Experience of Using Crushed-stone Reinforcing Elements in Various Ground Conditions

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Abstract. Stone columns are one of the widely used methods for improving weak foundation soils, since this method is not only cost-effective, but also ecologically safe, since natural materials (stone, gravel etc.) are used as stone column aggregate. Stone columns increase the bearing capacity of the foundation soils, reduce settling and help to accelerate the consolidation process. This paper presents the results of field research of crushed-stone reinforcing elements and soil between them by the plate test method and the static sounding method.

Introduction

Currently, due to the dense urban development and shortage of free land on their territory, new construction is underway to the newly developed areas that are characterized by complex engineering and geological conditions, including the presence of structurally unstable soils (weak saturated clay soils, filled soil, peats, etc.). As a rule, structurally unstable soils have low strength, high compressibility, and high porosity, have sufficiently high humidity, they are sensitive to the vibration effects and other factors associated with the construction industry.

There is a large number of methods that improve the engineering and geological conditions of the construction site and a setting up method of crushed-stone piles (stone columns) is one them. This method is used to increase the strength and reduce the compressibility of structurally unstable foundation soils as well as to accelerate the consolidation process and reduce the soils tendency to liquefaction under the action of external dynamic loads.

For the first time this method was applied in France in 1830. Since the 1950s, this method has been widely used in Europe and since the 1970s in the United States.

Literature References

Both Russian and foreign scientists were engaged in the study of crushed-stone piles [1-12]. Nguyen Thanh Tung in his work proposed a method for calculating crushed-stone piles, revealed their advantages and disadvantages, as well as possible reasons for the refusals of their work [13]. L.R. Stavnicer, V.Ya. Shishkin, A.A. Anikev investigated the soils compaction under the base of existing and newly constructed foundations in conditions of weak soils. Their research showed the results of the applying the transformation of the construction soil properties by the crushed-stone piles. Studies of the compaction effect using ground piles on the foundation soil resistance to the vibration effect [14]. Jan Privac’s work is based on the Priebe’s theory about development of the improvement factor, which is among the most used analytical methods, and describes numerical and laboratory models of...
stone columns [15]. R.R. Maurya, B.V.R. Sharma and D.N. Naresh in their work conducted a series of tests of stone columns by support load, and described the behavior of a single stone column and a group of columns under load application [16]. In the work of S.F. Kwa, E.S. Kolosova, M.Y. Fattaha, experimental studies of the behavior of a stone column enclosed in a geogrid are presented [17].

Currently there are several ways to install crushed-stone piles:

1. Vibroflotation: a) installation of crushed-stone piles with top supply of crushed stone. The well is formed with the help of a vibroflot, which is submerged under the vibration and compressed air influence (water is used if it is necessary to reduce friction on the side surface of the vibroflot). Further, crushed stone is fed into the formed well, and the vibroflot moving up with vibration forms and compacts the pile while the soil around the pile is compacted in the radial direction; b) installation of crushed stone piles with the lower supply of crushed stone. The well is formed similarly to the first method. Further, crushed stone is fed into the formed well through a pipe parallel to the vibroflot using the compressed air. The vibroflot moves upward with the simultaneous supply of crushed stone and forms the pile body due to the vibration.

2. Installation of crushed-stone piles by tamping sand and gravel mix.

**Materials and methods**

This article describes the method improving the engineering and geological conditions of the construction site by constructing crushed-stone reinforcing elements (CSRE), produced using the «IMPACT» technology, which makes it possible to build piles filled with crushed stone in water-saturated non-connected cohesive or organic soils. To reduce the settlement of the foundation soils and accelerate the consolidation process, crushed-stone piles were made with a diameter of 600 mm on a grid of 1.5 x 1.5 m (1 platform) and 1.2 x 1.2 m (2 platform) from crushed stone of a fraction of 5-20 mm according to GOST 8267 [18]. Span was selected based on the condition for determining the reduced deformation modulus (RDM):

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

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

The process of performing work on the installation of crushed-stone reinforcing elements consisted of the following stages: 1) vibration immersion of the working equipment to the design level of the well bottom (to tamp the well); 2) formation of the pile body by layer-by-layer compaction of crushed stone (to ram into the ground).

The soil compactor is immersed in the bottom of the well to the design elevation. Then, through the funnel, the cavity of the vibrating tamper was filled with crushed stone. The obturator was raised by 0.3-0.5 m; the well formed during this was filled with crushed stone through the hole in the lower end of the vibrating tamper. After that, vibratory compaction of each layer of crushed stone was carried out, and the impact frequency was about 10 Hz. The compaction time of each layer was determined depending on the engineering and geological conditions of the construction site and the physical mechanical characteristics of the soils used for the pile construction by means of test load, and was approximately 12-20 seconds. Figure 1 shows the CSRE schematic diagram.

After the installation of crushed-stone reinforcing elements, field tests of static indentation load (plate tests) and tests by static sounding were performed to determine the actual deformation moduli of crushed-stone piles and reinforced soil between the piles to compare them with the calculated values. The tests were carried out in accordance with the of GOST 20276 requirements [19].
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 pile body; e) ready crushed-stone pile.

For testing, a stamp with a flat sole with an area of 5000 cm$^2$ and 10000 cm$^2$ was chosen. Each pressure stage during the experiments was maintained until the conditional stabilization of deformation. The criterion of conditional stabilization was taken as the rate of stamp settlement not exceeding 0.1 mm for the time $t$ indicated in GOST 20276. The reduced deformation modulus according to the results of field tests was determined in accordance with the instructions of Clause 5.5 of GOST 20276.

