Experimental studies of deformation anisotropy of gravel soils

A Bestuzheva1*, A Abduloev2

1Moscow State University of Civil Engineering (National Research University), Yaroslavskoe shosse, 26, Moscow, 129337, Russia
2Moscow State University of Civil Engineering (National Research University), Yaroslavskoe shosse, 26, Moscow, 129337, Russia
alex_bestu@mail.ru

Abstract. When gravel-pebble soil is laying and compacting into the dam body, particles are reoriented to form a layered body (transversely isotropic soil), in which not only the filtration but also the deformation properties are different in directions along and across the layering. To analyze the differences in the gravel-pebble soil deformations in correspondence with the particles’ orientation we have performed experimental researches on the river pebble gravel using odometer, vacuum triaxial compression machine, and a large scale triaxial apparatus. To obtain the deformation characteristics of the soil in different directions we’ve carried out experiments according to two schemes with gravel particles (fr. 10-60 mm) laid horizontally and vertically. More deformations occur in the cross-layerage axis of the soil rather than in the parallel direction ($\varepsilon_y > \varepsilon_x$), so for the soil in the dam body $E_x > E_y$. The experiments showed that for gravel-pebble soil the strain-induced anisotropy coefficient $\eta$ is dependent on its loading conditions and changes in the range from 1 to 1.8. The change of anisotropy degree is bound with the main tension value $\sigma_1$ with the increase in which the anisotropy decreases.

1. Introduction
For precise forecasting of the earth and rockfill dams yield and displacement we need to know the physical and mechanical characteristics of the rock toes, considering the induced anisotropy that occurs due to layer by layer soil compacting (transversely isotropic material). Figure 1 [1, 2]. In modern literature, there is no data from experimental researches regarding the gravel-pebble soil strain-induced anisotropy, despite the fact that the anisotropy occurring in clayey soil, where the strain-induced anisotropy is also present, is studied in detail [3, 4, 5, 6, 7, 8, 9, 10]. According to the data received from the tests in vacuum triaxial compression machine, the deformation modulus of clayey soil in different directions is dependent on the deviator stress tensor, e.g. with $\sigma_2 = 0.1 \, MPa$ and $(\sigma_1 - \sigma_3) = 0.2 \, MPa$ were calculated $E_x = 6.6 \, MPa$, $E_y = 4.5 \, MPa$, so the anisotropy coefficient is $\eta = \frac{E_x}{E_y} = 1.45$ [11]. From the experiments of W.H. Ward and S.J. Samuels on London’s clayey soil [12] we know that the correlation for the straining branch is $\frac{E_x}{E_y} = 1.2 \div 1.95$ and for the stress relief: $\frac{E_x}{E_y} = 1.3 \div 2.0$. According to the data acquired by L. Barden for the same clay of undisturbed structure [13], $\frac{E_x}{E_y} = 1.5 \div 4.0$, and experimental researches of A.K. Loh and R.T. Holt [14] on the brown-banded clay of lake origin with small gravel inclusions showed the following
moduli correlation: \( \frac{E_x}{E_y} = 1.85 \). The presence of strain-induced anisotropy in the soil is also confirmed in the works of V.M. Furs [15], A.K. Bugrov, A.I. Golubev [16], G.G. Boldyrev [17, 18], Z.G. Ter-Martirosyan [19, 20], O.A. Korobova [21, 22], etc.

Anisotropic properties of the soil are expressed in the differences of deformations that occur under the influence of its weight and lateral pressure (e.g. hydrostatic) due to the inequality of the deformation moduli for different directions. Most commonly soil deformation modulus is higher in the layerage axis than in the cross direction. Thus disregarding the anisotropic properties leads to a higher calculated horizontal offset value of the dam and conclusively to unreasonable slope flattening and overpricing of the dam construction in general.

Figure 1. Transversely isotropic material. The two-dimensional subspace of the layers is parallel to the XZ two-dimensional subspace.

