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Multi screw type elements for weak soil reinforcement

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Abstract:

Research aims to develop a method for weak soils reinforcement by using multi helical vertical elements. Model of settlements forecast is required. Article represents the results of investigation held during several years. Structure of vertical reinforcement is designed by using fiber reinforced pipe and helical screws those have differentiated from bottom to top diameters. Reinforcement elements are located within weak soil with certain step. Reinforced soil is considered as a composite structure where vertical elements and surrounding weak soil have joint and simultaneous settlements. These settlements' calculation model was developed. Calculation equation is based on newly proposed reinforcement factor. Reinforcement factor is appointed considering existing researches and depends on vertical reinforcing element's structure. Developed model needs to be confirmed by site full scale axial loading tests. Five sets of site load tests were performed before and after reinforcement of a weak soil. Test samples varied by structure of reinforcing elements. A comparative analysis of the calculated vertical deflections and the results of site loads test proofed possibility of settlements calculation method use.

1 Introduction

Weak soils are widely distributed in the world. Mainly they are located in a water saturated areas. Weak soils have low deformability module limited by 10 MPa. Construction on this type of soil is risky not only due to high settlements but due to unpredictable settlements in different points of landplot those can lead to superstructures inclination.

Use of regular settlements calculation methods those summarize vertical deflections at each elementary part by predicting the compaction depth lead to underestimation. Sometimes difference between results reaches several times. It leads to unacceptable mistakes during design of foundation. It happens because intermolecular structure of weak soils is not considered. Settlements happened due to soil's decompaction toward horizontal plane are not considered either.

Construction on this type of soils without specific measures is complicate or even impossible. Specific measures can be divided on improvement of ground parameters and structures modification in order to avoid influence of settlements. Structures modification can be made by increase of structures rigidity (belts, box foundations etc.), buildings division into independently settled rigid blocks and parts. Soil modification is mainly performed by increase of water flow out of the soil, strengthening and hardening by creating new structural connections (chemical, physical etc.) between soil grains, incorporation of new elements. Newly incorporated elements do not influence on intermolecular connections between soil parts but increase deflection module. It can be installation of piles, strengthening elements, reinforcement.

Reinforcement term assumes creation of composite structure by incorporation into the soil of more rigid elements those create connection at the boundary of surfaces. Initially reinforcement was mainly used for road and hydraulic engineering construction. It was mainly horizontally oriented structures. Horizontal reinforcement is mainly made with fabrics, nets, bars [1], [2], [3], [4],

37. Goldin, A.L., Dzung, N.F. Plotting the stress-path for unsaturated soil during consolidated undrained tests in stabilometer. Magazine of Civil Engineering. 2012. 35(9). Pp. 35–40. DOI: Pp.10.5862/mce.35.5.

38. Badanin, A.N., Kolosov, E.S. Determining the bearing capacity of soil foundation reinforced by geogrid. Magazine of Civil Engineering. 2012. 30(04). Pp. 25–32. DOI: Pp.10.5862/mce.30.4.

Recent researches [5] study the work of reinforcement mat made with bamboo, wood or straw. Researcher underlies low cost of this type of reinforcement and absence of negative effect on environment.

Reinforcement classification by Mustakimov V.R. [6] beside horizontal presents vertical, inclined, cross-shaped, horizontal intermittent etc. Initially reinforcement of weak soils was performed with sand and lime piles used for increase of soil deflection module.

Результаты сравнительного анализа, описанные в работах Гришиной А.С. [7], показали, что существуют различные способы, используемые для увеличения жесткости грунтового основания. Сабри М.М.С. [8] отмечает, что у каждого способа есть своя область применения, основанная на определении целесообразности её использования в условиях того или иного проекта, зависящая от технико-экономического обоснования, от результатов инженерно-геологических изысканий, а также в соответствии со степенью требуемого усиления.

Nowadays jet injections are widely applied

40. Sokolov, V.A., Strakhov, D.A., Sinyakov, L.N., Garmanov, G.V. Effectiveness of jet grouting method for soil base strengthening. Construction of Unique Buildings and Structures. 2017. 5(56). Pp. 55–63. DOI: Pp.10.18720/CUBS.56.5.

Reinforcement is made by selfhardening mortars penetrated into weak soils. Soil icompacted by penetrated mortar creats reinforcement. In addition to penetrated mortar vertical oriented reinforcing element is created. Similar reinforcement method is investigated by Sabri M.M.S. [9], [10]. He proposed a method of strength and deformabillty of the soil reinforced by penetrated into soil of selfexpanded polyurethane rubber.

Thermally reinforced soil is considered by

is calculated in a separate part of geotechnic class (horizontal or vertical).

