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Parametric analysis of a strain state of a soil base strengthened with vertical elements

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Abstract

Purpose is to identify vertical displacements of the “soil basem strengthened with piles or micropiles based upon drilling-mixing technology” system relying upon parametric analysis of strain state of the mentioned system, and arrangement of the strengthening elements.

Methods. Mathematical modeling took place for twelve finite-element models using the computing complex SCAD intended to analyze strength of structures by means of finite-element method. Numerical analysis was carried out with variation of elastic-strain modulus of vertical reinforcing elements and change in distance between them (3*d* and 6*d* of micropiles).

Findings. Results of parametric analysis have been obtained for a model without a micropile (non reinforced soil base); a model with a single micropile; a model with two micropiles where distance between them is 1.5 m, i.e. 3*d* of micropiles; and a model with two micropiles where distance between them is 3.0 m, i.e. 6*d* of micropiles. The performed comparative analysis has made it possible to obtain the results proving the hypothesis by the authors as for the specific nature of vertical displacement formation of the “soil base strengthened with piles or micropiles based upon drill-mixing technology” system.

Originality. It has been identified for the first time that basing upon the standardized document for the auger or displacement piles, it is impossible to decrease efficiently vertical displacements while approaching micropiles since distance between the micropiles is 3*d* for elements, developed on the basis of the drilling-mixing, is minimal.

Practical implications. The obtained results of a strain state may become the keystone for the development of the generalized strain theory of the composite “soil base strengthened with piles or micropiles based upon drilling-mixing technology” system as a medium differing in minor changes of strain characteristics.

Keywords: *soil base, vertical element of strengthening, micropiles, drilling-mixing technology, parametric analysis, strain state, finite element method*

1. Introduction

Construction of any structures, based upon soil, needs provision of strength and stability of the aggregate natural and engineering system. If the soil is of low strength or experiences significant strain then extra measures should be taken to provide the required operational factors [1]-[4]. In the process of pressure application to a soil base, exceeding its strength (i.e. its design strength), elastic-plastic strain state is formed making the constructed object either nonoperational or even unserviceable.

Lately, a new concept of object construction on a soil base has originated and developed usefully. The concept relies upon the following. Before construction, the base should be straightened, i.e. it is required to increase its strength and stability parameters in view that after the construction process is over, the margin will be slightly reduced [5]-[7] In this regard, despite the fact that the strengthened system loses some share of strength and stability values, it preserves the margin helping it operates normally.

Among dozens of techniques of a soil base strengthening, a method of vertical elements (i.e. piles and micropiles) based upon either jet-grouting [8]-[11] or drilling-mixing technology [12]-[15] has become the most popular recently in Ukraine as well as in the EU countries. It should be mentioned that despite technological elaboration of the procedures, no theoretical generalization is available.

The problem is dramatized by the fact that practices have shown the following. Piles with 0.5-1.2-m diameter and 6.0-12.0-m length, made on the basis of jet-grouting or drilling-mixing technology, can be shortened and transformed into micropiles [16]-[18]. The practical step, helping solve successfully the problem of soil base strengthening with reinforcement elements which length is up to 6 meters (3.0-6.0 m on the average), i.e. micropiles, complicates understanding of the situation under analysis. The matter is that external similarity of such micropiles with the auger or displacement piles cannot explain their interaction with surrounding soil [19]-[21].

To the first approximation, the system “soil base strengthened with vertical elements (piles or micropiles) made on the basis of drilling-mixing technology” may be understood as the composite one [1], [3], [13]. Nevertheless,

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such understanding cannot explain interaction between the strengthening elements and soil base surrounding them with the assumption that there are hundreds and thousands studies of the specific cases, analyzed by scientific papers, even primary generalization has not been carried out. It should be mentioned that the paper considers right drilling-mixing technology to produce piles and micropiles since it differs in its technological simplicity. Moreover, unlike jet-grouting, it consumes less materials (i.e. cement, sand, pressure air etc.).

To save place for the author's results of parametric analysis, only the main difference between jet-grouting and drilling-mixing technology should be mentioned. The former method is based upon the following. A tool (so-called monitor) is immersed inside the soil base. While rotating, it ruins the soil by means of high-pressure jet (200-350 MPa) [8]-[10], [22]. In such a way, soil-cement column, where cement is the volume majority, shapes instead of the weak unstable soil. The latter technology also relies upon the idea that a tool (so-called boring bit) is immersed inside the soil base. However, the soil is ruined by cutting during the tool rotation rather than a cement jet (under 0.20-0.35 MPa pressure) [1], [13], [23].

Soil chippings, obtained while the destructing, are mixed with cement forming soil-cement element, i.e. soil is not replaced by cement, they are mixed. Such a composite system "soil base strengthened with piles and micropiles made on the basis of drilling-mixing technology" operates much differently from the procedure involving the auger or displacement piles since it forms the specific interaction between the pile (micropile) and the soil base [24], [25]. The interaction specificity relies upon the ratio of strain characteristics of the mentioned system, namely upon insignificant (to compare with the auger and displacement piles) ratio of stress-strain moduli.

