Optimization of calculation of the stress-strain state of a base reinforced with inert material

A Z Ter-Martirosyan, S A Sergeev and L Yu Ermoshina
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

E-mail: stanislav_sergeev91@mail.ru

Abstract. In this article, we performed a comparative analysis of the results of calculating the stress-strain state of a soil base reinforced with crushed stone columns, with calculation results obtained using a well-known technique that allows optimizing the calculation of the deformation characteristics of base soils. The calculations were performed by the finite element method (FEM) in the PLAXIS 3D software package. The base reinforcement was carried out in order to reduce the stabilized settlement by transforming the properties of the soil using crushed stone reinforcing elements. A comparative analysis showed good convergence of the values of the settlements of slab foundations, which allows us to apply the methodology for calculating the deformation characteristics of soils to optimize the calculation of the stress-strain state of the bases according to the second group of limiting states.

1. Introduction
Currently, there are various ways of transforming the properties of base soils using vertical reinforcing elements (installation of lime piles, installation of stone columns using jet grouting technology, compaction of foundations with soil and sand piles). The installation of crushed stone piles is one of such methods. The technology for the construction of crushed stone piles allows not only to improve the mechanical characteristics of structurally unstable soils, but also to reduce their compressibility and speed up the consolidation process in weak water-saturated soils.

In this research, we considered stone columns constructed using the «IMPAKT» technology, which makes it possible to construct piles filled with crushed stone in water-saturated, incoherent, cohesive, or organic soils. The process of construction of stone columns consisted of the following stages: vibration dipping of working equipment to the design depth of the bore (bore compaction); the construction of stone columns up to the design mark for reinforcing the soil of the base (crushed stone compaction). To confirm the achievement of the strength and deformation characteristics of the base soil (deformation modulus, adhesion, and the angle of internal friction) defined in the design documentation, a set of additional engineering and geological surveys was carried out, including static sounding and stamp tests. Figure 1 shows a schematic diagram of the construction of stone columns.

Today, for the design of buildings and structures for estimate the stress-strain state of base soils, software systems that implement FEM are always used. The calculation time in software systems directly depends on the number of finite elements in the model. So when modeling a large number of piles in the PLAXIS 3D software package, there is a need for an alternative way of specifying pile elements in the software package.
Figure 1. Schematic diagram of the device of crushed-stone reinforcing elements: a) vibration immersion of the working body in the ground; b) filling the cavity of the working body with crushed stone; c) removing the working body from the soil while simultaneously filling the resulting well with crushed stone; d) layer-by-layer compaction of crushed stone in the body of the pile; e) ready crushed-stone pile.

2. Literature References

A large number of scientific papers have been devoted to the study of stone columns, showing their main advantages and disadvantages, applications, methods for calculating stone columns based on various theories, as well as the experience of their application in the construction of various objects, etc. Studies in this area were carried out by: Nazari Afshar J. and Ghazavi M. [1], Sarvaiya H. K. and Solanki C. H. [2], Marto A. et al. [3], Zahmatkesh A. and Choobbasti A. [4], Mokhtari M. and Kalantari B. [5], Arman H. et al. [6], Niroumand H. et al. [7], Christoulas St. et al. [8], Nguyen Th. T. [9], Stavnicer L. R. et al. [10], Tandel Y. K. et al. [11], Maurya R. R. et al. [12], Adalier K. et al. [13], Gniel J. and Bouazza A. [14], Poorooshasb H. B. and Meyerhof G. G. [15], Han J. and Ye S. L. [16].

In his research S.F. Kwa, E.S. Kolosov and M.Y. Fattah performed the modeling of stone columns with a geogrid using the FEM in the PLAXIS 3D software package. This simulation was performed in order to compare the results obtained in the course of experimental studies with the results of model tests [17]. J. Kawalec and T. Warchal in their research performed the calculation of the road embankment along which there will be a highway using FEM. The embankment is based on soft soils transformed by stone columns made using dynamic replacement technology [18]. A. Zahmatkesh and A.J. Choobbasti proposed a method for estimate the settlement and bearing capacity of soft clay reinforced with stone columns, and also performed a numerical analysis by the FEM in the PLAXIS software package. Two types of calculations were performed: one for calculating the bearing capacity coefficient, and the second for calculating the settlement reduction coefficient [19]. Jan Privac's research is based on Priebe's theory of developing a coefficient of improvement, which is one of the most commonly used analytical methods, and also describes numerical and laboratory models of stone columns. Improvement coefficients calculated by numerical and laboratory models are compared with improvement coefficients according to Priebe theory [20].