Existing methods of reinforced soil settlements' calculations presented within open source scientific literature is limited to few methods. Thus Zhang D.J.Y. and Polischuk A.I. use "cylindrical shear surface" term for description of joint work performed by shear screw shaped extensions and surrounding them soil. They explain the process of increased shear force involvement due to soil locked between screw shaped extensions.

Mirsayapov I.T. and Popov A.O. [97] propose to calculate the settlements by calculation equivalent deflection module of reinforced soil. Their equivalent module considers length and density of reinforcement as per soil volume.

$$S_{аэ} = \frac{\beta}{E^{экв}_{гр,н}} \cdot \sum_{i=1}^{n} \sigma_{zp}^{ao,cp} \Delta_i \tag{1.5}$$

$$E^{экв}_{гр,н} = \left[\frac{E_{гр}(A_{гр} - A_{аэ})(\gamma_{\varepsilon i} + \gamma_{\zeta i})}{A_{гр}} + \frac{E_{аэ} A_{аэ}(\gamma_{\varepsilon i} - \gamma_{\zeta i})}{A_{гр}}\right] \cdot \gamma_n \tag{1.6}$$

$$E^{экв}_{гр,т} = \left[\frac{E_{гр}(A_{гр} - A_{аэ})(\gamma_{\varepsilon i} + \gamma_{\zeta i})}{A_{гр}} + \frac{(\gamma_{\varepsilon i} - \gamma_{\zeta i}) \sum f_i u_i l_i^{аэ}}{A_{гр}} \cdot \frac{n}{A_{гр}}\right] \cdot \gamma_n \tag{1.7}$$

Bartolomey A.A. developed and systemized alternative factors of vertical structures' shear and bottom surfaces contacting the soil.

Popsuenko K.I. notices that current reinforced soil mass is considered within actual codes as transversely isotropic. Settlements calculation formulas are based on reinforcement volume to soil volume ratio. Hence they do not consider behavior of reinforcement elements' surface contact with surrounding soil. This approach leads to conservative reserve and materials overconsumption.

Zahmatkesh A. also proposes to calculate vertical deflection by considering equivalent elasticity modulus comparing with results of Poorooshasb and Meyerhof [11] investigations.

However existing methods are not enough for calculation of settlements in case weak soils are reinforced with multi helical vertical reinforcing elements. Current research aims to develop a method for weak soils reinforcement by using multi helical vertical elements. Model of settlements forecast is required. Developed model needs to be confirmed by laboratory scaled and site full scale axial loading tests.

Investigated weak soils are limited by deflection module 5-10MPa.

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110. Sabri M.M., Shashkin K.G. Subsoil stabilized by polyurethane resin injection: FEM calculation // Construction of Unique Buildings and Structures. 2020. № 6(98). DOI:10.18720/CUBS.91.8.
111. Korneeva E., Sabri M.M.S., Babanina A., Zaytsev E., Poberezhskii S.

Как описано в трудах Сафина Д.Р. и Нурмухаметова Р.Р. [104], [105], рассматривая деформации армированного грунтового элемента видно, что армирующие элементы становятся связью, препятствующей свободной деформируемости. Опираясь на труды Крутова В.Н. [106], подтверждающие снижение деформативности армированного грунта, предполагается совместное деформирование за счет устройства ребристой поверхности, винтовых уширений или уменьшающихся жесткостных характеристик от центральной оси армоэлементов к их краям, соприкасающимся непосредственно с грунтом.

Таким образом, предлагаемая схема позволяет увеличить несущую способность основания за счет дифференциации диаметров уширений. Наиболее гармоничным конструктивным решением будет соотношение диаметров лопастей, увеличивающихся к верху обратно пропорционально несущей способности основания. Несущую способность основания при практическом применении допускается определять методом статического зондирования по [107] либо по физико-механическим характеристикам по [108]. По результатам определения несущей способности основания подбираются диаметры уширений. Обеспечивая одинаковое соотношение давления к модулю деформации слоя грунта, на который опирается винтообразное уширение, таким образом, чтобы получались деформации единой величины под каждой лопастью и по длине всего армирующего элемента.

2 Materials and Methods

2.1. Model

Investigated method assumes installation of vertical reinforcing elements into the weak soil. Aim is to increase a soil's deformation module. It can be achieved when reinforcing elements and weak soil become joint material with unified deformation parameters. Hence reinforcement installation depth is not as deep as depth of sub laying strong soil with higher bearing strength.

Depth of the soil reinforcement depends on load applied to the weak soils' surface and the depth of compacted soil H_{hc} (figure 1).

Proposed method assumes using a number of vertical elements. Vertical elements are installed into the weak soil field with the step calculated based on a method described herein.

