Calculation of vertical deformations of the rigid foundations on the soft soil improved by geotextile encased stone columns.

Roman I. Shenkman[1], A.B. Ponomaryov[2]

[1] Candidate of Technical Sciences, docent of department «Building production and geotechnics», Perm National Research Polytechnic University

[2] Doctor of Technical Sciences, Professor, Head of the department «Building production and geotechnics», Perm National Research Polytechnic University.

ABSTRACT

The article presents an engineering methodology for calculating deformation of rigid foundations on the soft soil improved by geotextile encased stone columns. A comparison of the calculation results according to the proposed method with the data of experimental studies on one of the construction sites of the Perm city of Perm region of Russia is presented. Also paper presents analysis of the presented results which shows a good convergence of calculations with experimental data and numerical simulation data using the finite element method.

Keywords: soft soil, soil improvement, geotextile, stone columns/

1 INTRODUCTION

The construction of foundations of buildings and structures in soft soil conditions represented by water saturated clay often requires the improvement of the base. One of the effective methods for improving these types of soils is reinforcement of the base with geotextile encased stone columns (GESC). This approach can significantly reduce the deformability of the base, as well as to increase its bearing capacity. The most common area of application of this technology is to improve the foundations of embankments and other areal structures. On the other hand, this type of improvement can be a good alternative to the use of long driven and bored piles for the construction of lightly loaded buildings and structures in conditions of a large thickness of soft clay soils that cannot act as an effective bearing layer for pile foundations. The calculation of the deformations comes to the fore in case of using this technology to improve the base of foundations of buildings and structures which leads to the need to develop a method that will allow its calculation. This technology has proven itself in such soil conditions according to numerous studies Paul and Ponomaryov (2004), Raithel M. et al (2005), Alexiew (2012), Kempfert and Gebreselassie (2006),

2 THE MAIN POINTS OF THE PROPOSED METHOD

In the considered application area, these columns will act as an alternative to driving piles therefore the foundation structure itself will have considerable rigidity with respect to the most improved soil base.

Analysis of existing scientific studies allows us to draw the following conclusions about the stress-strain state of an improved soil massif:

- there is a distribution of stresses between the improvement elements and the soft ground;
- most of the load is transferred to the GESC due to their high rigidity;
- GESC will push through the underlying soil base if they are made in a hanging version (without bearing on incompressible soils), the part of the surrounding soil will move along with the elements of improvement;
- the filling material of the GESC will expand to the sides, its movement is limited by the geosynthetic shell acting as reinforcement and the lateral pressure of the surrounding soil;
- the geosynthetic shell perceives the load equal to the difference between the active pressure in the body of the columns and the resistance of the surrounding soil;
- an equilibrium state will be reached which will correspond to the final stress distribution in the improved soil massif;
- the vertical deformation of a separate stone columns will consist of the deformations associated with its radial expansion, the compressibility of the filling material and the pushed deformation of the underlying soil.

An engineering method for calculating the vertical deformation of. foundation on soft soil base improved by GESC was proposed on base of the analysis of existing studies and regulatory base (EBGEO), as well as data on the stress-strain state of the improved soil massif. It is proposed to use an algorithm based on the following assumptions to calculate the deformation:

-determining for the calculation is drained (end) state, as it gives the greatest deformation and maximum radial tensile stresses in the geosynthetic shell;

- vertical deformations of soft soil and GESC are equal at the level of the bottom of rigid foundation;

- shell material (geosynthetic) - linearly elastic;

- the soil foundation is represented as an elastic linearly deformable half-space;

- the coefficient of the active pressure of the soil is $K_a=tan^2(45-\varphi/2)$ act inside the geotextile encased stone column;

- the coefficient of lateral pressure of the soil is $K_p=1-sin\varphi$ and act in a soft soil mass,

- performing of the improvement does not significantly affect the process of deformation of a soft soil but only significantly reduces the load that is transferred to it, that is the deformation of a soft soil can be determined separately from the improvement elements, in case that the stresses in it are known;

The main purpose of the proposed calculation method will be to determine the stress distribution under the base of the foundation which will ensure equality of the total vertical deformation of the soil-ground elements and of soft soil under the base of the foundation.

