Soil Improvement Using Rigid Large Elements in the Engineering Practice of the Republic of Belarus

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Abstract. The results of research and development of methods for the calculation, design and practical application of a method for technique of improvement soft soil bases for slab foundations with the use of rigid large elements are reported. The optimal percentage of rigid elements, structural characteristics of improved soils (increment and diameter of rigid elements) are presented and principles for their calculation and design are given. As exemplified by a specific construction site, it is demonstrated that technological schemes for the arrangement of improved soils, developed by RUE Institute BelNIIS, reduce the deformability of soft soil bases by four times and more.

Keywords: soft soil base ($E \leq 7$ MPa), soil improvement with the use of rigid elements, research, direct shear box test, plate loading tests (PLT), deformation modulus, calculation, design.

Conference topic: Design experiences and theoretical solutions.

Introduction

At the present time, the technology of strengthening of soft soil base by means of rigid large elements followed by the construction of slab foundation on top of it has become a frequent practice in foundation engineering in the Republic of Belarus. The improvement of soft soil bases with the use of rigid large elements is much more cost-effective than vibration methods (heavy tamping, vibratory rollers), and slab foundations installed on top of such improved bases are more economically viable than deep foundations (Seskov 2010; Kravtsov 2013; Mirsoyapov 2005).

This technique allows to strengthen foundation slab base to the desired properties (E , ϕ , c) using inexpensive prefabricated elements both in the form of driven (precast) and cast-in-place piles, including the use of local materials (gravel, large sand, soil-concrete), which are arranged in previously drilled, drilled and expanded or punctured holes. This is particularly effective in constrained urban environment, where dynamic impact methods are not allowed. Given the fact that there were no reliable methods for the calculation and design of improved bases with due regard to all special aspects of their construction and performance (increment and diameter of rigid elements, the degree of strengthening, etc.), RUE Institute BelNIIS performed a relevant research to study the specifics of strengthening of soft soils by means of rigid elements using both driven and cast-in-place piles (Ses'kov *et al.* 2011). The aim of this research was the development of an effective technology for the arrangement of improved soil bases, methods for its calculation and design ensuring cost savings of up to 30% as compared to traditional soil improvement methods (rolling, tamping, including soil reinforcement).

Methods and results of the research

The research was performed in laboratory and field conditions, using standard soil testing methods to determine soil characteristics (E , ϕ , s) before and after improvement. The evaluation of strength and deformation characteristics of improved soils with different percentages of rigid elements was performed in the laboratory by analyzing the results of a series of consolidated direct shear box and odometer compressibility tests.

Based on the experimental design (Adler 1969 *etc.*), the main factors affecting the strength and deformation properties of soils were determined and the results obtained were analyzed using mathematical statistics methods and STATISTIKA 10.0 software suite.

The first stage of the research was carried out using homogeneous pre-dried soil samples (sand, clay soil). The obtained results were used as a reference.

During the second stage, the samples were formed from a mixture with a given mass content and the properties of the original soil and rigid elements with the percentages of elements in the main soil of 8%, 16% and 30% (Fig. 1).

In order to ensure the comparability of test results, soil samples with homogeneous composition and elements were grouped as follows.

According to the experimental design matrix, a series of test samples of soils (sand, clay) with the volume of $V = A \cdot h$ (where A is the area of the sample in cm^2 and h is the height of the sample in cm) with predetermined baseline characteristics: density ρ_0 , humidity ω_0 , deformation module E_0 were prepared and subjected to direct shear box and odometer compressibility tests. The subsequent series of test samples were prepared from the test soil with characteristics similar to control samples, but with a different percentage of rigid elements

(8 to 30% by weight). The equivalent density of these samples was established based on the following assumptions:

$$(V - n \cdot V_{ap}) \cdot \rho_0 + m \cdot V_{ap} \cdot \rho_{ap} = \rho_{\text{экс}} \cdot V, \quad (1)$$

where n is the number of rigid elements in pcs.; V_{ap} , ρ_{ap} are the volume and the density of rigid elements in g/cm^3 ; $\rho_{\text{экс}}$ is the equivalent density of reinforced soil in g/cm^3 .