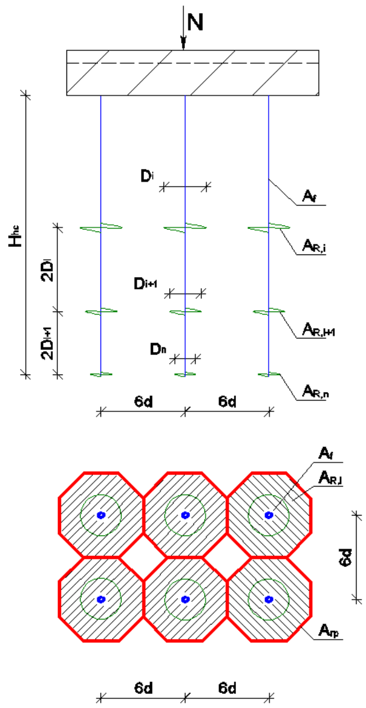

Fig. 1 – Soil reinforcement scheme. A_f – shear surface of reinforcing element, $A_{R,i}$ – bottom bearing surface of reinforcing screw, d – vertical pipe's diameter, D_i – diameter of *i* screw, A_{rp} – area of surrounding soil working mutually with reinforcing element.

Installation of vertical reinforcing elements aims to achieve joint resistance of the soil and vertical elements. Joint reaction of the vertical reinforcement and surrounding soil takes place in case both components have equal and simultaneous deflections. Based on review of existing approaches for vertically reinforced weak soil settlements calculations following predesign conditions are designated:

- specific geometry of shear helical screws;
- allocation of vertical elements with certain step between each other;
- reinforcing elements' elasticity module higher than soil's elasticity module;
- shear extensions' materials harder than soil.

Shadunts K.Sh. [12] notices importance of taking into account the sticking load required for joint deflection of weak soil and vertical reinforced elements. Referring to Deryagin B.V. [13] and Terzaghi K. [14] he considers the sticking load as an influence between molecules of both materials.

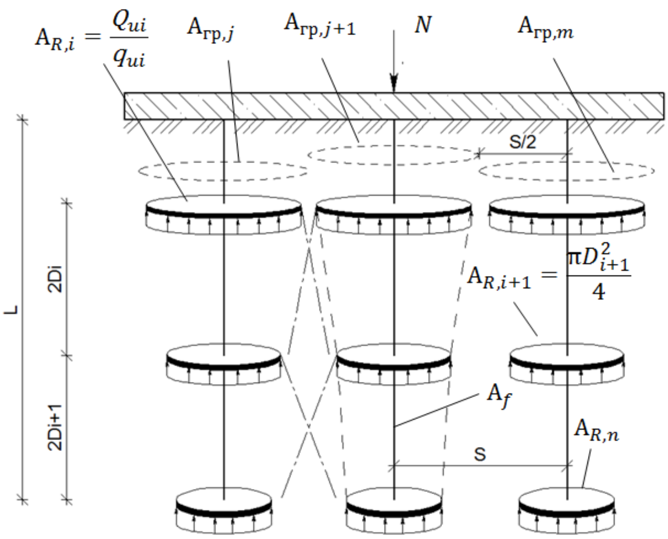

Fig. 2 – Reinforcing elements loading scheme.

2.2. Reinforcing element structure

Reinforcing elements produced with fiber reinforced plastic (FRP) pipes and cast iron screws fixed to the pipe. FRP pipes are produced by pultrusion method. Screws are fixed to the pipe by using glue or rivets.

Screws diameters are increased from the bottom to the toe. Distance between screws is equal to two screws diameters.

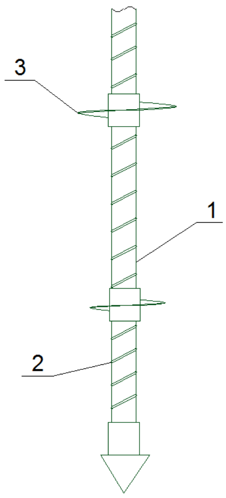

Fig. 3 – Multi screw type reinforcing element. 1 – fiber reinforced plastic pipe, 2 – spiral extra roving, 3 – screws.

Стеклопластик своими конкурентными преимуществами в сравнении с другими материалами доказывает право на последующие исследования и производство [15]. Стеклопластик является диэлектриком, обеспечивая преимущество при применении в качестве основания для зданий и сооружений из легких стальных тонкостенных профилей [16]. Отсутствие электронной связи с грунтом определяет отсутствие электрохимической коррозии каркаса из тонкостенных профилей.

