The influence of stress state, density and moisture on the dynamic properties of soil cement samples created by the method of deep soil mixing

A Z Ter-Martirosyan and E S Sobolev

Moscow State University of Civil Engineering, 26 Yaroslavskoe shosse, Moscow, 129337, Russia

E-mail: e.s.sobolev@mail.ru

Abstract. The transformation of the properties of the bases by the method of deep soil mixing allows the construction of buildings and structures on sites with soft soils. As a rule, adverse geological conditions are accompanied by the presence of dynamic effects on the designed buildings. The objective of this research is to forecast changes in the mechanical properties of the base under dynamic loads. The object of study is the propagation velocity of elastic shear waves, since these parameters significantly affect the calculations of deformations and stability of earthquake-resistant industrial and civil buildings and structures, as well as objects of energy and transport construction. The paper contains a review of similar studies, on the basis of which the conclusions obtained during the experiments are further generalized. Based on the analysis of the results of laboratory tests performed by the authors of this work, by the method of low-amplitude torsion vibrations in a resonant column in the anisotropic triaxial compression mode, the influence of the density of soil cement samples, humidity, and additional load on the propagation velocity of elastic transverse waves is estimated. The paper provides a description of the essence of the research method, a review of the equipment on which special laboratory tests were performed. The tests were carried out on samples of unbroken soil cement taken from the base of a nuclear power plant (NPP) under construction. Dried samples of soil cement were investigated, and tests were carried out at full water saturation and at a given humidity. The anisotropic stress state of soil cement samples during triaxial tests in a resonance column was due to the features of the base of the designed NPP. Studies have shown that the most significant factor affecting the shear wave velocity is the additional vertical load. It is noted that with increasing density, the velocity of the shear waves decreases. Humidity is directly related to the density of soil cement and the amount of water in the pores, so the assessment of its effect on the dynamic properties of soil cement is similar to the effect of changes in density.

1. Introduction

To date, a significant number of technologies have been developed and introduced to strengthen and stabilize soft base soils in relation to a wide range of construction tasks [1-3]. The object of this study is soil cement samples taken from the base of a nuclear power plant under construction, transformed using deep soil mixing (DSM) technology [4, 5]. The method of strengthening the bases with the help of GHS leads to the improvement of physical and mechanical properties by mixing soils with cement or other cementitious materials to form a soil-cement mixture (soil-mix). The resulting material has
greater strength, lower permeability and compressibility than the original soil (Fig. 1). This technology has an advantage relative to the jet cementation method and pile foundation, using a smaller volume of cement [6-10]. The work is regulated by the European standard BS EN 14679: 2005 Execution of special geotechnical works. Deep mixing.

![Figure 1](image1.png)  
**Figure 1.** The process of deep soil mixing. 1 - direct stroke of the working body; 2 - return stroke; 3 - finished cement columns [2].

The aim of the study presented in this article is to study the propagation velocity of elastic waves in the soil of the base, converted by the DSM method based on laboratory studies. The objective of this study is to establish the laws of change in the propagation velocity of elastic transverse waves depending on the physical (density, moisture) and mechanical (value of the load) soil properties by laboratory tests in a resonance column.

2. Description of the research methodology
Laboratory determinations of the dynamic properties of soil cements presented in this work were performed by the method of low-amplitude dynamic tests in a resonance column.

![Figure 2](image2.png)  
**Figure 2.** Photograph of soil cement (sample No. 1) in a state of complete water saturation, installed on a base of equipment for installing samples in a resonance column.

Hermetically sealed in polypropylene pipes, samples of undisturbed structure were delivered to the laboratory in the form of cylinders with a base radius of 0.0415 m and a height of 0.166 m (Fig. 2).
Before testing, samples No. 1 and No. 2 were dried to constant weight $m_1$ in an oven at a temperature of 105 °C. After that, a series of tests was carried out (experiments No. 1-3, 10-12 according to Table 1), in which the moisture $W_1$ content of the cement was about 0.0 units, and the density of the cement was equal $\rho_1$ (the values are presented in Table 1).