Taking into consideration the results of the abovementioned analysis of strengthening situation, the paper implements numerical parametric analysis of such a system. The analysis is intended to obtain vertical displacements of the system with variation of arrangement of the strengthening elements as well as their strain characteristics.

2. Methods

Two conceptually polar approaches are applied to analyze the strain state of soil bases strengthened with piles or micropiles on the basis of drilling-mixing technology. To some extent, each of them takes into consideration interaction between the soil base and strengthening elements developed in it. Nevertheless, for objective reasons neither of the approaches can involve the whole specificity of the interaction since the piles and micropiles, based upon the drilling-mixing technology, are the specific elements with their unique parameters.

Approach one relies upon understanding of a strain state of "a soil base strengthened with piles or micropiles on the basis of drilling-mixing technology" system as a medium having insignificant changes in strain characteristics. The conceptual approach corresponds to the actual situation under which the strain state of the analyzed system is formed. Really, both parts of the system, i.e. base and pile (micropile), differ in dozens of times as for their strain characteristics, being elastic-strain modulus if Poisson's ratio is 0.2-0.3. Strain modulus of loamy soil to be strengthened is of 18-35 MPa range. At the same time, materials of the elements, based upon jet-grouting, have considerably higher values (Table 1).

Table 1. Averaged data for materials of piles (micropiles)

Pile material	Density (ρ), t/m^3	Rigidity (R), MPa	Strain modulus (E), MPa
Jet-grouting pile or micropile according to [3], [8], [9]			
Soil cement on the basis of loess collapsing sandy clay	1.66	4.2-12.6	600-1200
Soil cement on the basis of dusty hard sandy clay	1.83	10.2-14.3	620-1300
Soil cement on the basis of mild plastic clay	1.73	3.7-6.7	450-600
Pile of micropile on the basis of drilling-mixing technology (cement is 15 %) according to [1], [12], [13]			
Soil cement on the basis of dusty sandy clay	1.38	3.70	350.0
Soil cement on the basis of mild plastic clay	1.36	3.80	376.0
Soil cement on the basis of hard loam soil	1.48	4.05	402.0
Pile of micropile on the basis of drilling-mixing technology (cement is 20 %) according to [1], [13]			
Soil cement on the basis of dusty sandy clay	1.38	5.00	487.5
Soil cement on the basis of mild plastic clay	1.38	5.23	503.0
Soil cement on the basis of hard loam soil	1.46	5.46	529.0
Displacement pile (micropile)			
Reinforced concrete (on the basis of B30 concrete)	2.5	30.0	32500…38500

If one considers such a system but replaces the strengthening component by another one, made industrially of the reinforced concrete (the auger pile or micropile is meant), it will become understandable that interaction within the system differs greatly. It can be explained by the fact that interaction between elastic-strain moduli of the weak soil and the pile (micropile) reinforced concrete will be thousand times more (Table 1).

Hence, the approach has been applied to develop theoretical provisions of the system involving either averaged or weighed elastic modulus. To some extent, the "soil base, strengthened with piles or micropiles based upon drilling-mixing technology" system is considered as homogeneous. Nevertheless, it is provided with strain characteristics obtained while reducing elastic-deformation modulus of base and pile (micropile) to some equivalent (average) E_{ec} value:

$$E_{ec} = \frac{\left(E_s \cdot A_s\right) + \left(E_m \cdot A_m\right)}{\left(A_s + A_m\right)}, \tag{1}$$

where:

E_s, E_m – elastic-deformation moduli of the base and pile (micropile), respectively;

A_s, A_m – areas of the base and pile (micropile), respectively.

It is no doubt that such a conceptual approach as well as theoretical provisions, resulting from it, helps consider the mentioned system within the powerful and well-designed models of elastic semi-space or finite-thickness layer. After elastic moduli are averaged, it is quite simple to calculate strain state values of the analyzed system while staying within conceptual field of soil mechanics.

However, provisions of the approach one should be criticized. It goes without saying that the method, used by it, is correct. Moreover, it demonstrates situation of the strain state formation. Nevertheless, averaging of the deformation characteristics of the system while elastic-strain moduli weighing is incorrect idea. Following argument proves the incorrectness. The available procedures to strengthen weak soil bases using piles or micropiles, based upon drilling-mixing technologies are those ones characterized by uniform arrangement of the strengthening elements. Namely, arrangement of the elements follow the rules formulated for displacement or auger piles: their interaction arises at 3-6*d* distance (i.e. diameters of the piles). It depends upon the fact that there is no general theory for form strain state of a system with the insignificant ratio between deformation characteristics. Having assumed approach one, designers adopt unequivocally the arrangement scheme being similar to displacement piles. The abovementioned is also substantiated by the fact that if one adopts another arrangement scheme, it will be very difficult to apply the mentioned formula. Since, the arrangements scheme, just transferred from the situation of displacement and auger piles, prevents from relying upon provisions of approach one. Hence, it is expedient to consider approach two being more differential.