2. Methods

To analyze the differences in the gravel-pebble soil deformations in correspondence with the particles’ orientation we have performed experimental researches on the river pebble gravel using odometer [23], vacuum triaxial compression machine [24], and a large scale triaxial apparatus in the geotechnical laboratory of the Moscow State University of Civil Engineering (National Research University). All experiments were run according to the standard procedures described in the National State Standard 12248-2010 [25]. The gravel-pebble soil grains from 10 to 60 mm in diameter were laid in horizontal and vertical directions with the filling of grains less than 10 mm in diameter. The grain size composition [26] of the soil is shown in figure 5. The density of the soil specimen is \( \rho_d = 2.19 \pm 2.22 \) t/m\(^3\). The specimens that were used in the compression tests have the following parameters: \( d = 255 \) mm; \( h = 255 \) mm. The parameters of specimens used in the tests on the triaxial compression machine and the large scale triaxial apparatus are \( d = 300 \) mm and \( h = 600 \) mm.

The strain-induced anisotropy coefficient \( \eta \) can be evaluated by correlation of the axis deformations or by the correlation of deformation moduli for different pebble laying schematics:

\[
\eta = \frac{\varepsilon_y}{\varepsilon_x}
\]

where: \( \varepsilon_y \) stands for the axis deformation with particle laid horizontally;
\( \varepsilon_x \) stands for the axis deformation with particle laid vertically.

3. Results and Discussion

Compression tests

To reduce the influence of friction on the walls of the odometer, the tests were run in a dual stamp oedometer. The external forces were applied in steps with 0.49 MPa intervals and conditional
stabilization of 0.01 mm/min till the maximum force of 7.343 MPa. The results of the test were recorded automatically by the software used in this experiment. The schematics of the odometer and the soil laying are shown in figures 2 and 3. The compression curve charts are shown in figures 4a and 4b. The strain-induced anisotropy coefficient is displayed in table 1.

Figure 2. Schematics and photo of the odometer

Figure 3. Schematics of the larger particles laid: a) vertically; b) horizontally; c) the final test specimen.
Figure 4. Compression curve chart $\varepsilon=f(\sigma)$

a) The first series of tests with particles laid horizontally ($d \geq 10$ mm)

b) The first series of tests with particles laid vertically ($d \geq 10$ mm)
The main advantage of the all-round compression tests is the possibility to evaluate the strain-induced anisotropy of the soil in a single test [27]. In these tests the equations \( \sigma_1 = \sigma_2 = \sigma_3 \) and \( \varepsilon_1 = \varepsilon_2 = \varepsilon_3 \) give us the parameters of the strain-induced anisotropy.

To perform such a test the Hydraulics and Hydrotechnical engineering department of National Research University MSUCE has constructed a vacuum triaxial compression machine with a test chamber that is 300 mm in diameter and 600 mm in height. To create a vacuum in the test chamber we have used a single step vacuum air pump ZVP-1-45. To note the readings for vertical deformations we have placed the dial test indicators on both sides of the machine. The horizontal deformations were determined by the deformations of three round belts by the height of the specimen. The initial squeeze

| Tension interval, MPa | Anisotropy coefficient \( \eta = \frac{\varepsilon_1^{vert}}{\varepsilon_1^{horiz}} \) |
|----------------------|----------------------------------|
| 0.49-0.979           | 1.328                            |
| 0.49-1.469           | 1.303                            |
| 0.49-1.958           | 1.294                            |
| 0.49-2.448           | 1.283                            |
| 0.49-2.937           | 1.267                            |
| 0.49-3.427           | 1.239                            |
| 0.49-3.916           | 1.239                            |
| 0.49-4.406           | 1.230                            |
| 0.49-4.895           | 1.221                            |
| 0.49-5.385           | 1.207                            |
| 0.49-5.874           | 1.211                            |
| 0.49-6.364           | 1.200                            |
| 0.49-6.853           | 1.195                            |
| 0.49-7.343           | 1.191                            |

*Tests in vacuum stabilometer*

The grain size composition of the gravel-pebble soil

![Grain size composition of the gravel-pebble soil](image)
reduction of 0.3 kg/sm² was made by removable formwork during the soil filling with further dismantlement of the formwork.

The dependencies $\varepsilon = f(\sigma)$ are shown in figure 6. The schematics of the machine are present in figure 7.

Figure 6. The dependences of relative deformations from vertical ($\varepsilon_y = f(\sigma)$) and horizontal ($\varepsilon_x = f(\sigma)$) deformations.