After expressing in the formula (1) the volumes V and V_{ap} through their area A , A_{ap} , height h and dividing all the terms by samples height, the following equation is obtained:

$$h(A - n \cdot A_{ap})\rho_0 + n \cdot A_{ap} \cdot h \cdot \rho_{ap} = \rho_{\text{экс}} \cdot A \cdot h, \quad (2)$$

it allows to determine the equivalent density required for the formation of samples and design of improved soil bases:

$$\rho_{\text{экс}} = \frac{(A - n \cdot A_{ap})\rho_0 + n \cdot A_{ap} \cdot \rho_{ap}}{A}. \quad (3)$$

A solution for the equivalent modulus of soil deformation $E_{\text{экс}}$ was obtained by a similar analytical method:

$$E_{\text{экс}} = k \cdot E_{ap} \left(1 + \frac{E_0 \cdot A}{k \cdot E_{ap} \cdot A_{ap}} \right) \frac{A_{ap}}{A}, \quad (4)$$

where E_{ap} , E_0 are the modulus of elasticity of rigid elements and the modulus of deformation of soil, MPa;

k is the coefficient, which makes allowances for the variability of properties of rigid elements.

The mixtures, formed in this manner, were subjected to consolidated direct shear box and odometer compressibility tests according to the standard procedure established by GOST 12248 (GOST 12248-2010 2013), the physical characteristics of rigid elements were determined in accordance with GOST 5180.

Based on the results of these tests, the values of modulus of constrained and total deformation $E_{\text{экс}}$ in the pressure range of 0 to 600 kPa and the values of the angle of internal friction φ were obtained (Figs 1, 2).

Fig. 1. General view of samples of fine sand for shear tests with different percentage of reinforcement elements ranging from 8 to 30% (Series 3)

In order to assess the reliability of experimental findings obtained from test results, the values of E and φ were compared to respective deformation and strength characteristics obtained by means of finite-element modelling.

After determining the optimal percentage of rigid elements in test soils, small-scale model bench tests of improved sand and clay bases were carried out (Fig. 3). The methodology and the results of bench tests are given in Kravtsov (2013), Yakunenکو (2013), etc.

The results of laboratory study of the properties of improved soil and bench tests of small-scale models demonstrated that:

- improved soil bases by rigid elements performs not as a piled foundation, but rather as a reinforced (consolidated) base with equivalent characteristics (ρ_s , c_s , E_s) surpassing the respective values in non-improved soils by not less than 2–3 times, and is characterized, as compared to natural soils, by pronounced strength and stress-induced anisotropy and the presence of the arch effect.

Fig. 2. Representative curve of changing of drained angle of internal friction φ for the fine sand samples with various percent of reinforcement ($i = 8\text{--}30\%$, see the graphs)

Fig. 3. General view of low scale simulation tray tests

– the destruction of improved soil bases by rigid elements under ultimate load occurs according to the following patterns:

a – upheaval of the buffer layer from under the foundation, if its thickness exceeds the limiting thickness ($h_{16} > 0.75b$, where b is the width of the foundation or $E \leq 20$ MPa);

b – frictional sliding (squeezing) of reinforcement elements relative to the natural soil under more critical loads on the base $p_0 \geq 0.8R$ or in the absence of the buffer layer;

c – loss of stability of improved soil, as evidenced by explicit relatively rectilinear sliding surfaces.

Thus, it is quite obvious that in order to assess the stability and to study the conditions for the emergence of any displacements in slab foundation base, it is possible to apply the general theory of soil mechanics, specifically rock equilibrium theory, discussed in the works of K. Tertsagi, B. V. Bakholdin, V. L. Berezantsev, V. A. Florin, etc.

– equivalent modulus of deformation E_s and cohesion c_s are increased by several times with the increase of percentage of rigid elements in the soil of up to 30%, with a slight change in angle of internal friction ϕ , whereupon any further increase in reinforcement percentage yields virtually no increase in soil strength;

– predominantly vertical deformation of the base occurs within the improved soil up to the critical load.

A complex of full-scale (field) tests was carried out at 9 test plots in order to validate the results of laboratory tests, as well as to test the developed equipment and different methods of arrangement of improved soil bases.

Field tests of soil bases carried out at test plots both before and after soil strengthening with consolidating piles with the determination of soil characteristics by means of standard field and laboratory methods. Improved soil bases was tested in situ by means of standard (SPT), cone (CPT) penetration tests as per GOST 19912-2001 (2004) and by a rigid stamp (a fragment of foundation) with an area of $A \geq 5,000$ cm² as per GOST 20276-99 (2000) (PLT).

The tests were performed in improved sandy and clay soils strengthened with shallow cast-in-place soil-concrete piles (in drilled, drilled and expanded, stamped or punctured holes) with the diameter of 100–200 mm and the length of 1.5–3 m and precast driven micropiles with the diameter of 150–200 mm and the length of 1.5–5.0 m. The basic results of field tests are presented in the articles (Seskov 2010; Kravtsov 2013; Yakunenko 2013, etc.) and in Section 3 of this paper.