Before analyzing provisions of approach two, it is worth emphasizing that arrangement of piles and micropiles, based upon drilling-mixing technology, unrelated to displacement and auger piles, is the substantiated technique. The matter is that in the context of numerous options of the analyzed system, the maximum stresses and strains arise locally, within some areas. The overstressed and heavily deformed areas are agreed completely with soil mechanics terms (areas of Pusyrevski; zone of the maximal deformation under the load action etc.). In such a way, arrangement of piles and micropiles is planned preliminary in accordance with the areas. Right the arrangement of strengthening elements with the defined 3-6*d* pitch (diameters of piles) cannot result in the maximum effect of vertical displacement decrease.

To compare with approach one, approach two is based upon theoretical provisions of continuum mechanics, implemented in the finite element method, rather than upon analytical provisions of soil mechanics. The method, which does not involve any long explanation concerning its use, makes it possible to represent completely the “soil base strengthened with piles or micropiles based upon drilling-mixing technology” system through a finite-element model. In this regard, the process of the model development prevents from the approach one being artificial to some extent, i.e. there is no necessity to define the averaged (weighed) elastic-strain modulus.

The finite-element method, implemented by means of the specialized calculation complexes ANSYS, Cosmos, NASTRAN, Lira, and StructureCAD (SCAD), makes it possible to demonstrate fully the real deformation characteristics of both parts of the system. In addition, it should be mentioned that another outstanding feature is the follows. Finite-element model of the system helps perform quite easily the option of arrangement of piles or micropiles as well as changes in deformation characteristics of the system.

Rather often, supporters of the approach two are criticized for the fact that the numerical analysis is aimed at specific solutions and cannot provide regularities of the strain state. Nevertheless, the argument has been invalidated by dozens and hundreds of scientific papers where, owing to variation of a model parameters (so-called parametric analysis), the numerical analysis has expressed itself as an excellent tool making it possible to solve wide range of problems as for determination of the strain state regularities in the context of any systems.

No doubt that the purpose achievement needs the development of a finite-element model of the “soil base, strengthened with piles or micropiles based upon drilling-mixing technology” system helps vary its parameters promptly and in the controlled manner. Towards this end in view, the system has been expanded a little while a rigid element reproducing (i.e. die; foundation; cross tie; slab; beam) through which load is transferred to a soil base. Such a methodological step has been substantiated in several works. Moreover, its use approximates the system to the functioning one since it does not ignore additional rigidity which effect causes phenomena of the strain state non-uniformity mentioned by the paper.

Study of nonreinforced base has become the primary research helping compare results of future parametric analysis. In this regard, one should take into consideration that during following variation of arrangement of the strengthening elements, distance between them has to be also varied. Consequently, spatial finite-element prototype has been developed based upon the volume elements. The prototype can join as a module producing larger models (Fig. 1).

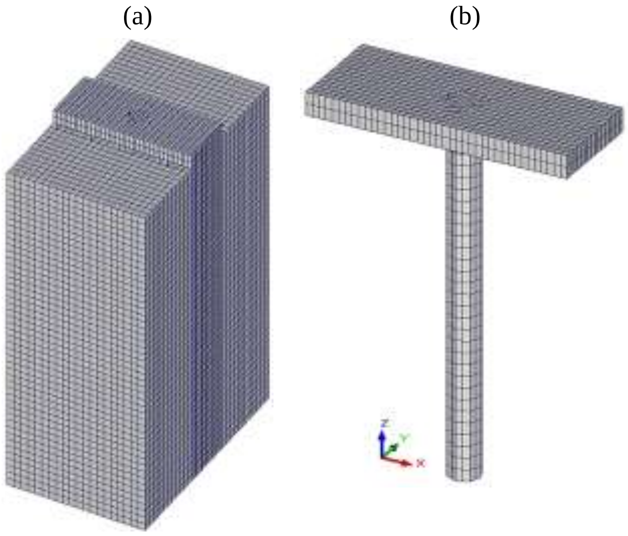

Figure 1. Finite-element model: (a) finite-element model (option 1); (b) finite-element model fragment being a foundation with micropile

All the finite-element models are based upon actual geometry of girder foundation with 1.6-m width and 0.4-m thickness. The object has been selected to compare the obtained strain state values of the developed models with analytical indicators from the paper of the authors. The micropile dimensions have been selected relying upon the sources and field tests at the territory of Dnipropetrovsk Region. They are as follows: 6.0-m length and 0.5-m in diameter.

The four types of finite-element models, based upon spatial prototype, were planned and implemented:

– variant 0 being a model without micropile (i.e. weak soil base);

– variant 1 being a model with single micropile (Fig. 1);

– variant 2 being a model with two micropiles distance between which was 1.5 m, i.e. 3*d* of micropiles;

– variant 3 being a model with two micropiles distance between which was 3.0 m, i.e. 6*d* of micropiles.

All the problems, solved using the developed models, are of high dimensionality (more than 150 thousand of degrees of freedom, Table 2).