### Table 1. Parameters of soil cement tests in a resonant column

| Test Number | Sample Number and Name | Weight $m$, g | Density $\rho$, g/cm$^3$ | Humidity $W$, u.f. | Vertical stress $\sigma_1$, MPa | Horizontal stress $\sigma_3$, MPa |
|-------------|------------------------|--------------|-------------------------|------------------|-------------------------------|-----------------------------|
| 1           |                        | 899          | 1.00                    | 0.00             | 0.15                          | 0.04                        |
| 2           |                        | 1282.6       | 1.43                    | 0.43             | 0.55                          | 0.14                        |
| 3           | Sample #1              | 1441.2       | 1.60                    | 0.60             | 0.75                          | 0.19                        |
| 4           | Grey-good mixed-stiff  | 857.9        | 0.96                    | 0.00             | 0.15                          | 0.04                        |
| 5           |                        | 1128.9       | 1.26                    | 0.43             | 0.55                          | 0.14                        |
| 6           |                        | 1398.8       | 1.56                    | 0.60             | 0.75                          | 0.19                        |
| 7           |                        |              |                         |                 |                               |                             |
| 8           |                        |              |                         |                 |                               |                             |
| 9           |                        |              |                         |                 |                               |                             |
| 10          |                        |              |                         |                 |                               |                             |
| 11          |                        |              |                         |                 |                               |                             |
| 12          |                        |              |                         |                 |                               |                             |
| 13          | Sample #2              |              |                         |                 |                               |                             |
| 14          | Gray-mixed-good mixed stiff |   |                         |                 |                               |                             |
| 15          |                        |              |                         |                 |                               |                             |
| 16          |                        |              |                         |                 |                               |                             |
| 17          |                        |              |                         |                 |                               |                             |
| 18          |                        |              |                         |                 |                               |                             |

After a series of tests on dry soil cement samples, they were fully saturated. A sample of dry cement and distilled water were placed in a hermetically sealed container. Then the container with the sample and water was evacuated. After 6 hours, the sample was removed from the tank, weighing was performed in order to establish its actual mass. Then repeated water saturation was carried out under vacuum and repeated mass measurements after another 20 and 24 hours, until the mass measurements showed identical readings. That is, until the cessation of further absorption of water into the sample. In a state of complete water saturation, a sample of soil cement had mass $m_3$, moisture $W_3$, and density $\rho_3$ (values are presented in Table 1). A series of tests was carried out on fully water-saturated samples No. 1 and No. 2 (experiments No. 7–9, 16–18 according to Table 1).

Given the known mass of a dry soil cement sample $m_1$ and the mass of a fully water-saturated sample $m_3$, it seems possible to determine the mass of the sample $m_2$ at which the degree of water saturation will correspond to 0.5. Water-saturated samples of soil cement at the previous stage of research were dried to a constant initial mass $m_1$. After drying, water saturation was carried out, according to the method described above, with a control of the mass of the sample every 0.25 hours, until the mass of the samples reached a value $m_2$. In this case, after reaching the specified mass, the sample was kept without water under vacuum to uniformly distribute the pore liquid inside the sample. Such samples had a density $\rho_2$ and humidity $W_2$ (indicated in Table 1) with a degree of water saturation close to 50%. The third series of tests was carried out (experiments No. 4–6, 13–15 according to Table 1).
The processing of the test results consisted in calculating the relative shear deformations $\gamma$ (u.f.), calculating the resonant frequency $f$ (Hz), determining the shear wave velocity $V_s$ (m/s) for this frequency, and then determining the dynamic shear modulus $G$ (MPa).

\[ V_s = A \cdot \ln(\sigma_1) + B, \]

where $V_s$ – shear wave velocity in m/s; $\sigma_1$ – the vertical pressure, kPa; $A$ and $B$ – dimensionless empirical coefficients obtained from laboratory tests of soil cement samples in a resonance column.