Closest structure was developed earlier by Svetlov L.P. [17]. It was a micro pile fabricated with FRP pipe with single screw located at the pile's bottom. Structure was earlier described by Nurmukhametov R.R. and Mirsayapov I.T. [18]. Disadvantage of proposed structure was a necessity to install micro piles deeper till the layer of strong soil. It led to increase of FRP pipe consumption and complexity of installation. Installation was more complicate due to necessity of extra torque moment application. Increase of rotation moment required increase of pipe's stiffness since thin pipe's wall led to material delamination (figure 4).

Fig. 4 – FRP delamination after overdesigned torque moment application.

Closest structure was also investigated by Boyarintcev A.V. [19]. It has similar structure but with smaller screw's diameter that is required to be applied within permanent frozen soils. Specific structure for permafrost regions is not applicable for weak soils due to small bottom bearing strength.

Proposed soil reinforcing method can be applied for construction of low rise buildings and dismountable structures due to fast track installation method.

Due to low weight designed structure is applicable in North regions and in the areas where delivery is complicate. Especially method is applicable for roads infrastructure and power supply construction.

2.3. Calculation method

Terzhagi's K. theory of soil compaction and results of Gersevanov's N.M. researches were used as a base. They assumed soil as an elastic porous material and considered plastic deflections through factor of elastic plastic deflections υ.

Created method considers uniaxial loading due to simultaneous combined deflections of reinforcing elements and surrounding soil. Therefore stress appeared within reinforced soil during external load application can be defined as per following formula:

$$\sigma_{\text{аэ}}(\alpha) = \varepsilon_{\text{аэ}} E_{a э} = \frac{\sigma_{\text{гр}}}{E'_{\text{гр}}} E_{a э} = \sigma_{\text{гр}} \alpha \frac{1}{\upsilon}, \quad (1)$$

where $\alpha = \dfrac{E_{aэ}}{E_{гр}}$ is a deformability factor defined as a ratio of reinforcement deformability module to soil deformability module,

υ – is a factor of elastic-plastic deflections defined as a ratio of elastic deflections to sum of elastic and plastic deflections.

Considering static equations external load is balanced by internal stresses in the loaded element. Balance equation will look as follows:

$$N = \sigma_{\text{гр}} \text{A}_{\text{гр}} + \sigma_{\text{аэ}} \text{A}_{\text{аэ}} = \text{A}_{\text{гр}}(\sigma_{\text{гр}} + \zeta_{\text{A}} \sigma_{\text{аэ}}) = \text{A}_{\text{гр}}(\sigma_{\text{гр}} + \zeta_{\text{A}} \sigma_{\text{гр}} \frac{\alpha}{\upsilon}), \quad (2)$$

$$N = \sigma_{\text{гр}} \text{A}_{\text{гр}} \left(1 + \zeta_{\text{A}} \frac{\alpha}{\upsilon}\right), \quad (3)$$

where ζ_A *is a* reinforcement factor that defines equivalent area of reinforced volume as per following equation:

$$\zeta_{\text{A}} = \frac{\gamma_{Frn} * \text{A}_f + \gamma_{Rrn} * A_{R,\text{ср}}}{\text{A}_{\text{гр,ср}}}, \quad (4)$$

where A_f – shear surface of reinforcing element,
$A_{R,cp}$ – average area of reinforcing screw's bearing surface,
$A_{rp,cp}$ – area of surrounding soil working mutually with reinforcing element,
γ_{Frn} and γ_{Rrn} – factors of shear and bottom surfaces reaction those are taken as per nomograms (figures 5, 6). These nomograms were developed as a rule-of-thumb based on Bartolomey A.A. and Antonov V.M. investigations. These factors depend on ratio of reinforcements' step to length, soil's type (clay particles ratio) and soil's porosity factor.

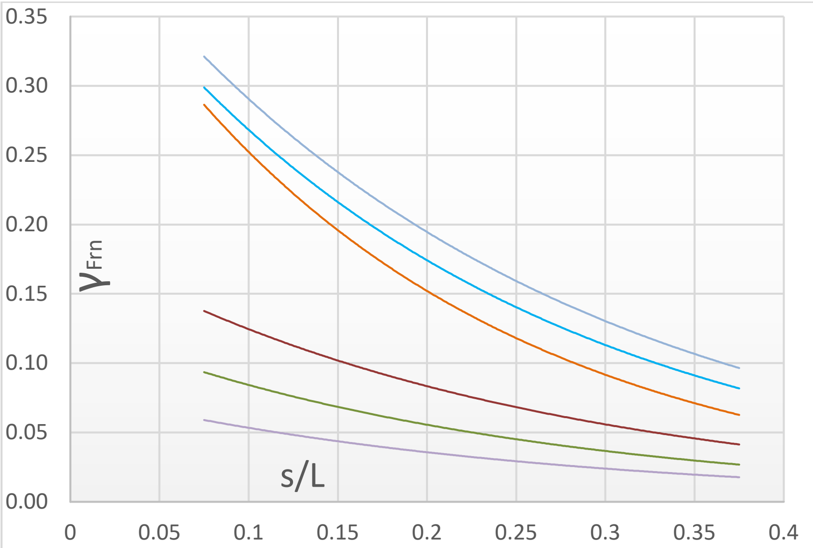

Fig. 5 – shear surface reaction factor.