Table 2. Characteristics of the finite-element models

Finite-element model	Number of nodes, thous.	Number of finite elements, thous.	Number of degrees of freedom, thous.
Variant 0 (1)	60.3	57.3	180.0
Variant 2	89.5	86.0	268.3
Variant 3	118.6	114.5	355.6

The finite-element models for variants 0 and 1 are similar as for the number of nodes, finite elements, and degrees of freedom. Nevertheless, they differ in their strain characteristics: in the variant 1, some part of the finite elements have characteristics of the pile material. Finite elements of SCAD library, namely prisms and tetrahedrons, have been applied for the abovementioned models. The number of the forms is not more than 7% of the numbers of finite elements of the developed models. In the plan, geometry of the finite elements is as follows:

– 0.05-0.12 × 0.05-0.1-m pile;

– 0.1 × 0.1-m basement;

– 0.2 × 0.2-m zone of a soil base;

– 0.2-m height of all finite elements.

The dimensions as well as the number of finite elements speak for high discretization degree of the analytical area which geometry for all the variants was:

– 6.4-m length along the *y* axis of software complex SCAD;

– 9.6-m height along the *z* axis of software complex SCAD (where soil base is 9.0 m; and basement is 0.6 m (Fig. 1a).

Width of the finite-element model is a variable, i.e. 4.0 m along the *y* axis of software complex SCAD (variants 0 and 1); 6.0 m (variant 2); and 8.0 m (variant 3). The nature of vertical strain development along the *z* axis of software complex SCAD, which will be analyzed hereinafter (namely, nonavailability of visual artifacts being isoline breaks; sharp jumps of values; bends of isofields which are untypical for the classical picture of deformation of plates on an elastic base, etc.), also supports the idea that the analytical area dimensions as well as geometry of the finite elements have been selected correctly in accordance with the problem being solved.

Table 3 demonstrates the characteristics allocated for the finite-element models. Boundary conditions, applied for all variants of the finite-element models are as follows:

– upper share is free from the boundary conditions; lower plane has inhibit for all the axes $x = y = z = 0$;

– within its end faces, the soil base has the possibility to move throughout its height under the inhibit of other displacements $x = y = 0$;

– on the short side, the soil base as well as the basement end faces can move throughout the height under the inhibit of longitudinal displacement ($x = 0$, plane strain condition).

Table 3. Characteristics of the finite-element models

Fragment of the finite-element model; its material	Elastic modulus (E), MPa	Density (ρ), t/m^3	Poisson's ratio μ
Soil (mild plastic clay)	20	2.0	0.3
Basement (reinforced concrete)	$3.25 \cdot 10^4$	2.45	0.2
Micropile (soil cement)	375	1.36	0.3
Micropile (reinforced soil cement)	750	1.6	0.3
Reinforced auger micropile (reinforced concrete)	$3.85 \cdot 10^4$	2.45	0.2

316.83 kN/m^2 value has been adopted as load distributed throughout upper boundary of the basement since the value corresponds to analytical constructions in the paper of the authors [2], and makes it possible to compare the obtained vertical displacements.

All the studied finite-element models have helped solve the formulated problems. Comparative analysis of variants 0 and 1 has made it possible to identify influence by a micropile, namely its ability to decrease the strain state. Comparative analysis of variant 1 and variants 2 and 3 has helped define the impact by distance between the strengthening elements. Variation of micropile properties (i.e. soil cement, reinforced soil cement, and reinforced concrete) has made it possible to define the strain state features when deformation characteristics experience changes. Consequently, the twelve finite-element models have helped carry out parametric analysis of strain state. Following chapter represents the condensed version of its results; however, the most typical deformation moments have been considered in detail.

3. Results and discussion

3.1. Parametric analysis of the system during changes taking place in its strain characteristics

Before proceeding to the parametric analysis of vertical displacement with variation in distance between strengthening elements, introduce a pattern of isolines and isofields in variant 0 (weak soil base).

The section is represented along the axis transversely the basement (*y* axis of a software complex SCAD). The distribution pattern of isolines and isofields is typical for a system of rigid plate impressing into a soil base with minor elastic-strain modulus. "Kernel" of vertical deformations is shaped under the basement. Its maximum value is 15.98 mm; its typical value is 5 mm; and its depth is 5.0-5.2 m. The three indicators are reference for further comparison with strengthening options. The numerical analysis can also be considered as the test one since the maximum value of vertical displacement, compared with analytical, is $s = 16.0$ mm. It has been calculated using the Formula:

$$s = \beta \cdot \sum_{i=1}^{n} \frac{\left(\sigma_{zp,i} - \sigma_{z\gamma,i}\right) \cdot h_i}{E_i}, \qquad (2)$$

where:

β – dimensionless coefficient being equal to 0.8;

$\sigma_{zp,i}$ – average value of normal vertical stress (MPa) from external load in the i^{th} soil layer within a vertical passing through the foundation bed centre;

h_i – thickness of the i^{th} soil layer (m) adopted as a value being no more than 0.4 of the basement width;

n – the number of layers the base under compression is divided into;

$\sigma_{z\gamma,i}$ – average value of vertical stress resulting from sole weight of the soil (MPa), excavated from the foundation area in the i^{th} soil layer within a vertical passing through the foundation bed centre at z (м) depth from the foundation bed;

E – deformation modulus of the i^{th} soil layer according to the initial load branch (MPa).