The deformation of the soft soil is proposed to be determined on the basis of the classical method of layer-by-layer summation, presented in existing regulations of RF SP 22.13330.2011 which is based on the classic representation of a soil massif as a linearly deformable half-space. At the same time deformations will be determined from the reduced stress acting in soft soil with taking into account the design the of the improvement with GESC. At the same time, this deformation should be equal to the vertical deformation of the GESC at the bottom of the rigid foundation of building or structure. Vertical deformation of GESC will consist of the deformation S_{c1} associated with the radial expansion of the geotextile shell and the compression of the filling material, and the deformation of S_{c2} associated with pushing of the underlying soil by the lower end of the column. The design scheme for determining the vertical deformation of the ground reinforced element is shown in Figure 1.

It is proposed to use the iterative method to achieve the main goal of the calculation - to determine the distribution of stress in bottom of foundation, It is necessary to specify the initial distribution of stresses and determine for it separately the deformations of the GESC and the surrounding soft soil of the base, as well as the stress state of the soil base.

In the first approximation, this distribution can be taken within $\sigma_{zs0}/P=0.7$ as the first step of the iterative calculation process or another value is taken, where P is the average pressure at the base of the foundation. The vertical stress will act on the top of the GESC in this case:

$$\sigma_{zc0}=\frac{P\cdot A_f-\sigma_{zs0}\cdot(A_f-A_{c,tot})}{A_{c,tot}} \quad (1)$$

A_f - footing area;
$A_{c,tot}$ - total area of GESC.

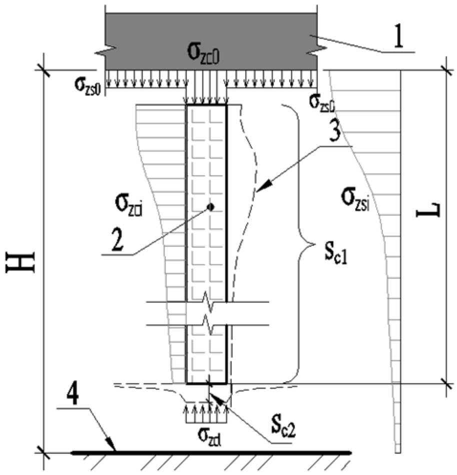

Fig. 1. - The design scheme for determining the vertical deformation: H - thickness of soft soil; L - the length of GESC; σ_{zc0} - vertical stresses in the GESC at the bottom of the foundation; σ_{zs0} - vertical stresses in the soft soil at the bottom of the foundation; σ_{zcl} – vertical stresses in the bottom of the GESC; 1– building foundation; 2 - GESC; 3 - deformed scheme of the GESC; 4 - incompressible soil.

The soil-reinforced elements are divided into separate layers along the length by analogy with soft soil when calculating by layer-by-layer summation for the calculation of S_c. The stress components acting in the soil massif, as well as radial and vertical deformations of the soil element will be determined within this layers. It is proposed to take the existing stresses uniformly distributed within the limits of one layer of a GESC.

Improved soil base should be divided into separate elementary cells for determining the radial deformations. This cell is GESC and the surrounding array of soft soil in the form of a hollow cylinder. An internal pressure equal to the contact pressure between the geosynthetic shell and the surrounding soil mass will act on the hollow cylinder of the soft soil. This pressure is equal to the difference between the active pressure in the column and the stresses in geosynthetics

The radial deformation of GESC for each elementary layer can be determined by solving the Lame problem "about a thick-walled cylinder loaded with internal uniform pressure", taking into account the boundary conditions of the presented problem.

Consideration of edge effects for elements related to the fact that vertical stresses under the base of the rigid foundation spread non-uniformly can be performed by averaging the vertical pressure acting in soft soil over various points. The calculation of the radial deformation will be made taking into account the averaged vertical pressure acting in soft soil. Also, the value of vertical stresses in GESC can be averaged over the foundation, depending on its area, configuration, and number of GESC.

The magnitude of the vertical stresses and contact pressure in the body of the cylinder will vary according to some law. The distribution of vertical stresses in weak soil is proposed to be determined when settlements are found by the method of layer-by-layer summation, the distribution of contact pressure - by solving the Lamé problem.

As a result of the solution, the maximum value of the radial displacements is achieved at a point lying on the surface of the soil element and will be equal to the radial displacement of the geosynthetic shell.

Since the wrapping material is assumed to be elastic, tensile forces in the geosynthetic envelope within the layer can be determined from the material stiffness.