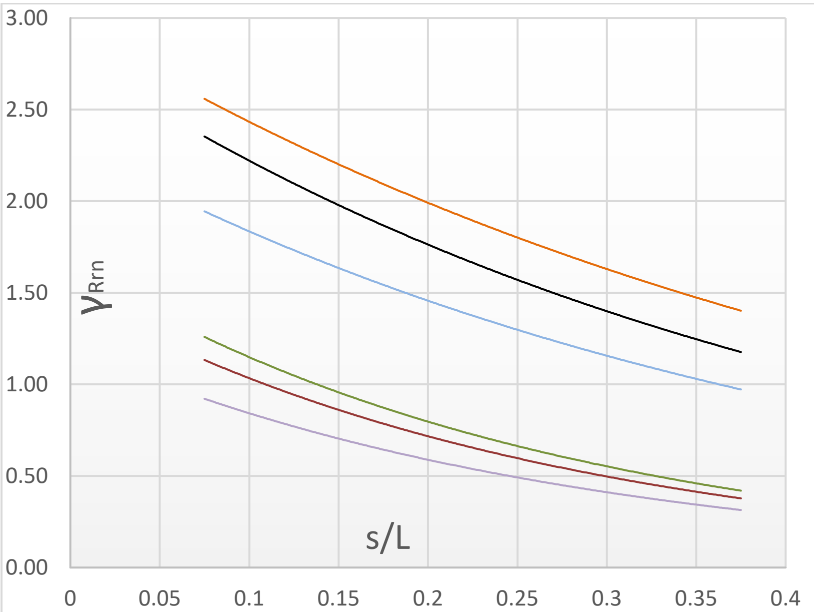

Fig. 6 – bottom surface reaction factor.

Compression strength that appears in the soil can be defined as per following equation:

$$\sigma_{\text{rp}}(\zeta_{\text{A}}) = \frac{N}{\text{A}_{\text{rp,cp}}\left(1 + \zeta_{\text{A}}\frac{\alpha}{\upsilon}\right)}, \tag{5}$$

where N is a force vertically applied to reinforced soil,
$A_{гр,ср}$ is an average area of surrounding soil.

$$A_{\text{гр,ср}} = \frac{\sum_1^m (A_{\text{гр},j} + A_{\text{гр},j+1})}{m}. \quad (6)$$

After use of (6) in the equation of stress definition (5) following was gotten:

$$\sigma_{\text{аэ}} = \sigma_{\text{гр}} \frac{\alpha}{\upsilon} = \frac{\alpha \cdot N}{A_{\text{гр}}(\upsilon + \zeta_A \cdot \alpha)} . \quad (7)$$

Formula (7) was applied in the law of layer by layer settlements calculation. Hence equation for settlements calculation became following:

$$s(\zeta_A) = m_\upsilon \int_0^{Hc} \sigma(z)dz = \sum_{i=0}^{Hc} h_i m_{\upsilon i} \sigma_{\text{гр}i}(\zeta_A) = \sum_{i=0}^{Hc} \frac{h_i m_{\upsilon i} N}{A_{\text{гр,ср}} \left(1 + \zeta_A \frac{\alpha}{\upsilon}\right)}, \quad (8)$$

In the equation (8) $\boldsymbol{m_\upsilon}$ corresponds to the compaction factor, *Hc* presents settlement depth, $\boldsymbol{\sigma}_{\text{гр}\boldsymbol{i}}$ stress in the soil that appears in the i layer of the soil.

As a result of performed investigation formula of settlements calculation depending on reinforcing elements structure, their number, their step and shear screws' diameter.