Error between numerical and analytical solutions is 0.13% thus proving high adequacy of the finite-element models to theoretical basis of soil mechanics.

In the process of the parametric analysis, the first conclusion is that one deriving from variant 0 and variant 1 comparison, i.e. deformation of basement with weak soil base, and the strengthened one (Fig. 2). Qualitative analysis of isolines and isofields of vertical displacements denotes significant influence by the vertical elements being destruction of a "kernel" under the basement, and perception of deformations into a micropile body.

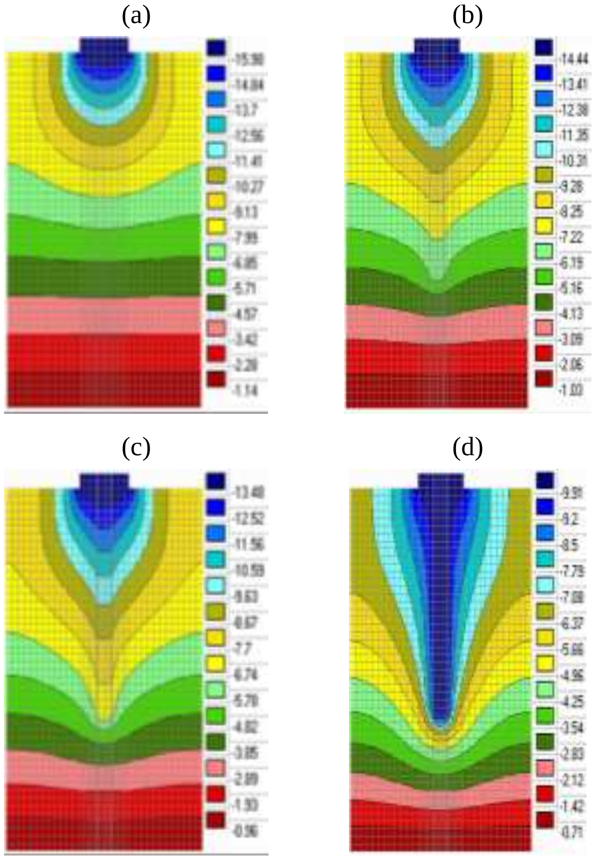

Figure 2. Isolines and isofields of vertical displacements (s), mm: (a) weak soil base without micropile (variant 0); (b) soil-cement micropile (variant 1); (c) micropile made of the reinforced soil cement (variant 1); (d) reinforced auger micropile (variant 1)

Obvious transition of stuffiness, i.e. the ratio between the soil elastic-strain modulus and the micropile material forms a pattern of displacements around it. In this regard, increase in the modulus of the strengthening element material results in "smearing" of the vertical displacement demonstrated clearly by the strain pattern (Fig. 2d). The auger reinforced micropile, which elastic modulus is even somewhat higher than elastic modulus of the basement, forms the strain state in a fundamentally different way to compare with soil cement micropiles. The abovementioned can be explained as follows. To compare with micropiles, based upon drilling-mixing technology, the auger or displacement piles operate in combination with the basement transferring its deformation to the soil base throughout its height. As for soil cement elements, distribution of vertical displacement is uniform throughout the micropile height (Fig. 2b, c). In turn, according to the classic papers on soil mechanics, the auger reinforced pile rest mainly on its tip. Following deformation pattern is formed: the auger pile and basement have similar displacement, which characterizes the structure as continuous.

Qualitative analysis supports positive influence of the vertical elements on the corresponding displacement component. Nevertheless, it differs for the variant1: soil-cement micropile decreases vertical displacement of the basement by 9.65%; the reinforced soil-cement micropile – by 15.7%; and the reinforced auger micropile – by 37.9%. In this regard, isoline of characteristic 5-mm value varies its location: its depth is 4.8-4.9 m for soil-cement micropile; 4.5-4.6 for the reinforced soil-cement micropile; and 4.0-4.1 m for the reinforced auger micropile. The results mean that increase of elastic modulus of the micropile material decreases deformation zone in depth while increasing somewhat around the pile. In such a way, strengthening element, added to the soil base, redistributes vertical displacements within the certain soil quantity around the pile shaping a new "kernel" of vertical deformations.

Parametric analysis of "soil base strengthened with piles or micropiles" system during changes in its deformation characteristics right at the research stage proves the following: it is a wrong methodological approach to consider the elements, based upon drilling-mixing technology, as the auger or displacement piles.

3.2. Parametric analysis involving variation in distance between the strengthening elements

As opposed to the results of analysis, described in 3.1, the strain state outcomes have been represented along the basement for greater representativeness (x axis of a software complex SCAD).