The results of full-scale field tests confirmed the data obtained under laboratory conditions and provided evidence of the efficiency of developed solution for strengthening slab foundation bases by means of soil improvement technique with the use of compacting piles (rigid elements), and served as basic material for the elaboration of a method for their calculation and recommendations regarding the design (calculation) and arrangement of improved slab foundation bases (RUE “Stroytehnorm” 2014) (see Section 2 of this paper).

Methods for the calculation of improved soil bases with the use of rigid elements

This method was developed on the basis of experimental data, basic assumptions of Section 1, basic provisions of soil mechanics for slab foundations with the base pressure of not more than 0.3 MPa and reads as follows:

1 – an allowable amount of settlement of slab foundation s_u in cm is determined for the designed structure. It is inserted in the formula (1), and the value of the minimum equivalent deformation modulus $E_{\text{экр. min}}$ of rigid elements, ensuring the allowable settlement of the structure, is determined.

$$E_{\text{экр. min}} = \beta \frac{p_{\text{max}} \cdot H_c}{s_u}, \quad (5)$$

where β is a non-dimensionalized coefficient equal to: at p_{max} of up to 0.2 MPa – $\beta = 1$; at p_{max} of 0.2 to 0.3 MPa – $\beta = 0.7$ –0.8; p_{max} – the maximum pressure of slab foundation transmitted to the base, MPa; s_u is the allowable ultimate settlement of slab foundation base according to the design or technological regulations in m (not more than 8 cm, $s_u \leq 5$ cm for administrative and residential buildings); $H_c = \beta \cdot p_{\text{max}} / \gamma_m$ is the conditional minimum depth of compressible zone in m, where β – see above; γ_m is the average specific weight of soil below the foundation bottom within the depth equal to not less than two of its widths, MN/m³.

2 – using the dependency between the modulus of total deformation E_0 (or compressibility factor a_0) and porosity factor e (compression dependency or the results of field tests with the use of a stamp), the required porosity factor $e_{\text{экр. расч.}}$ of the improved soil base with piles is determined for $E_{\text{экр. min}}$, which is the main indicator for the development of the design of a such bases, but not less than $e_{\text{экр. min}} \leq e_{0-m_v} \cdot p_{\text{max}}$, where e_0 is the porosity factor of soil prior to its improvement, $m_v = 1$.

3 – the required strength characteristics of improved soil (internal friction angle $\varphi_{\text{экр. (II)}}$, deg., and cohesion $c_{\text{экр.}}$, MPa) ensuring the stability of foundation base at $K_{\text{уст.}} = 1.2$ are determined;

4 – the required minimum soil porosity factor (sand, clay) is established using the known dependence of strength characteristics on density and moisture, using the formula (6) – for sand soils and (7) – for clay soils:

$$e_{n, \min} = e_{\text{макс}} - I_D(e_{\text{макс}} - e_0); \quad (6)$$

$$e_{\text{эл. min}} = \frac{\gamma_s}{\gamma_w \cdot 100} (\omega_p + 0.5 I_p), \quad (7)$$

where e_0 , e_{max} are, respectively, porosity factors in natural sand (prior to reinforcement) and extremely dense conditions; $I_D = 0.7-0.8$ is the index of relative density; w_p and I_p are, respectively, humidity at the limit of plasticity and the index of plasticity; γ_s , γ_w are, respectively, specific weight of particles of soil and water in kN/m^3 .

In the event that porosity factor $e_{\text{экр. расч}}$ required for the calculation as per (6) and (7) exceeds the minimum value of calculated porosity factor of reinforced soil $e_{\text{yn. min}}$ as per formulas in Paragraph 2 above, the application of reinforcing elements is effective, if less – it is ineffective.

5 – the increment a and the distance between rigid elements, in case of their checkboard arrangement, are determined using equations (8) and (9):

$$a_{\max} = d_a \sqrt{\frac{\pi \gamma_0}{3.5(\gamma_{\text{экр. расч}} - \gamma_0)}}; \quad (8)$$

$$l_{\max} = a_{\max} / 2 \cdot \cos 45^\circ, \quad (9)$$

where d_a – is the diameter of reinforcement elements in m; $\gamma_{\text{экр. расч.}}$ is the required specific weight of soil after reinforcement as per (10) in kN/m^3 ; γ_0 is the specific weight of soil prior to reinforcement in kN/m^3 ;

$$\gamma_{\text{экр. расч}} = \frac{(A - n \cdot A_a) \gamma_0 + n \cdot A_a \cdot \gamma_a}{A}, \quad (10)$$

where A , A_a is the area of improved soil base and rigid elements in m^2 ; n is the number of rigid elements in 1 m^2 , $n = A/A_a((e_0 - e_{\text{экр. min}})/(1 + e_0))$ in pcs.; γ_0 , γ_a is the specific weight of soil in kN/m^3 , respectively, before and after improvement (for concrete $\gamma_a = 23 \text{ kN/m}^3$).

