Study of coarse-grained soils design characteristics

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Abstract. The article presents the results of deformation characteristic studies for soils containing various amounts of rock clastic material during its use as a working layer of the subgrade and the foundations of pavements. The studies were performed on coarse soil models using the geotechnical software package Plaxis, which avoided the cumbersome and laborious laboratory tests of soil mixtures. Also, to compare the obtained results of numerical modeling, an analytical analysis of coarse soil deformation conditions was performed. They presented the graphical representation of the relative strain and the deformation modulus of soils belonging to large-clastic varieties, as well as the pattern of their change depending on the percentage of fragments larger than 2 mm. Thus, it was first established that the dependence of the relative vertical deformations of soils on the quantitative content of the coarse fractions in them is strictly linear. However, as for its deformation modulus, the same dependence is no longer linear, but parabolic. The obtained patterns are confirmed by analytical calculations and processing of previously performed studies on physical models. They proposed the methods to refine the calculated characteristics of coarse soil with a varying amount of rock fragments for pavement calculation.

1. Introduction
Coarse-grained soils are widely used both in the construction of hydroelectric station dams, and in the erection of subgrade and foundation of various types of engineering as well as transport structures. These soils have the advantages of good deformation and strength characteristics as compared with cohesive soils.

Depending on the percentage of large debris, the soil massif may be characterized by the deformation-strength index of one or another type of constituent component (fine aggregate or skeletal fraction). The influence of a large debris on the deformation characteristics of soils begins to take place when its soil content is more than 10 % by mass. With large fragment content increase up to 60–70 %, the value of vertical deformation of the soil decreases, and a further increase of skeletal fractions does not significantly affect the change in the deformation characteristics of coarse soil [1].

As they already noted, the main influence on the deformation modulus of heterogeneous soils is the percentage of large fragments. The content of large fragments of about 30 % increases the deformation modulus by 13 % [2]. This is due to the massif rigidity increase, mainly by large fragments.

The classification of soils has no specific quantitative and qualitative characteristics of fine aggregate that regulate the classification of coarse material to one or another group of soil. However, the calculated characteristics of these types of soils are not found in regulatory documents on the design of pavement [3].
2. Research methods
The main methods which determine the deformation characteristics of coarse soil are laboratory test methods and an analytical method. In this work, it was planned to conduct experiments in the PLAXIS finite element software package and determine the deformation characteristics of coarse soil by the analytical method.

2.1. Numerical simulation via PLAXIS program
The geometric model in PLAXIS 2D consists of points, lines and clusters, by which soil massifs should be separated by types and separate layers, objects by structures and stages of construction, as well as by load effects.

Suppose that coarse soil has a continuous particle size distribution and is located in a discrete medium. For convenience, we divide all fractions into two groups: the particles up to 2 mm and more than 2 mm – up to 200 mm. Considering that all fractions smaller than 2 mm have a negligible effect on the stress-strain state of inclusion volume, we model them as a continuous medium. After entering the general settings, we create a geometric model with a block size of 1.0 × 1.0 m. Inside the model, we select large fragments in the form of polyhedral particles. We reproduce the filling of large fragments taking into account the percentage (from 10 to 80 % by volume).

The boundary conditions were set as follows: full fixation (embedment) at the base of the model, and sliding embedment on vertical faces (U_x = 0; U_y = free). A uniformly distributed load of 0.5 MPa acts on the block. The calculated parameters of the elements are shown in table 1.

Table 1. Main characteristics of materials

| Item № | Indicator name          | Designation | Un. of meas. | Amount skelet. | Stone-free |
|--------|-------------------------|-------------|--------------|----------------|------------|
| 1      | Soil model              | Model       | –            | LE             | MC         |
| 2      | Soil behavior type      | Type        | –            | Drained        | Drained    |
| 3      | Soil specific gravity   | ρ<sub>unsat</sub> | kN/m³ | 20.5           | 16.5       |
| 4      | Saturated soil specific gravity | ρ<sub>sat</sub> | kN/m³ | 21.0           | 18.5       |
| 5      | Elasticity modulus      | E<sub>ref</sub> | kN/m² | 350000         | 25000      |
| 6      | Poisson’s ratio         | ν            | –            | 0.27           | 0.35       |
| 7      | Clutch                  | C<sub>ref</sub> | kN/m² | -              | 10.0       |
| 8      | Internal soil angle     | φ            | °            | -              | 21         |

Based on the simulation results, a sediment block of 1.0 × 1.0 m was determined under the influence of a static load with different contents of fine earth aggregate (sandy loam, loam, clay) and rock fragments of one size or another (Figure 1).

Figure 1. Coarse soil model: a) soil model with 50 % rock fragments under a uniformly distributed load of 0.5 MPa; b) finite element mesh; c) isofields of vertical displacements.
It was determined that the dependence of soil sediment block under the influence of a static load on the percentage of large fragments is linear, and the dependence of the elastic modulus on this factor is non-linear (Figure 2).

![Figure 2. Dependence of the relative strain and the deformation modulus of the soil block on the content of large rock fragments](image)

The increase of rock fragment amount at the same aggregate moisture (sandy loam, loam and clay) leads to the increase of soil elasticity modulus. When the content of large particles is more than 30% by volume, the formation of contacts between particles occurs mainly due to "skeletal" particles. If the content of small particles constituting the aggregate of the soil mixture exceeds 30% by volume, then the gradual development of contact stresses between adjacent small particles begins, as well as contact stresses between smaller and “skeletal” fractions [4]. In this case, the magnitude of the deformation modulus decreases and tends to the characteristic of the aggregate itself.

