Management of the dynamic properties of a base modified by deep soil mixing technology

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Abstract. Conversion of building properties is performed primarily to reduce the compressibility of the base and increase strength. However, in addition to changing the static properties of soils, it is necessary to take into account changes in dynamic properties, such as dynamic shear modulus, damping coefficient, velocity of elastic shear and longitudinal waves. Thus, it is possible to control the dynamic properties of the base by converting the construction properties of soils. In this paper, we consider the change in the velocity of shear waves in a base transformed by the technology of deep soil mixing (DSM). In the work, the influence of additional vertical stresses on the dynamic properties of the bases transformed using deep soil mixing technology was evaluated. As a parameter that allowed us to evaluate the dynamic properties, the propagation velocity of elastic shear waves was chosen. Shear wave velocity was estimated based on the results of triaxial tests using the method of low-amplitude torsional vibrations in a resonant column. The research results showed that at small values of axial strains, there is no significant increase in the velocity of shear waves, an increase in the speed of shear waves by two times with an increase in stress by 0.6 MPa.

1. Introduction

Site selection for erecting structures usually implicates compromising between optimal site location (the proximity of natural or manmade water reservoirs, certain distance to the nearest settlements, developed engineering and transport infrastructure, etc.) and unfavorable geotechnical conditions. Dynamic response of a foundation depends on the presence and thickness of loose unstable clay soil layers, floury and fine water-saturated sands in soils located close to the surface of water-bearing ground in seismic-prone areas [1].

When designing buildings and structures, avoidance of combined stress development in foundations and structures exceeding the admissible limit value could be seen as one of the principal issues. On the territory of the Russian Federation, technical guidance documents stating admissible limit values are enforced. They include Design and Construction Specification (DCS) 22.13330.2016 «Soil bases of buildings and structures», Guidance Documents in Construction (GDC) 50-1.2007 «Design and works on bases, foundations and substructure blocks of multi-functional high-rise buildings and multi-purpose structures», DCS 23.1330.2018 «Foundations of hydraulic structures», Rules and Norms of Nuclear Power Industry (RNNPI) 5.10-87 «Foundations of reactor’s compartment of nuclear power plants». 
In the international practice, it is meant to be used European rules and norms (CEN EN 1997-1-2004 Eurocode 7: Geotechnical design, CEN EN 1998-5: Eurocode 8: Design of structures for earthquake resistance), American regulations (IBC 2012/15 - ASCE/SEI 7-10), and many others. It is often the case that in order to reach design stress or ensure dynamic stability of soils, without relocating the structure to another construction site, it is essential to carry out actions aimed at transformation of foundation’s structural properties.

The object of the present study are soil-cement specimens taken form the foundation of the designed power-generating facility transformed by means of deep soil mixing (DSM) method. Application of DSM-method results in enhancement of physical and mechanical properties by means of mixing soils with cement and other binders in order to form soil mix [2-3]. Works execution is regulated by the European Standard EN 14679:2005 "Execution of special geotechnical works. Deep mixing".

When designing earthquake proof structures, the values of propagation velocity for elastic shear and compressional waves in soils are widely used for the computation of seismic ground settlement $S_{eq}$, horizontal displacement $U_{eq}$, and tilt $i_{eq}$ of the foundation of reactor compartments for nuclear power plants under the spectral method of calculation (in compliance with RNNPI 5.10-87). In this case, stresses depend on the ratio of seismic forces $P_i$ acting on the contacting surface of building and foundation to dynamic stiffness of foundation when relocating the structure $K_i$. For the foundations in the form of a compressed layer of fixed thickness with set parameters, dynamic stiffness $K_i$ depends on geometric adjectives of a foundation base and the propagation velocity of compressional (P-waves) $V_p$ and shear waves $V_s$ in soils. As a rule, the values of velocity for P-waves and shear waves are estimated in the course of field geotechnical studies, however, using prescribed field methods, not all the variations could be fixed. Thus, to evaluate variation of waves’ propagation velocity in soils for constructed buildings could become an extremely labor-consuming process when field methods are applied. In this scenario, it is recommended to use laboratory tests.