2.4. Verification by site tests

Site tests were performed in order to verify the method of settlements calculation proposed by the authors. Reinforcement was developed based on structural calculations of the FRP pipe. Five types of reinforcement elements were developed (figure 7). First reinforcing element was produced from steel pipe. Second element was produced from FRP pipe. Pipes' diameter was unified and equal to 100 mm, length was 800 mm. Reinforcing elements #3 and 4 were developed from pipes with diameter 75 mm and length 2000 mm. Reinforcing elements #3 differ from elements #4 by additional screw of same diameter 300mm located 1200mm higher after bottom's screw. Reinforcement element #5 has the same pipe as used for elements #3 and 4 but screw's arrangement is made as per figure 1. Hence for element #5 three screws were used. Diameters of three screws are 150, 225 and 300 mm. Fiberglass and steel pipes' thickness was taken 4 mm.

Reinforcement was installed into the soil till the surface level. Pipes were cut. Sand bed was installed above reinforcing soil surface in order to perform stamp tests. Sand's bed's thickness was 200 mm. Stamp tests were performed as per GOST 20276.1-2020. Loading of reinforced by vertical elements soil was performed by hydraulic jack by 0,6 kN steps. Load was controlled by manometer's gauge measurements those were converted into force created by the jack.

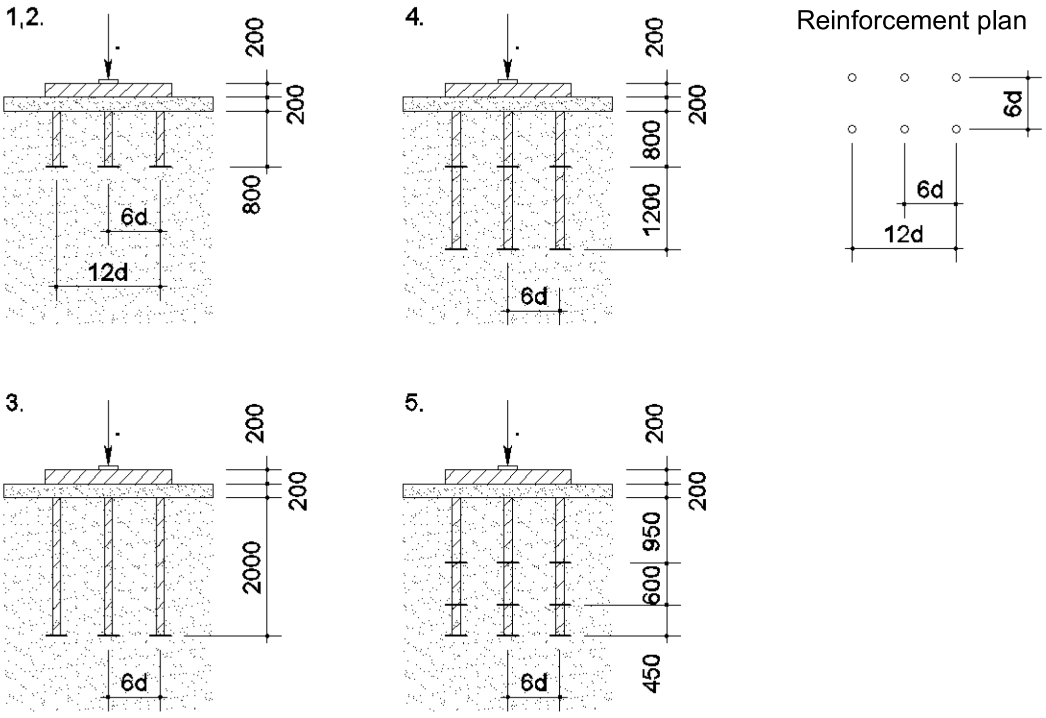

Fig. 7 – Scheme of performed site tests. 1 – reinforcement elements made with steel, ζ_A = 0.23, 2 – reinforcement elements made with fiberglass diameter 100 mm, ζ_A = 0.27. 3 – reinforcement elements made with fiberglass diameter 75 mm, ζ_A = 0.33, 4 – reinforcement elements made with fiberglass diameter 75 mm with two screws, ζ_A = 0.51, 5 – reinforcement elements made with fiberglass diameter 75 mm with three different screws, ζ_A = 0.72.

Load was applied through concrete slab installed on sand bedding. Concrete slab's thickness was 200 mm. Slab was acting as a rigid stamp. Rigid stamp allowed involving soil between reinforcing elements to evaluate the work of reinforced soil as a solid element. In addition slab allowed providing additional loading till ultimate condition is achieved.

3 Results and Discussion

Settlements measurements were verified during full scale tests. Results of described above test are presented within figure 8.