It should be emphasized that to save space, the strain state of variant 2 for soil cement and the reinforced soil cement, where distance between piles is 3.0 m (6d of micropile), is not mentioned since it coincides both qualitatively and quantitatively with a strain state of a single pile (Fig. 2b, c). It proves finally that upper distance boundary between piles (6d of micropile), based upon drilling-mixing technology, does not correspond to understanding of the regulated interaction. In this context, analysis of variant 3 for the reinforced auger pile (Fig. 3a) also means that 6d is boundary distance. It is substantiated by the following: nature of isolines and isofields of the case is quite close to a single pile (Fig. 2d); however, their combination is mentioned within the space between the piles. Values, being rather close to the single pile case, also support the idea that 6d of micropile is the boundary ones for displacement or auger piles.

Consequently, the parametric analysis, based upon finite-element method, has proved that for such vertical strengthening elements the standard upper boundary (i.e. 6d of pile or micropile) is correct.

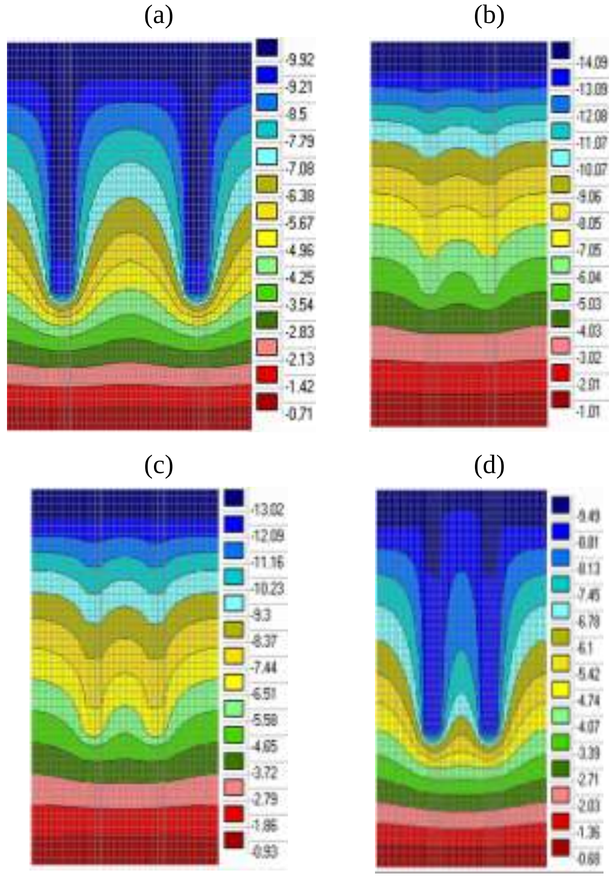

Figure 3. Isolines and isofields of vertical displacements (s), mm: (a) reinforced auger micropile (variant 3); (b) soil-cement micropile (variant 1); (c) micropile made of the reinforced soil cement (variant 2); (d) reinforced auger micropile (variant 2)

However, for strengthening elements, based upon drilling-mixing technology, even if they have been reinforced (variant 2, the reinforced soil cement), the parameter cannot be correct since it does not mirror the actual strain pattern of the system where deformation potential of the strengthening element is comparatively low in contrast to elastic-strain modulus of the soil base.

Analysis of deformation state reproduction of lower boundary of the distance (3*d* of micropile) determines the following: for each of the strengthening types, the parameter can be considered as correct for the conclusion about interaction of the strengthening elements. Comparative analysis of the reinforced auger piles 6*d* (Fig. 3a) and 3*d* (Fig. 3d) needs emphasizing that a lower boundary in 3*d* strengthening element, regulated by [26] document, is also defined clearly.

Qualitative analysis of the two distances shows that if 3*d* (Fig. 3d) takes place then the interaction is both unequivocal and doubtless being proved by nature of isolines and isofields within the space between piles. The isolines and isofields are elongated clearly to compare with a single pile denoting influence by ratio of strain characteristic of the strengthening element. Approaching of the reinforced auger micropiles from 6*d* to 3*d* results in the fact that the "soil base-micropiles" system forms its sole strain state. By the way, use of approach one, relying upon the use of the ave-raged or weighed elastic modulus (Formula (1)), is rather adequate to identify promptly the maximum basement deformations. Purely for the case, such a methodological path is operating also because it is in the conceptual field of the regulative document [26] while helping consider the system as a conditionally mat foundation.

Qualitative analysis of the two distances (Fig. 3) also supports the idea that decrease down 3*d* results in interaction between the basement, reinforced auger micropiles, and soil base. Hence, if distance is 3*d* of micropile instead of 6*d* then vertical displacement value decreases by 4.3-11.1%. If one compares the indicators with variant 0 (weak base) (Fig. 2a), it will become understandable that use of such micropiles decreases vertical displacement by 40.6-42.0%.