Considering all the above, we can express the value of contact pressure. The complete derivation of the presented formula is given in other works of the authors Shenkman (2016).

$$\sigma_{con,i} = \frac{\sigma_{ha,i} + \dfrac{J \cdot \mu \cdot \sigma_{zs,i}(R^2 - r_0^2)(\mu + 1)}{Er_0(2r_0^2\mu + R^2 + r_0^2)}}{1 + \dfrac{J \cdot (R^2 - r_0^2)(\mu + 1)}{Er_0(2r_0^2\mu + R^2 + r_0^2)}} \quad (2)$$

J - axial stiffness of the shell material;

R - the radius of the unit cell (GESC and the surrounding soft soil;

r_0 - the radius of the GESC;

$\sigma_{ha,i}$ - active pressure in the elementary layer of GESC;

$\sigma_{zs,i}$ - vertical stresses in the elementary layer of the surrounding soft soil of unit cell;

μ - Poisson's ratio.

An important aspect of the solution is to determine the distribution of vertical stresses in the body of the GESC. The dispersion of vertical stresses with depth occurs due to the action of tangential stresses along the lateral surface on contact with soft soil, due to the lower end of the soft soil being pushed be GESC.

If we consider a single elementary layer of the soil element then the increment of vertical stresses along length of GESC will be equal to the sum of tangential stresses acting on the side surface of the elementary layer. The equilibrium scheme of the elementary layer is shown in Figure 2.

The tangential stresses at the contact of GESC and the surrounding massif can be determined by the strength condition of the Coulomb and will depend on the lateral reduction of the surrounding mass of soft soil acting on the geosynthetic shell or contact pressure.

It is possible to calculate the contact pressure across the entire length of the soil element and the corresponding radial displacements of GESC with taking into account the distribution of vertical stresses in the body of GESC.

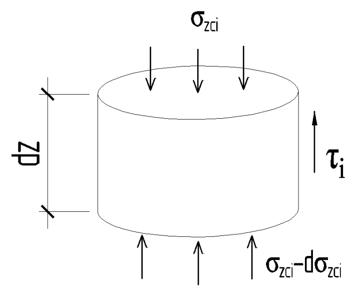

Fig. 2. - The equilibrium scheme of the elementary column layer with thickness dz

The amount of deformation of each of the considered layers of the GESC can be determined on the assumption of the constancy of its volume.

The value of this deformation may be supplemented by the deformation associated with the material compaction depending on the strain modulus of the used aggregate.

We can also calculate the stress acting under the base of the GESC and take into account pushing by the lower end of the GESC by analogy with hard stamp settlements.

As it mentioned above, the vertical deformation of the soft soil should be equal to the deformation of the GESC, which is the boundary condition of the iterative process, if this condition is not met, then the ratios of vertical pressures along the base of the foundation initially adopted changes and the calculation need to be repeated. Deformations of the shell due to its tension (manufacturing defects) can be additionally taken into account.

3 NUMERICAL SIMULATION

Comparison of numerical simulation data with using Plaxis software package and calculated wit using the presented methodology was made to verify the presented engineering method. An elementary volume of the improved soil volume — a cell — was chosen for the numerical simulation in axisymmetric formulation.

Characteristics of the soil base was taken by example of the average soft soil of the city of Perm. Elastic-plastic model of Mohr-Coulomb was used in the numerical simulation of the test problem.

A uniformly distributed load of 200 kPa was applied over the top of the improved soil base model. According to the simulation results, the value of the vertical deformation of the unit cell was obtained, as well as the data on the distribution of radial deformations of the geosynthetic shell over the depth.

Numerical simulation results and comparison of deformations according to the calculation and modeling data are presented in Figure 3,4.

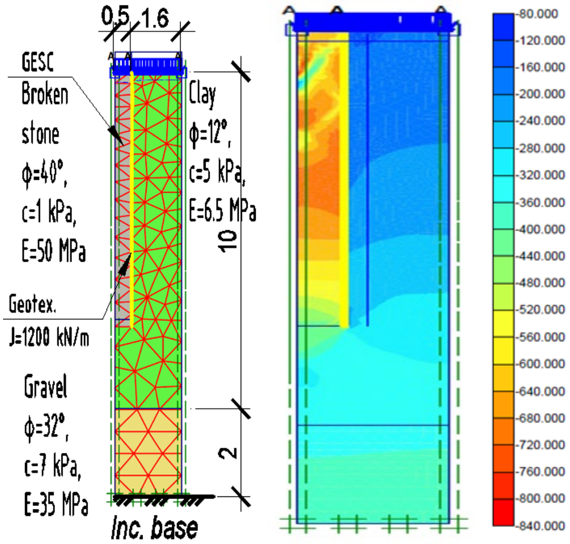

Fig. 3. – Vertical stress in improved soil base, kPa.