Figure 7. a) Vacuum triaxial compression machine schematics; b) Photo of the machine
Table 2. Calculations of deformation moduli and anisotropy coefficient according to the results of the tests in vacuum triaxial compression machine.

| Tension, kg/sm² | Relative deformations | Deformation modulus | Anisotropy coeff. \( \eta = \frac{E_x}{E_y} \) |
|----------------|-----------------------|---------------------|-----------------------------------------------|
|                | Vertical \( E_y \) (Avg) | Horizontal \( E_x \) (Avg) | Tangent \( E_y \) (Avg) | Secant \( E_x \) (Avg) | Tangent \( E_y \) (Avg) | Secant \( E_x \) (Avg) |
| 0.3            | 0.00042               | 0.00022             | -                  | -                  | -                  | -                  |
| 0.4            | 0.00079               | 0.00043             | 236.3             | 450.3             | 236.3             | 450.3             | 1.905             | 1.905             |
| 0.5            | 0.00113               | 0.00063             | 269.1             | 481.9             | 251.7             | 465.6             | 1.791             | 1.850             |
| 0.6            | 0.00145               | 0.00082             | 295.0             | 503.5             | 264.6             | 477.6             | 1.707             | 1.805             |
| 0.7            | 0.00174               | 0.00101             | 321.0             | 517.9             | 276.8             | 487.0             | 1.613             | 1.760             |
| 0.8            | 0.00203               | 0.00120             | 339.8             | 529.8             | 287.4             | 495.0             | 1.559             | 1.722             |
| 0.9            | 0.00237               | 0.00140             | 345.8             | 533.8             | 295.8             | 501.1             | 1.544             | 1.694             |

Tests in the large scale triaxial apparatus

The experiments in the large scale triaxial apparatus for macrofragmental soil were run in the geotechnical laboratory of the Moscow State University of Civil Engineering (National Research University). The edge milling in the apparatus was set as \( \sigma_3 = 0.2 \) MPa, \( \sigma_3 = 0.4 \) MPa and \( \sigma_3 = 0.6 \) MPa (Figure 8).

Contrastingly to the tests in vacuum triaxial compression machine, these tests performed in the conditions of all-round non-uniform compression \( \sigma_1 \neq \sigma_3 \). Therefore, we need to perform several tests with different particles’ laying run by the same protocol. All test data is recorded automatically by the apparatus with the same intervals approx 22 times a minute. The results of the tests with different particle laying with their comparison are shown on figures 9a and 9b.

Figure 8. Photos of the apparatus and the specimen before and after the test.
Figure 9. a) Dependences of $\varepsilon_y$ and $\varepsilon_y$ from the deviator stress tensor; b) Dependences of $\varepsilon_y$ and $\varepsilon_y$ from the deviator stress tensor

Since the tests in the large scale triaxial apparatus, odometer, and in the vacuum triaxial compression machine there performed on the soil with the same peculiar features, the results of these tests can be combined.

Figure 10. The dependence of the strain-induced anisotropy coefficient from tension.
The graphs show that in all tests the anisotropy coefficient \( \eta \) has changed in the interval between 1 and 1.8 with the soil axial compression modulus for the vertical laying of grains higher than the modulus for the horizontal laying of grains.

However, the so-called “direct” anisotropy is only common to the compaction stage. As shown on graph “*” after reaching the maximum density we can observe the “reverse” anisotropy when the correlation \( \eta = \frac{\varepsilon_{\text{vert}}}{\varepsilon_{\text{horiz}}} \) is less than 1. The change of anisotropy degree is bound with the main tension value \( \sigma_1 \) with the increase in which the anisotropy decreases.

4. Conclusions
1. Induced anisotropy occurs in the body of the earth-rockfill dam during the pebble soil laying and compacting (transversely isotropic soil), and it is necessary to take into consideration the difference between the deformation characteristics in two directions: \( E_x \) and \( E_y \).
2. Pebble soil suffers more deformations in the cross-layerage axis than in the parallel direction (\( \varepsilon_y > \varepsilon_x \)), so for the soil in the dam body \( E_x > E_y \).
3. The performed experiments showed the dependences of the strain-induced anisotropy coefficient from different loading conditions, reaching maximum (approx. 2) with lesser tension and decreasing with the increase of the applied tensions.

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