Static sounding was performed by continuously impression the probe into the ground. Indicators of soil resistance were recorded at intervals of the probe’s immersion depth of no more than 0.2 m. The probe’s immersion rate in the soil was 1.0 m / min.

Results
At the site of the proposed construction, two sites with different engineering and geological conditions were identified. Sands of different particle size and density represent the soils that lie at the base of the first site. At the base of the second site, there are sandy soils with different granulometric composition and density and clay soils represented by loams in a different state. Due to the fact that weak soils with a low modulus of deformation lay at the base of the two sites as well as some of the soils were in the water-saturated condition it was decided to strengthen these foundation soils to increase the bearing capacity, reduce stabilized settlement, and cut back on the length of consolidation time installing crushed-stone reinforcing elements.

Table 1 shows the deformation moduli of crushed-stone reinforcing elements. Table 2 shows the deformation moduli of soil before reinforcement with crushed-stone reinforcing elements and after reinforcement, determined from the results of static sounding for two sites with different geotechnical conditions. In addition, there are reduced deformation modulus of reinforced soil, obtained from the results of field tests and in accordance with the design documentation in the table. As a result of the work on transformation the construction properties of the foundation soils of two different sites by constructing crushed-stone reinforcing elements the modulus of the foundation soils deformations increased.

Table 1. Deformation moduli of crushed-stone reinforcing elements
### Deformation moduli of crushed-stone reinforcing elements

**E**

- **pile**

According to the project documentation based on stamp test results

**Table 2.** Deformation moduli of soils determined by the results of static sensing and the reduced deformation moduli of reinforced soil

| № EGE | Soil title                                         | Deformation moduli of soil according to the results of static sensing, E [MPa] | Reduced deformation moduli of reinforced soil, **E<sub>RDM</sub>** [MPa] |
|-------|---------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
|       |                                                   | before strengthening | after strengthening | actual before strengthening | in accordance with the project documentation |
| Site 1|                                                   |                                                                     |                                                                     |                                                                 |
| 1     | Medium sand, medium density, a, fII-III            | 31          | 26.4-29.7             | 37.29                        | 37.15  |
| 1a    | Medium sand, loose, a, fII-III                    | 15          | 21.6-27.4             | 35.32                        | 23.16  |
| 1b    | Medium sand, dense, a, fII-III                    | 36          | 33.4-39.1             | 41.85                        | 41.53  |
| 4     | Fine sand, medium density, a, fII-III              | 29          | 26.9-33.0             | 38.35                        | 35.40  |
| 4a    | Fine sand, loose, fQII-III                        | 16          | 20.4                  | 33.04                        | 24.04  |
| 4b    | Fine sand, dense, a, fII-III                      | 37          | 41.0                  | 44.49                        | 42.40  |
| 14    | Fine sand, medium density, lbQIII-IV              | 24          | 26.8                  | 36.60                        | 31.03  |
| 14a   | Fine sand, loose, lbQIII-IV                       | 9           | 41.0                  | 44.49                        | 17.92  |
| Site 2| Powdery sand, dense, water-saturated, fQII-ims   | 27.0        | 41.0                  | 35.83                        | 33.48  |
| 3a-2  | Fine sand, medium density, aQIV                   | 29.0        | 23.2                  | 24.21                        | 35.08  |
| 3a-2p | Fine sand, dense, aQIV                            | 37.0        | 41.0                  | 35.83                        | 41.51  |
| 3a-2p | Fine sand, loose, aQIV                           | 10          | 17.0                  | 20.16                        | 19.81  |
| 3a-4  | Coarse sand, medium density, aQIV                 | 24.0        | 22.6                  | 23.81                        | 31.06  |
| 3a-4p | Coarse sand, dense, aQIV                          | 38.0        | 41.0                  | 35.83                        | 42.32  |
| 3a-4p | Coarse sand, loose, aQIV                          | 17.0        | 17.0                  | 20.16                        | 25.44  |
| 8a-4  | Loam, high-plastic, aQIV                           | 4.7         | 8.4                   | 14.54                        | 15.55  |
| 8a-4g | Loam, high-plastic,                               | 4.0         | 3.5                   | 11.35                        | 14.99  |
Summary
Analysis of the work of Russian and international scientists has shown the prospects for the use of crushed-stone, gravel and other soil reinforcing elements in terms of reducing technical and economic costs and environmental requirements.

Installation of crushed-stone reinforcing elements allowed to transform the physical and mechanical properties of the construction site, including soils that are between the reinforcing elements, which deformation moduli grew by an average of 40%.

Obtained results show that the deformation moduli of a crushed-stone pile, obtained from the results of stamp tests is on average 35% more than the deformation moduli obtained in accordance with the design documentation on site 1 and on average 50% less on site 2 that may require additional calculations of settlement structures in order to comply with safety requirements. Consequently, the deformation properties of crushed-stone piles strongly depend on the surrounding soil and require confirmation by direct tests.

It should be taken into account in design practice that the proposed relationship (1) does not take into account the growth of the deformation characteristics of the soil around the reinforcing element that undoubtedly goes to the reserve. The overall course of the calculation should be improved in order to more accurately predict the deformation properties of the transformed base as a whole and its elements.

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