Comparative analysis of variant 2 for soil cement and the reinforced soil cement case (Fig. 3b, c) also makes it possible to speak for the fact that interaction between strengthening elements also arises; however, it is not so obvious as in the case of variant 2 where the reinforced auger micropile is applied. Qualitative analysis helps conclude that the shaped isolines and isofields of vertical displacements do not coincide with a single pile case (Fig. 2b, c). Evident curve of the isofields as well as their displacement along the vertical axis down to lower boundary of the basement is observed. Hence, in terms of variants 1 and 2, their interaction is formed if 3*d* distance between the strengthening elements is available. It is also possible to say that the boundary is upper for elements based upon drilling-mixing technology. Increase in distance between such elements (even if they are reinforced) results in their deformation which corresponds to a case with a single pile.

Quantitative analysis of the variants, intended to strengthen soil base, also supports the conclusion that distance, being 3*d* of micropiles, based upon drilling-mixing technology, is the upper boundary of the distance within which interaction between strengthening elements is formed. In such a way, when strengthening is performed using soil-cement micropile and distance is 3*d* instead of 6*d*, the value of vertical displacements decreases by 2.4-4.6%; when the reinforced soil-cement micropile is applied, the decrease becomes 3.4-9.1%. If one compares the indicators with variant 0 (weak base) (Fig. 2a), it becomes understandable that such micropiles decreases vertical displacements by 11.7-11.9% (soil-cement micropile), and by 18.1-18.5% (the reinforced soil-cement micropile).

Consequently, reducing the distance between micropiles, based upon drilling-mixing technology, decreases vertical displacements by 2-3%. Thus, it is impossible to decrease vertical displacements through approaching micropiles relying upon regulatory guidelines [26] developed for displacement or auger piles. The obtained results prove the following. The micropiles, based upon drilling-mixing technology interact with soil base differently than displacement or auger piles because of proper strain property. The research may become the basis for the development of the generalized theory to deform "soil base strengthened with piles or micropiles based upon drilling-mixing theory" composite system as a medium having minor changes in deformation characteristics.

To understand mutual influence between soil-cement micropile, the reinforced soil-cement micropile, and the reinforced auger micropile, which values are shown in Table 3, numerical analysis of finite-element models has been performed with 3*d* distance between micropiles, and variation in soil elastic modulus (5 to 20 MPa, with interval being 5 MPa). Then the calculation results have been analyzed. To generalize them, spatial graph of vertical displacements of the models dependence upon elastic moduli of the micropile and weak soil has been constructed (Fig. 4).

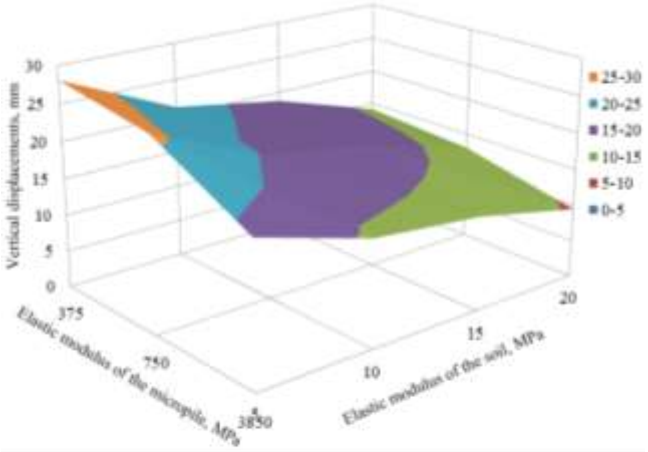

Figure 4. Graph of dependence of vertical displacements of the models upon elastic moduli of the micropile material and weak soil

The surface is space of all possible vertical displacements for micropiles, made from three materials, and a range of elastic modulus of a weak soil E = 5-20 MPa. Consequently, the graph can be applied in practice to define the desired values of vertical deformation decrease. For the purpose, it is sufficient to be restricted to the soil elastic modulus, defined in a lab environment, and the required level of the vertical deformations. In such a way, having the two boundary values, it is possible to select values of elastic modulus of the micropile, i.e. decide on its material. The problem can be solved inversely. Having set the elastic modulus of the real soil, which deformation is to be decreased, one should select the value of the elastic modulus of the micropile, i.e. involve proper limitation of the material it will be made of. Having the two restrictions and using the graph, shown in Figure 4, it is possible to identify the desired level of vertical displacement.

Finally, one important moment, which follows from the comparative analysis of strengthening materials (i.e. soil cement; the reinforced soil cement; and the reinforced auger micropile) but can be interpreted mistakenly. Even in case of single micropiles, the obtained result show that use of the reinforced auger micropile is 2.4-3.9 times more efficient (37.9% decrease in vertical displacements) than the use of soil-cement micropile (9.65% decrease in vertical displacements) or the reinforced soil cement where the decrease is 15.7%. The fact may lead to a wrong conclusion that the use of piles, based upon drilling-mixing technology, is nor efficient. However, it is required to correct such a conclusion while analyzing both technological and financial components of the strengthening. To compare with the auger use, implementation of the strengthening by means of drilling-mixing technology is simpler since it does not involve any additional tools; for instance, it concerns application of a guide while drilling. Cash expenditure is the most important argument since 1 m of vertical soil-cement element (even if the reinforced option is applied) is 2-2.5 times cheaper to compare with auger micropile. If the guide becomes lodge in a well then the cash expenditure grows up to 3.0 times. In this regard, if composition of the soil cement is correct (i.e. cement amount is reduced; sand is replaced with tailings etc.) then the strengthening elements, based upon drilling-mixing technology, become cheaper. It goes without saying that economic aspects need additional research and cannot be detailed within the paper. However, relying upon the parametric analysis results, it is possible to set the level of vertical displacement decrease as for weak soil base (the level is 10-15%), and achieve it successfully while using micropiles based upon drilling-mixing technology.

