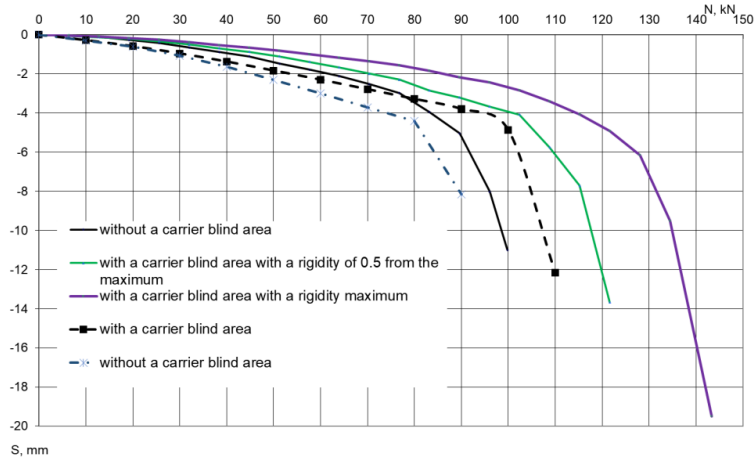

Fig. 2. Graphs of dependence of the foundation settlement on the load (dotted lines are curves obtained by calculation using FEM)

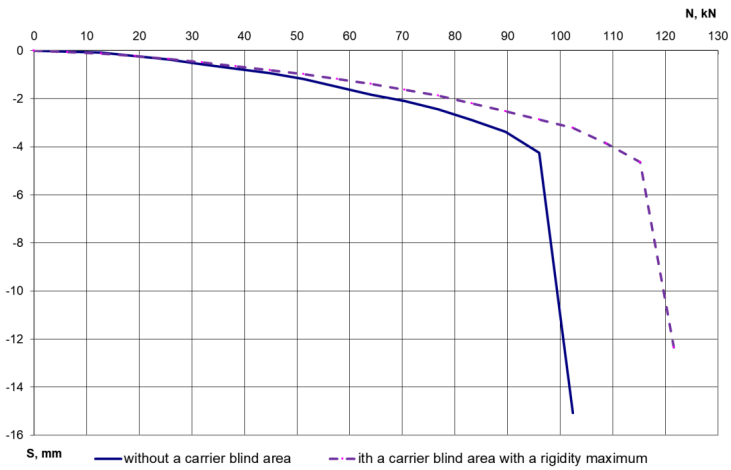

Fig. 3. Averaged experimental dependences of settlement on load for foundations with a basement

Table 1 Bearing capacity of the strip foundation

Feature of the tested foundation structure	Limit load on the foundation, Nu, kN		$\frac{N_{u,e}}{N_{u,t}} \cdot 100\%$
	experimental $N_{u,e}$	theoretical $N_{u,t}$	
Foundation without strengthening construction			
without a basement	99,8	90	110,89
with a basement	96		106,67
Foundation with strengthening construction maximum rigidity			
without a basement	143,3	110	130,27
with a basement	121,6		110,54

4 Discussion

The load corresponding to the beginning of the formation of zones of plastic deformations under the edges of the foundation coincided quite well with the load determined by the Puzyrevsky formula, the discrepancy in the results is up to 5%

The data of the limit bearing capacity of a strip foundation with and without strengthening construction obtained experimentally and based on the results of numerical studies are presented in Table 1.

Comparison of the results of determining the limit load by calculation and according to experimental data gives a discrepancy between them:

- for foundation without strengthening construction – 6-10 %;
- for foundation with strengthening construction – 10-30 %.

Analysis of the graphs of foundation settlement obtained numerically and experimentally (fig. 1, 2) showed that the dependence of deformations on stresses in both cases is nonlinear. At the same time, the settlement curves obtained theoretically correspond to experimental ones to a greater extent on a conditionally linear deformation site.

It should also be noted that as a result of numerical studies, the process of formation of plastic areas in the soil massif has been traced. It is established that when the base interacts with the foundation, the nucleation of zones of plastic deformations begins under the edges of the foundation and with increasing load develops laterally, up along the lateral surface of the foundation up to the surface of the array and down under the sole of the foundation until their complete unification and the formation of a triangular compacted core. The indicated character of the development of zones of plastic deformations is in good agreement with the results of similar studies given in the work [17].

In the case of interaction with the foundation base strengthened with the "carrier blind area " construction, the beginning of the formation of zones of plastic deformations fully corresponds to the case without the reinforcement structure, until they reach a depth of 0,25·b, which corresponds to the value of the calculated resistance of the base soil. Further formation of zones of plastic deformations occurs under the strengthening construction. At the same time, the ground shift occurs both outwards from under the edge of the " carrier blind area " and towards the "dead zone" above the sole of the foundation. After the shear zones from under the "carrier blind area" get access to a free surface, the movement of the shear zones deep into and under the sole of the foundation begins until their complete unification and the formation of a triangular compacted core.

5 Conclusion

1. The effect of using the strengthening construction under consideration is achieved mainly by increasing the bearing capacity of the foundation base and, accordingly, reducing the plastic deformations of the base at a constant load level, as well as by increasing the bending stiffness of the strip foundation, which leads to a redistribution of contact pressures along its footing.