6 – the length of rigid elements L in m shall be taken as equal to not less than its compressed width H_c in saturated clay soils, in other cases, as a rule, up to the mark, where additional vertical specific pressure on subsoil below the bottom of improved soil does not exceed its design strength R , but not less than two widths for column-type, and three to four widths for belt-type slab foundations;

7 – a buffer layer made of sand and gravel mix compacted to a density factor of $K_{\text{com}} \geq 0.98$ is arranged between the rigid elements and the bottom of slab foundation. Its thickness $h_{\text{б}}$ is determined as per formula (7), but should not be more than 1/5 of the width of slab foundation b and not less than 0.15 m.

$$h_{\text{б}} = \frac{s \cdot E_{\text{б}} \cdot \sum A_a}{p_{\max}}, \quad (11)$$

where $p_{\max}$ – see above, MPa; $\sum A_a$ – the area of heads of all rigid elements in m^2 ; $E_{\text{б}}$ is the modulus of deformation of compacted intermediate buffer layer depending on the material. It should be not less than: for medium-grained sand – 20 MPa; for coarse sand and lime gravel – 25 MPa; for crushed granite – 40 MPa; in case of other materials $E_{\text{б}}$ can be determined based on the condition that the settlement does not exceed $s_u \leq 15 \text{ mm}$;

8 – Improved soil bases by rigid elements designed as per paragraphs 1–7 and its structural elements are checked in terms of strength of the materials, settlement and strength of the subsoil $\sigma_{\text{зп}} < R_{\text{подст.}}$. The modulus of elasticity of rigid elements should be not less than 20 MPa.

Evaluation of research results in production environment

The proposed methods for the design of improved slab foundation bases with the use of rigid elements were evaluated during the construction of administrative building at refuelling station under reconstruction managed by OOO “Geo Plus” and located at Kolodischi agricultural settlement in Minsk Raion (hereinafter referred to as the “facility”).

Baseline information of the facility

The designed facility is a large block one-storey building, the walls are made from LECA blocks, belt-type foundations are made of standard concrete blocks with the width of 400 mm, the distributed load on foundation base amounts to 0.158 MPa. A complicating factor in the construction of foundation is the presence of loose, non-uniform filled soil compressible in vertical and horizontal directions with the elements of construction debris and plant residues (Fig. 4). This conditioned the necessity of developing the design and technology for strengthening the upper part of foundation base.

Rigid elements was placed only under strip foundations as per recommendations in RUE “Stroytehnorm” (2014). Proceeding from the capabilities of the local construction company, driven soil-concrete piles arranged in drilled and expanded holes were used as rigid elements without soil excavation (Fig. 5). The holes were made with a $\varnothing 250 \text{ mm}$ metal pilot bore manufactured according to the drawings of RUE Institute BelNIIS. It was installed instead of a helical screw on a UGB-PVS truck-mounted drilling rig (without any additional alterations of the joint). The wells were filled with soil-concrete as per “Recommendations for designing and arranging soil-concrete piles in drilled and expanded holes” (Ministry of Architecture... 2005), the proportion of local soil to M150 cement in the mixture being 5:1.

Fig. 4. Layout of foundation on base reinforced by piles. 1 – filled soil of up to 3.5 m thick ($\gamma = 16.4 \text{ kN/m}^3$, $E = 11 \text{ MPa}$); 2 – medium coarse sand of medium strength ($\gamma = 17.3 \text{ kN/m}^3$, $\phi = 36^\circ$, $c = 0.001 \text{ MPa}$, $E = 34 \text{ MPa}$)

The required equivalent density of reinforced soil, the thickness of buffer layer and the increment of reinforcing elements were calculated as per recommendations in RUE “Sstroytechnorm” (2014) using formulas (5)–(11) for 1 m^2 of the area of slab foundation base in the following sequence.