The research results are presented in graphical form in Fig. 3, on which trend lines are grouped according to close densities $\rho$ and vertical loads $\sigma_1$. The highest approximation confidence coefficient $R^2 = 0.6$ was obtained for trend line No. 2, here the coefficient values for expression (1) leave: $A = 37.7$ and $B = 585.6$.

There is a tendency to increase the effect of vertical pressure $\sigma_1$ on the velocity of shear waves $V_s$ with an increase in the density of soil cement samples, since the coefficient $A$ for a sample with a density of 1.56 g/cm$^3$ is 1.6 times larger than a sample with a density of 0.96 g/cm$^3$. 

Figure 3. Correlation dependences of shear wave velocity $V_s$ (m/s) on vertical stresses $\sigma_1$ (MPa) obtained from the results of studies of soil cement in a resonance column.

Based on the description of the interaction between the pile and the surrounding soil under static action, we turn to the solution of the dynamic problem.

3. Results

In the course of experimental studies, the resonance frequencies $f$ of soil cement samples, shear wave velocities $V_s$, shear modulus $G$, and the corresponding amplitude of shear deformations $\gamma$ were obtained. The objective of these laboratory studies of soil cement samples in triaxial compression mode was to establish the relationship between the vertical pressure (load) and the elastic transverse waves $V_s$. The experimental dependences characterizing the obtained correlation relationships are presented in graphical form in Fig. 3.

According to the results of 18 determinations, a logarithmic correlation dependence is presented, characterized by an equation of the following form

\[ V_s = A \cdot \ln(\sigma_1) + B, \]

where $V_s$ – shear wave velocity in m/s; $\sigma_1$ – the vertical pressure, kPa; $A$ and $B$ – dimensionless empirical coefficients obtained from laboratory tests of soil cement samples in a resonance column.

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Further, during the analysis of the experimental results, a relationship was established between the shear wave velocity $V_s$ and the density $\rho$ of soil cement samples. The dependence is written off by a decreasing logarithmic function of the form

$$V_s = -333,1 \cdot \ln(\rho) + 649,5,$$

(2)

where $\rho$ – density of soil cement, g/cm$^3$.

With an increase in the density of samples of soil cement taken from the base, converted according to the DSM, by a value from 0.96 to 1.60 g/cm$^3$, a decrease in the velocity of elastic transverse waves from 663 to 493 m/s follows.

Since the density of soil cement samples and their moisture content in the present study are directly related, then, in turn, the relationship between humidity and shear wave velocity will generally correspond to formula (2). The influence of humidity of soil cement samples on the shear wave velocity during tests in a resonant column is estimated as the following dependence

$$V_s = -39,32 \cdot \ln(W) + 488,93,$$

(3)

where $W$ – soil cement moisture, u.f.

In accordance with (3) an increase in moisture content of soil cement from an air-dry state ($W \approx 0,05$ u.f.) to full wave saturation ($W = 0,63$ u.f.) leads to a decrease in the velocity of elastic transverse waves by 20%, from 609 to 507 m/s.

4. Conclusions

Summarizing the obtained test results of 18 samples from two soil cement samples taken from the base, converted by the method of deep soil mixing, we can draw the following main conclusions in accordance with the tasks set earlier.

1. In the course of the research, the influence of additional vertical pressure (load) from the designed NPP structure on the cement-cement base on the propagation velocity of elastic transverse waves was revealed. During tests with increasing values of vertical pressure on soil cement samples, an increase in the shear wave propagation velocity was recorded.

2. With increasing density of soil cement, the propagation velocity of elastic transverse waves decreases. For further study of this issue, studies should be carried out on samples of soil cement taken from various depths and having different densities, since the correlation of shear wave velocity and density is especially important in the context of technological features of work on the transformation of building properties of soils by the DSM.

3. The influence of moisture of the studied samples of soil cement on the change in the shear wave velocity is closely related to the density. Since the mass of dry samples is constant, an increase in moisture leads to an increase in mass due to water in the pores, which leads to an inevitable increase in density. In this regard, in our opinion, it makes no sense to evaluate the effect of moisture separately from density.

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