2. The process of the emergence and development of the regions of marginal equilibrium of the soil, as well as the formation of a compacted triangular core at the base of a non-strengthened foundation, obtained as a result of numerical studies, generally corresponds to the results of theoretical and experimental studies described in the literature. At the same time, the discrepancy between the theoretical and experimental values is within the limits: for the initial critical pressure – up to 5%, for the maximum critical pressure – 24%. This allows us to consider the results obtained for the case of a strengthening foundation, for which there are no analytical solutions, to be sufficiently reliable.

3. The decrease in the precipitation of the belt foundation strengthened with a " carrier blind area" at pressures equal to the limit of linear deformability and the ultimate strength of the base of the non- strengthened foundation is 10-35% and 300-500%, respectively. The use of the strengthening construction "carrier blind area" allows to increase the load-bearing capacity of the strip foundation up to 20%.

4. Analysis of the stress-strain state of the base of the strip foundation strengthened by the "carrier blind area" construction showed that an increase in the bearing capacity of the foundation is achieved by restraining the formed areas of limit equilibrium and preventing them from exiting on free surface.

5. The most effective application of this strengthening construction is in conditions in which the maximum critical pressures can be reached on certain sections of the strip foundation. For example, with significant uneven settlements along the length of the strip foundation.

References

1. V. V. Yarkin, Modelirovanie sistemy «Osnovanie – fundament – sooruzhenie» v slozhnykh inzhenerno-geologicheskikh usloviyakh : monografiya [Modeling of the "Bases – foundation – structure" system in difficult engineering and geological conditions : monograph.]. Accessed on: August 16, 2023. [Online]. Available: https://www.iprbookshop.ru/93864.html
2. A. Prokopov, et al., E3S Web of Conf. 164, 07002 (2020). https://doi.org/10.1051/e3sconf/202016407002
3. H. Yao, et al., J. of Rock Mechanics and Geotechnical Eng. 12(1), 188-196 (2020). https://doi.org/10.1016/j.jrmge.2019.07.008
4. Set of RF Rules SP 22.13330.2016 Soil Bases of Buildings and Structures. (Standartinform, Moscow, 2016)
5. A. Shaldykova, et al, Appl. Sci. **10**, 2920 (2020). doi:10.3390/app10082920
6. B. A. Garagash, Nadezhnost' prostranstvennykh reguliruemykh sistem «osnovanie-sooruzhenie» pri neravnomernykh deformatsiyakh osnovaniya [Reliability of spatial adjustable systems "base-structure" with uneven deformations of the base]. Vol I. Moscow: ASV, 2012
7. B. A. Garagash, Nadezhnost' prostranstvennykh reguliruemykh sistem «osnovanie-sooruzhenie» pri neravnomernykh deformatsiyakh osnovaniya [Reliability of spatial adjustable systems "base-structure" with uneven deformations of the base]. Vol II. Moscow: ASV, 2012
8. A. I. Polishchyk, A. A. Petukhov, Bulletin of PNRPU. Construction and Architecture. **1**, 42-51 (2018). doi: 10.15593/2224-9826/2018.1.04
9. C. Zhang, et al., Computers and Geotechnics. **126**, 103734 (2020). https://doi.org/10.1016/j.compgeo.2020.103734
10. V. S. Dalinchuk, M. S. Ilmenderov, V. V. Yarkin, Construction of Unique Buildings and Structures. **11(38)**, 15-26 (2015).
11. I. Galiev, et al., Mater. Sci. Eng.: IOP Conf. Ser. **890 (1)**, 012140 (2020). doi:10.1088/1757-899X/890/1/012140
12. N. Ali Fakher, Fakhruldin M. Kadhim, Al-Qadisiyah Journal for Engineering Sciences. **13 (4)**, 301-305 (2020). https://doi.org/10.30772/qjes.v13i

13. V. Subbotin, Construction and architecture. **8(1)**, 39-47 (2020). doi: 10.29039/2308-0191-2020-8-1-39-4
14. A. A. Altaweel, R. R. Shakir, Mater. Sci. Eng.: IOP Conf. Ser. **1094 (1)**, 012043 (2021). doi:10.1088/1757-899X/1094/1/012043
15. A. O. Viktorova, et al., Inzhenernyj vestnik Dona. **5 (56)**, 59 (2019).
16. V. Golubeva, Science. Engineering. Technology (polytechnical bulletin). **2**, 318-321 (2020).
17. V. G. Berezantsev, Raschet osnovanij sooruzhenij [Calculation of the foundations of structures]. (Izdatel'stvo literatury po stroitel'stvu, Leningrad, 1970)
18. N. Lobacheva, V. Griniov, E3S Web of Conf. **97**, 04006 (2019). https://doi.org/10.1051/e3sconf/20199704006.
19. L. A. Igosheva, V. I. Kleveko, Transport. Transportnye sooruzheniya. Ehkologiya, **3**, 74-86 (2014)
20. Plaxis 2D Reference Manual CONECTION Edition V20 2020 p 523