The goal of the present research is the study of propagation velocity for elastic waves in foundation soils treated by DSM-method on the base of implemented laboratory tests [4]. The purpose of the investigation is to establish consistent patterns of propagation velocity for elastic shear waves under anisotropic stress state by means of laboratory test in the resonant column.

2. Methods
Processing of test results comprised computation of relative shear strains $\gamma$, resonance frequency $f$, determining shear waves’ velocity for this frequency $V_s$ followed by estimating dynamic shearing modulus $G$.

Propagation velocity of elastic shear waves $V_s$ was calculated under the formula:

$$V_s = \omega h \left( \frac{J}{J_0} \right)^{-0.5},$$

(1)

where $J$ – inertia couple of the solid cylindrical sample of mass $m$ and radius $r$, $J = 0.5mr^2$; $J_0$ –inertia couple of machine straining system (indicated by the manufacturer), $h$ – sample height; $\omega = 2\pi f$ – resonance frequency.

Having determined shear waves’ velocity $V_s$ by the formula (1), dynamic shearing modulus $G$ could be estimated by the formula:

$$G = \rho V_s^2,$$

(2)

where $\rho$ – soil consistency.

The process of samples’ preparation (Figure 1), test procedure and results analysis have been done in compliance with the clause 7 of GOST R 56353-2015 «Soils. Laboratory methods for determination of soil dynamic properties» (the statements of which correlate with ASTM D4015–15e1. Standard Test Methods for Modulus and Damping of Soils by Fixed-Base Resonant Column Devices).
Laboratory tests of cement-soil dynamic properties presented in the present paper were carried out by the method of low-amplitude dynamic tests in the resonant column. By its structure, a resonant column is a chamber of triaxial compression with the possibility of lateral widening samples of cement-soil exposed to triaxial, axially symmetric loading at $\sigma_1 \geq \sigma_2 = \sigma_3$ (where $\sigma_1$ – the maximum, and $\sigma_2 = \sigma_3$ – the minimum main stresses); simultaneously, low-amplitude torsional vibrations of the set frequency range were induced in the sample in compliance with the GOST R 56353-2015 «Soils. Laboratory methods for determination of soil dynamic properties» (ASTM D4015–15e1. Standard Test Methods for Modulus and Damping of Soils by Fixed-Base Resonant Column Devices). The method dwells upon the theory of vibrational motion propagation in elastic nail, with its lower end fixed, and shear strain is equal to zero.

For laboratory tests, the cement-soil samples were used, taken from the site of the designed object of power industry. Initially, soils were presented by fine sands and sandy silt of alluvial origin. At the given site, the project provides for construction of a massive structure with the pressure below the base not less than 600 kPa; the base preparation was done by the DSM technology. Portland cement, type V, in compliance with ASTM C150/C150M-19a «Standard Specification for Portland Cement» was used as a binder (compressive strength after 28 days 21 MPa).

Samples with undisturbed structure, hermetically sealed in polypropylene pipes, were delivered to the laboratory in the shape of cylinders with diameter 83 mm and height 166 mm. Cement-soil samples sent to the laboratory had moisture level close to water saturation.

3. Results
The tests performed in the mode of low-amplitude shear oscillations made it possible to establish a correlation between the additional vertical load and the propagation velocity of elastic shear waves. The parameters obtained during the tests are presented in Table 1. The results are presented in graphical form in Figure 2.
Figure 2. Soil cement test results in a resonance column. The dependence of the velocity of propagation of elastic shear waves $V_s$ (m/s) on vertical stress $\sigma_1$ (MPa).