According to the formula (1) at $p_{\max} = 0.158 \text{ MPa}$, settlement $s = 5 \text{ cm}$ and the depth of compressible zone $H_c = \beta \cdot p_{\max} / \gamma = 1 \cdot 0.158 / 0.0164 = 9.63 \text{ m}$, it was determined:

$$E_{\text{экр. min}} = \beta \frac{p_{\max} \cdot H_c}{s_u} = 1 \cdot \frac{0.158 \cdot 9.63}{0.05} = 30.43 \text{ MPa}.$$

Fig. 5. Process of making the reinforcing elements at the building's construction site

According to the formulas (2)–(7) and Paragraph 2 it was determined:

$$\gamma_{\text{экр. расч}} = \frac{(A - n \cdot A_a) \gamma_0 + n \cdot A_a \cdot \gamma_a}{A} = \frac{(1 - 2 \cdot 0.05) \cdot 16.4 + 2 \cdot 0.05 \cdot 23}{1} = 17.06 \text{ kN/m}^3.$$

$$e_{\text{экр. расч}} = e_0 - m_v \cdot p_{\max} = 0.7 - 1 \cdot 0.158 = 0.54.$$

$$n = A \left(\frac{e_0 - e_{\text{экр. расч}}}{1 + e_0} \right) / A_a = \frac{1}{0.05} \left(\frac{0.7 - 0.54}{1 + 0.7} \right) = 2 \text{ pcs./m}^2.$$

$$a_{\max} = d_a \sqrt{\frac{\pi \gamma_0}{3.5(\gamma_{\text{экр. расч}} - \gamma_0)}} = 0.25 \sqrt{\frac{3.14 \cdot 16.4}{3.5(17.06 - 16.4)}} = 1.17 \text{ m}.$$

$$l_{\max} = a_{\max} / 2 \cdot \cos 45^\circ = 1.17 / 2 \cdot 0.71 = 0.82 \approx 0.9 \text{ m}.$$

The design concept makes provisions for the arrangement of two rigid elements per 1 m of the length of strip foundation.

The required thickness of sand buffer layer between the foundation and rigid elements is calculated as follows:

$$h_{fb} = \frac{s \cdot E_b \cdot \sum A_a}{p_{\max}} = \frac{0.015 \cdot 20 \cdot 0.1}{0.158} \approx 20 \text{ cm}.$$

1, 2, 3 – graphs of $s = f(p)$ at TP1-TP3 test plots prior to vertical reinforcement, respectively, with the modulus of deformation $E_{01} = 12.6$ MPa, $E_{02} = 9.5$ MPa, $E_{03} = 9.7$ MPa; 1a, 2a, 3a – same, but after vertical reinforcement, respectively, with $E_{a1} = 38.3$ MPa, $E_{a2} = 32.4$ MPa, $E_{a3} = 27.6$ MPa

Fig. 6. Results of stamp testing of vertically-reinforced foundation base at the test facility. Graphs of dependency of stamp settlement $s = f(p)$ at TP1, TP2, TP3 test plots before and after strengthening

Examination of vertically reinforced foundation base of the test facility

The base was tested with the use of a 2,500 cm² stamp in accordance with the standard procedure as per GOST 20276-99 (2000) in order to evaluate the effectiveness of design solutions on strengthening the foundation base. The tests were conducted before and after the arrangement of improved soil base.

The load was applied with the help of a hydraulic jack with the capacity of 500 kN. Reactive forces were received by a steel beam attached with screw anchors.

PLT test results are given in Figure 6.

The results of field in-situ tests of improved soil bases designed as per recommendations (RUE "Sroystekhnorm" 2014) confirm the reliability of the developed calculation method (see Section 2) and effectiveness of vertical reinforcement of strip foundation base using soil-concrete consolidating piles.

Conclusions

1. Methods for the design, construction and the technology for the arrangement of improved soil base of soil with the use of compaction piles were proposed, researched and tested in a production environment.

2. The reliability and efficiency of research results, developed methods for the calculation of the proposed improvement technique with the use of consolidating piles were confirmed by means of experiments. For example, the mean value of the modulus of deformation of bulk loose soil after improvement, based on the results of PLT tests, was $E_{ba} = 33$ MPa, while the initial value was $E_0 = 11$ MPa, thus proving 3.3 – fold strength increase. Furthermore, the deviation of actual modulus E_{ba} from the modulus $E_{pacu} = 30.4$ MPa calculated according to the formula (1) does not exceed 10%.

Breaking stress for the load of $P = 0.5$ MPa was not reached on the "load-and-settlement" $s = f(P)$ graph, i. e. the bearing capacity of improved soil will be ensured in case of construction of 2 additional storeys with the load on the base of $3 \cdot 0.158 = 0.47 < 0.5$ MPa.

3. The research results and the Recommendations for the design and construction of improved slab foundation bases with the use of rigid elements (RUE "Sroystekhnorm" 2014) developed on their basis served as a cause for active introduction of the proposed soil strengthening technique in the Republic of Belarus, thus ensuring a reduction in material consumption and labour intensity in the construction of slab foundations in the amount of not less than 30% as compared to vibro-percussion or pile underpinning methods without any deterioration in reliability.

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