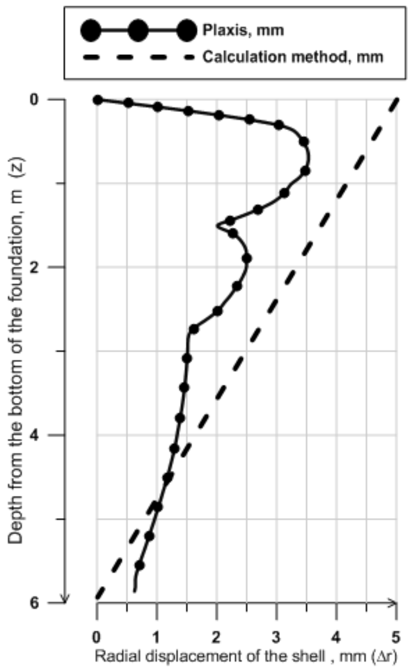

Fig. 4. – Radial displacement of geosynthetic shell

It should be noted that in the presented model the soil will be under conditions of odometric compression, therefore it is necessary to make the appropriate corrections in the method for determining the deformation of a soft base.

According to the numerical simulation data, the average vertical stresses in soft soil amounted to - 150 kPa, according to the calculation data - 154 kPa. According to the numerical simulation data, the average vertical stresses in the reinforcement element were 660 kPa, and according to the calculation data - 625 kPa. According to the numerical simulation the settlements of the improved base was - 141 mm, according to the calculation data according to the presented method - 132 mm.

4 CONCLUSION

Analyzing the data of the presented results, we can conclude about the relatively good convergence of the presented results of numerical simulation and the calculation according to the presented methodology. It is also possible to conclude from the distribution of stresses and radial displacements of the reinforcement shell that the adopted coefficient of active pressure in the body of GESC is close to numerical modeling only at a high level of stress roughly corresponding to the loss of stability of the filling soil (upper section of the GESC). Deeper (lower voltages of vertical stress), it will be significantly less (lower section). Consequently, a further direction of research can be the determination of the exact value of the active pressure coefficient in the body of GESC which is necessary to increase the accuracy of the method.

Thus, the presented engineering method makes it possible to calculate the deformations of rigid foundations on a soft soil base, improved by GESC, and with sufficient accuracy to describe the stress-strain state of the improved soil massif.

REFERENCES

Paul A., Ponomaryov A.B. The bearing behavior of geogrid reinforced, crushed stone columns in comparison to non-reinforced concrete pile foundations // Proceedings of the Eurogeo 3. Volume II. Munich, 2004. P. 285–289.

Raithel M. et al. Foundation of Constructions on Very Soft Soils with Geotextile Encased Columns-State of the Art // Innov. Grouting Soil Improv. 2005. P. 1–11.

Raithel M., Kirchner A. Calculation techniques and dimensioning of encased columns — design and state of the art // Proc. 4th Asian Reg. Conf. Geosynth. June 17-20, 2008 Shanghai, China. 2008. № Raithel 1999. P. 718–723.

Alexiew D., Gmbh H.S. 15 Years of Experience With Geotextile Encased Granular Columns As Foundation System // International Symposium on Ground Improvement IS-GI Brussels 31 May & 1 June 2012. Brussels: ISSMGE - TC 211, 2012. № June.

Kempfert H.G., Gebreselassie B. Excavations and foundations in soft soils // Excavations and Foundations in Soft Soils. 2006. 1-576 p.

SP 22.13330.2011 “An updated version of SNiP 2.02.01-83 *. The foundations of buildings and structures”

Bräu G. Recommendations for Design and Analysis of Earth Structures using Geosynthetic Reinforcements - EBGEO, Second Edition // Recommendations for Design and Analysis of Earth Structures using Geosynthetic Reinforcements - EBGEO, Second Edition. 2012.

Shenkman R.I. Calculation of deformation of soft clayey bases, improved by vertical soil elements in a shell of geosynthetic materials: dissertation candidate of technical sciences: 05.23.02 /; 2016. - 147 p.