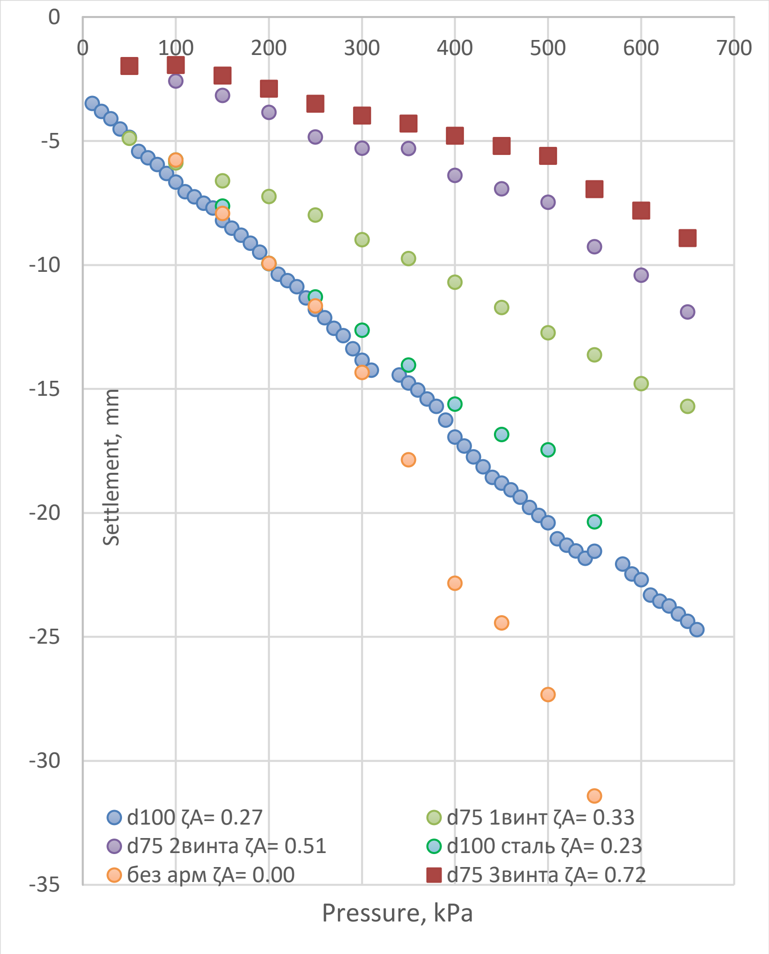

Fig. 8 – Load - settlement graphs of the tested samples before and after reinforcement.

Comparison of test results reflects reduction of vertical settlements with increase of reinforcement factor ζ_A. It is visible that samples under the applied pressure below 400 kPa with low reinforcement rate (ζ_A is equal 0,23 and 0,27) has reduced settlements on 26-32% compared to non-reinforced samples.

Comparison of samples differentiated by installation depth shows the difference 37%. Compared samples had reinforcement factor ζ_A equal 0,33 and 0,27. Pressure applied to the samples was 400 kPa. Distance between samples (step) was constant. Hence test results confirm hypotize of reinforcement elements'length influence on reinforcement factor and increase of rigidity of reinforced soil.

Use of second and third screw in the reinforcing element's middle part (ζ_A is equal 0,51 and 0,72) reduced settlements on 41% and 55% compared to the samples with single screw (reinforcement factor ζ_A = 0,33). Applied pressure for compared settlements is constant 400 kPa. Disproportionate increase of reinforced soil's rigidity while reinforcement is used with different diameters of reinforcement confirms soil's involvement that surrounds reinforced soil. In addition differentiated screws' diameters reduce influence of soil's decompaction by screws.

Measured vertical deflections proof the assumption about dependence of reinforcement factor from the ratio of screws' diameters and distance between them to the distance between reinforcing elements.

Secant deflection modules *E* were calculated for certain pressure figures (table 1). Calculation formulas were taken from GOST 20276.1-2020.

Table 1. Influence of reinforcement factor on deflection module.

	Reinforcement factor, ζ_A

	0	0,23	0,27	0,33	0,51	0,72
Deflection module E, MPa	3,69	5,79	6,80	11,59	16,27	21,69

Deflection module gotten during performed site tests (figure 9) corresponds to the approach of soil's rigidity increase. Deformability of reinforced samples reduced compared to reference unreinforced sample. Measured difference was 3%, 12%, 37%, 63% and 72% for the samples with reinforcement factor ζ_A equal

0,23; 0,27; 0,33; 0,51 and 0,72 accordingly. Comparison is made for constant applied external pressure 300 kPa.