Relying upon the research findings, it is worth mentioning that despite its termination, there is the opportunity to continue it. The scheduled research should follow the two tendencies. Since it has been proved that distance for micropiles, based upon drilling-mixing technology, is not a governing factor, one should lay down a program to analyze influence by deformation characteristics of soil cement. Increase in elastic modulus, achieved at the expense of the specific reinforcement procedures (for instance, fiber method) will help improve efficiency as for vertical displacement decrease. It is especially important for thick weak bases (with E = 5-10 MPa elastic modulus).

Another tendency to develop the studied area is an integral analysis of analytical situations involving technical and economic comparison of the proposed options of micropiles with the predetermined level of the strain state decrease, namely reduction of vertical displacements. The tendency is important from the viewpoint of the best decision development where material as well as cash expenditures are the key parameters. In this context, the level of vertical deformation decrease after arrangement of micropiles, based upon drilling-mixing technology, is substantiated basing upon theoretical provisions stated in the paper.

4. Conclusions

The paper has carried out a parametric analysis of vertical displacements of the “soil base, strengthened with piles or micropiles based upon drilling-mixing technology” system with the variation in their strain characteristics as well as arrangement of the strengthening elements. Relying upon the findings, a hypothesis has been proved that the composite system operates much differently from the case of auger or displacement piles.

It has been substantiated that basing upon the standardized document, developed for auger or displacement piles, it is impossible to decrease efficiently vertical displacements while approaching of micropiles since 3d distance between the micropiles for elements, based upon drilling-mixing technology, is minimal.

The results, obtained for single piles, mean that the use of the reinforced auger micropile is most efficient. Moreover, decrease in vertical displacements of weal soil base becomes 2.4-3.9 times (by 37.9%) to compare with soil-cement micropiles (by 9.65%) or the reinforced soil cement (by 15.7%).

Author contributions

Conceptualization: OT, VK; Formal analysis: OD, VK; Funding acquisition: OT; Investigation: OT, AR, OD, VK; Methodology: OT, AR, OD, VK; Project administration: OT, AR, OD; Supervision: OT, AR; Validation: OT, AR, OD, VK; Visualization: AR, OD, VK; Writing – original draft: OT, AR, OD, VK; Writing – review & editing: OT, AR. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Параметричний аналіз деформованого стану ґрунтової основи, підсиленої вертикальними елементами

О. Тютькін, А. Радкевич, О. Дубінчик, В. Харченко

Мета. Метою статті є визначення вертикальних переміщень системи "ґрунтова основа, підсилена палями або мікропалями, створеними на основі бурозмішувальної технології" на основі параметричного аналізу деформаційних характеристик зазначеної системи та розташування елементів підсилення.

Методика. Математичне моделювання виконувалося для 12-ти скінченно-елементних моделей в обчислювальному комплексі SCAD, який призначений для аналізу міцності конструкцій методом скінченних елементів. Чисельний аналіз проводився із варіацією модуля пружності-деформації вертикальних елементів підсилення та зміною відстані між ними (3*d* і 6*d* мікропалі).

Результати. Отримані результати параметричного аналізу моделі без мікропалі (непідсилена ґрунтова основа); моделі з поодинокою мікропалею; моделі з двома мікропалями, відстань між якими складала 1.5 м, тобто 3*d* мікропалі та моделі з двома мікропалями, відстань між якими складала 3.0 м, тобто 6*d* мікропалі. Проведений порівняльний аналіз дав змогу отримати результати, що доводять гіпотезу авторів про особливий характер формування вертикальних переміщень системи "ґрунтова основа, підсилена палями або мікропалями, створеними на основі бурозмішувальної технології".

Наукова новизна. Вперше визначено, що базуючись на нормативному документі, який розроблено для забивних або буронабивних паль, неможливо ефективно зменшити вертикальні переміщення шляхом зближення мікропаль, оскільки відстань між мікропалями в 3*d* для елементів, що створені на основі бурозмішувальної технології, є мінімальною.

Практична значимість. Отримані результати деформованого стану можуть стати основою для створення узагальненої теорії деформування композитної системи “ґрунтова основа, підсилена палями або мікропалями, створеними на основі бурозмішувальної технології” як середовища, що має незначну зміну деформаційних характеристик.

Ключові слова: *ґрунтова основа, вертикальний елемент підсилення, мікропалі, бурозмішувальна технологія, параметричний аналіз, деформований стан, метод скінченних елементів*

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