3. Materials and methods

To calculate the stress-strain state of the soil mass, composed of soft soils, the PLAXIS 3D software package was used. During the calculations, the following calculation stages were simulated: loading the calculated mass with its own weight of the soil and determining its initial stress-strain state;
modeling of excavation of a pit in natural slopes; the construction of stone columns; foundation slab modeling and transfer of full load to the base.

To build the finite element model of the soil mass, the results of engineering and geological surveys of the construction site were used.

The base soils under the foundation slab are sands of medium size, loose, low moisture - \( E = 12 \) MPa.

Taking into account the presence of weak soils in the base to reduce stabilized settlement, reduce consolidation time and installation and construction works, the project provides for reinforcing the base soils by converting the properties of soils using stone columns.

Transform of soil properties was carried out taking into account chapter 5.9. SP 22.13330.2016 [21] by reinforcing the soil base with stone columns of \( \varnothing 600 \) mm 4 m long on a 1.5 x 1.5 m grid. Stone columns were made of crushed stone of a fraction of 5-20 mm in accordance with GOST 8267-93 [22].

To simulate the stress state of the soil, tetrahedral finite elements were used. Soil behavior was described by an elastic, perfectly plastic Mohr-Coulomb soil model.

Table 1 shows the soil parameters used for the Mohr-Coulomb model.

| Soil                  | Soil density, g/cm³ | Porosity factor | Modulus of deformations, MPa | Specific cohesion, kPa | Angle of internal friction |
|-----------------------|---------------------|-----------------|-----------------------------|------------------------|---------------------------|
| Filled soil           | 1.70                | 0.5             | 15                          | -                      | -                         |
| Sand of medium size,  | 1.76                | 0.65            | 25                          | 1                      | 37                        |
| medium density        |                     |                 |                             |                        |                           |
| Sand of medium size,  | 1.69                | 0.77            | 12                          | -                      | 27                        |
| loose                 |                     |                 |                             |                        |                           |
| Medium-hard loam      | 2.14                | 0.45            | 28                          | 46                     | 22                        |
| Powdery, dense sand   | 1.92                | 0.4             | 39                          | 9                      | 33                        |

In the calculations, stone columns were modeled in the first calculation case in the form of separate volumetric elements of appropriate stiffness (Figure 2a), and in the second case, in the form of a solid soil mass with a reduced deformation modulus (Figure 2b).

![Figure 2](image-url)

**Figure 2.** Type of construction of stone columns during modeling: a) the first design case; b) the second design case

The total number of finite elements in the model in the first design case was 2 339 855, and in the second design case was 345 703.
The reduced modulus of soil deformation for the second design case was determined in accordance with the following relationship:

\[
E_{RMD} = \frac{E_{soil} \cdot A_{soil} + E_{pile} \cdot A_{pile}}{A_{total}}
\]

(1)

where \(E_{RMD}\) is the reduced modulus of soil deformation; \(E_{soil}\) the modulus of soil deformation; \(E_{pile}\) is the modulus of the total strain of the stone columns material; \(A_{soil}\) is the area of the soil; \(A_{pile}\) is the cross-sectional area of stone column; \(A_{total}\) is the total area.

Using (1) the reduced modulus of soil deformation for sand of medium size, loose amounted to 20.5 MPa. Dependence (1) does not take into account the growth of the deformation characteristics of the soil around the reinforcing element due to compaction, which goes to the reserve.

4. Results

Figures 3.4 show the phase vertical displacements of the soil mass at the stage of completion of construction in the calculations for the first and second design cases. In the first design case, the maximum vertical displacements were 5.1 cm, in the second - 4.79 cm, which does not exceed the maximum permissible values in accordance with applicable standards. The discrepancy between the results of the calculation of sediment does not exceed 10%.

Figure 3. Phase vertical displacements of the soil mass at the stage of completion when calculating the first design case, m
5. Conclusions

1. An analysis of the research of Russian and international scientists showed the prospects of using crushed stone, gravel and other soil reinforcing elements to reduce technical and economic costs and environmental requirements.

2. The construction of stone columns made it possible to transform the physical and mechanical properties of the construction site, including the soils located between the reinforcing elements.

3. In design practice, it should be taken into account that dependence (1) does not take into account the growth of the deformation characteristics of the soil around the reinforcing element, which goes into reserve. The general calculation process should be improved in order to more accurately predict the deformation properties of the transformed base as a whole and its elements. To confirm the achievement of the deformation characteristics of the base soil, it is necessary to carry out a complex of engineering and geological surveys, including static sounding and stamp tests.

4. Based on the results obtained, it is acceptable to use the given values of the deformation characteristics of soils in the case of calculating the stress-strain state of the foundations of slab foundations for the second group of limiting states.

5. In the case of calculating the stress-strain state of the bases according to the first group of limiting states, it is necessary to calculate the axisymmetric problem in a two-dimensional formulation.

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