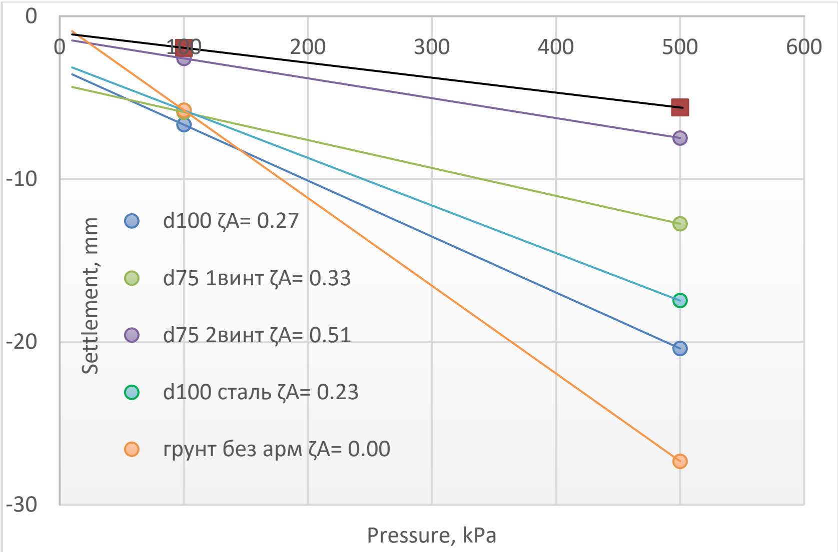

Fig. 9 – Graphs for deformation modules definition compared to reinforcement factor ζ_A.

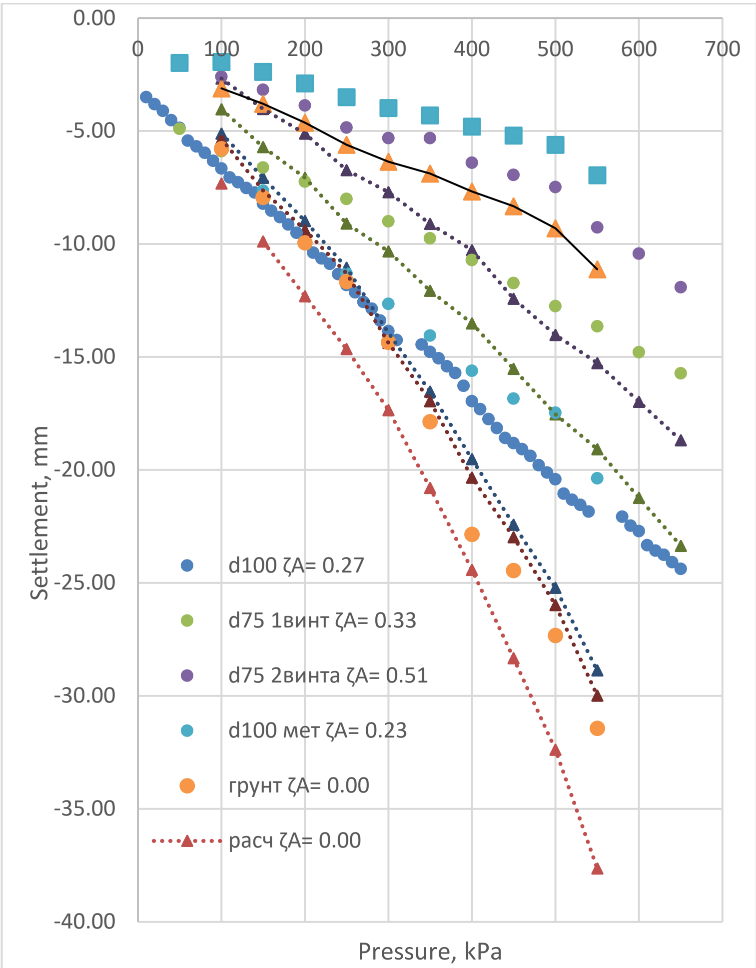

Fig. 10 – Tests results compared to calculated results.

Earlier tests results performed by Mirsayapov I.T., Safin D.R. and Nurmukhametov R.R. [22], [23], [24], [25] has already presented the way when reinforcing elements become the boundary that limits the deflections of weak soil.

4 Conclusion

Revised scheme of weak soil reinforcement was developed. Method proposed to use vertical elements with screws of different diameters. Diameter is increased from the bottom to the top what allows to involve bigger volume of weak soil without disturbing the soil structure.

Settlements calculation method was developed. Formula for calculation of reinforcement factors depending on geometry and elements' structure was proposed. Soil's settlements calculation method was revised considering geometry of FRP reinforcing elements with steel screws.

Site tests of weak soil's reinforcement by vertical elements were held. Results of withheld tests are following:

- Developed calculation method was proofed. It is confirmed the possibility to define settlements values by applying proposed method.
- Designed structure of reinforcing elements is developed. Reduction of settlements was verified.

results presented

Settlements reduction is reflected

Measured values were within …. … what proofs….

Measured results proofed proposed method….

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