Table 1. Test results of soil cement samples.

| Test Number | Sample Number and Name     | Resonant frequency $f$, s$^{-1}$ | Shear wave velocity $V_s$, m/s | Shear modulus $G$, MPa | Shear strain $\gamma$, u.f. |
|-------------|----------------------------|----------------------------------|-------------------------------|------------------------|-----------------------------|
| 1           | Sample #1 Grey-good mixed-stiff | 220                             | 699.99                        | 490.4                  | 3.20·10$^{-6}$              |
| 2           |                           | 227                             | 723.90                        | 524.5                  | 3.08·10$^{-6}$              |
| 3           |                           | 229                             | 730.28                        | 533.8                  | 3.17·10$^{-6}$              |
| 4           | Grey-good mixed-stiff     | 204                             | 544.65                        | 423.6                  | 2.85·10$^{-6}$              |
| 5           |                           | 218                             | 580.69                        | 481.5                  | 3.15·10$^{-6}$              |
| 6           |                           | 220                             | 586.03                        | 490.4                  | 3.31·10$^{-6}$              |
| 7           |                           | 204                             | 513.81                        | 423.6                  | 2.44·10$^{-6}$              |
| 8           |                           | 223                             | 560.41                        | 503.9                  | 2.91·10$^{-6}$              |
| 9           |                           | 227                             | 570.48                        | 522.2                  | 2.72·10$^{-6}$              |
| 10          | Sample #2 Gray-mixed-good mixed stiff | 171                             | 556.60                        | 295.9                  | 4.33·10$^{-6}$              |
| 11          |                           | 196                             | 639.84                        | 391.0                  | 4.65·10$^{-6}$              |
| 12          |                           | 201                             | 656.16                        | 411.3                  | 4.42·10$^{-6}$              |
| 13          | Gray-mixed-good mixed stiff | 170                             | 482.37                        | 292.5                  | 3.92·10$^{-6}$              |
| 14          |                           | 194                             | 550.66                        | 381.1                  | 4.17·10$^{-6}$              |
| 15          |                           | 197                             | 559.20                        | 393.0                  | 4.67·10$^{-6}$              |
| 16          |                           | 128                             | 327.24                        | 166.8                  | 3.67·10$^{-6}$              |
| 17          |                           | 184                             | 469.13                        | 342.8                  | 3.94·10$^{-6}$              |
| 18          |                           | 190                             | 484.47                        | 365.5                  | 3.90·10$^{-6}$              |

After processing the results of 18 determinations of the propagation velocity of shear elastic waves at various values of the additional vertical stress, the obtained experimental correlation dependencies are estimated, which allows us to develop an empirical formula:
\[ V_s = A \cdot \ln(\sigma_v) + B, \]  

where \( V_s \) – velocity of shear elastic waves (m/s); \( \sigma_v \) – vertical stress (MPa); \( A \) and \( B \) – non-dimensional coefficients whose values in the present experiments are \( A=38 \) and \( B=586 \).

We also note that with an increase in the density of soil cement samples, a greater increase in the velocity of shear waves with an increase in vertical stresses is observed. So, at a density of 1.56 g/cm³, coefficient \( A \) is almost two times greater than at a density of 0.96 g/cm³.

4. Conclusions
During laboratory research, 18 tests of soil cement samples in a resonance column were performed. Samples of soil cement were taken from the base of an industrial structure, converted using deep soil mixing technology. Analyzing the tests performed, the following conclusions can be drawn.

1. Tests of soil cement samples showed that with an increase in additional vertical stress, the propagation velocity of elastic transverse waves also increases. This conclusion is consistent with the results of previous studies [5-12].

2. Note that in natural soils, with increasing stress (hydrostatic or deviatorial), due to the compressibility of solid particles of the soil and their rearrangement, the density increases, which leads to a significant increase in the velocity of transverse waves. With an increase in density, an increase in the number of contacts between soil particles occurs, which leads to a change in acoustic characteristics [13-17].

3. Soil-cement substrates, in turn, are practically not compacted due to their poor compressibility in the stress variation ranges under the designed structure (0.15–0.75 MPa). In the course of these studies, the maximum axial displacements for the entire test period did not exceed 0.1%, which indicates the practical absence of compaction of soil cement samples. At small values of axial deformations, there is no significant increase in the velocity of shear waves (according to the results of experiments No. 16, 18 — an increase of 1.5 times with an increase in stress by 0.6 MPa) [17-20].

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