2.2. Analytical method for coarse soil deformation characteristic study

Similar results were obtained during the theoretical study of coarse soil block deformation (Figure 3), conditionally consisting of two layers. The upper layer with the thickness equal to the relative total volume of the coarse fraction (skeleton) in soil, and the other, with the thickness equal to the relative total volume of the fine earth aggregate [5].

![Figure 3. The design scheme of coarse soil reduced to a two-layer structure.](image)
The module of the total soil deformation is calculated by the following formula:

\[ E_0 = \frac{P}{\Delta h} h. \]  

(1)

The total deformation of two-layer structure \( \Delta h \) is equal to the sum of the deformations of the upper and lower layers:

\[ \Delta h = \Delta h_1 + \Delta h_2. \]  

(2)

The total deformation of the considered two-layer structure depends on the elastic modulus and thickness of each layer (skeleton and aggregate). This allows the equation (2) to be represented as follows:

\[ \Delta h = \frac{P}{E_1} h_1 + \frac{P}{E_2} h_2 = p \left( \frac{h_1}{E_1} + \frac{h_2}{E_2} \right) = p \left( \frac{h_1 E_2 + h_2 E_1}{E_1 E_2} \right). \]  

(3)

To find the thickness value of each layer, we take \( h = \frac{1}{n} h \), then \( h_2 = (1 - n) h \), where \( n = 0,1; 0,2; \ldots 1,0 \). Based on this, the deformation of the structure will be the following:

\[ \Delta h = p \left[ \frac{n E_2 + (1-n) E_1}{E_1 E_2} \right] h = p \left[ \frac{n}{E_1} + \frac{(1-n)}{E_2} \right] h. \]  

(4)

The formula for the deformation modulus calculation of two-layer structure material taking into account the calculated total deformation (formula 4) can be represented as follows:

\[ E_0 = \frac{E_1 E_2}{E_1 (1-n) + E_2 n}. \]  

(5)

Thus, the result of mathematical modeling and theoretical analysis indicates the presence of a linear dependence of the relative subsidence of the soil mass on the number of rock fragments and a nonlinear dependence of the deformation (elasticity) modulus on the ratio of coarse soil and fine earth aggregate, which is in good agreement with similar field measurements [1].

3. The purpose of elasticity modulus of coarse-grained soil

The results were used as the basis for required soil design characteristics calculation for the working layer of the subgrade. To obtain the estimated characteristics of coarse soil, it was necessary to have data both on the calculated characteristics of fine soil, and the values of coarse soil deformation and strength indicators containing more than 70 % of rock material. The standard values of the elastic modulus of gravel mixtures C5 with the largest particle size of 40 mm were adopted as the calculated values of the deformation characteristics of rocky soils.

Figure 4 shows one of the graphs for calculated elastic moduli determination for some types of soils.
Based on the obtained correlation equations, the elastic moduli were calculated for the soil containing a given amount of rock material, which allowed us to propose the calculated soil characteristics shown in Table 2.

**Table 2.** Recommended calculated values of elasticity modulus of soils with the content of rock material (with the degree of solubility in water $q_{sr} \leq 0.01$).

| Road climatic zone | The scheme of the working layer moistening | Number of large debris in soil, % | light sandy loam, dusty sand | light, heavy and heavy silty clay loam | clay | sandy loam, heavy silty sandy loam, light silty clay loam |
|--------------------|--------------------------------------------|---------------------------------|-----------------------------|--------------------------------------|------|---------------------------------------------------------|
| IV                 | 1                                          | < 15                            | 0.53 / 64                   | 0.55 / 90                            | 0.57 / 83 | 0.57 / 83 | 0.60 / 72 |
|                    |                                             | 15 – 30                         | 0.53 / 70                   | 0.55 / 95                            | 0.57 / 88 | 0.57 / 88 | 0.60 / 77 |
|                    |                                             | 30 – 50                         | 0.53 / 103                  | 0.55 / 123                           | 0.57 / 118 | 0.57 / 118 | 0.60 / 109 |
|                    |                                             | 50 – 70                         | 0.53 / 173                  | 0.55 / 181                           | 0.57 / 178 | 0.57 / 178 | 0.60 / 175 |
|                    |                                             | > 70                            | 220                         | 220                                  | 220     | 220     | 220     |
|                    |                                             | < 15                            | 0.52 / 66                   | 0.53 / 92                            | 0.54 / 94 | 0.54 / 94 | 0.57 / 83 |
|                    |                                             | 15 – 30                         | 0.52 / 72                   | 0.53 / 98                            | 0.54 / 99 | 0.54 / 99 | 0.57 / 88 |
| V                  | 1                                          | 30 – 50                         | 0.52 / 105                  | 0.53 / 124                           | 0.54 / 125 | 0.54 / 125 | 0.57 / 118 |
|                    |                                             | 50 – 70                         | 0.52 / 173                  | 0.53 / 181                           | 0.54 / 182 | 0.54 / 182 | 0.57 / 178 |
|                    |                                             | > 70                            | 220                         | 220                                  | 220     | 220     | 220     |

4. Summary
1. Mathematical modeling was performed using the PLAXIS software package and the theoretical analysis of coarse soil deformability depending on the percentage of skeletal material.
2. They determined the regularity of the change concerning the magnitude of the vertical deformation of coarse soil depending on the percentage of large debris in soil.
3. They determined the regularity of elastic modulus of coarse soil change depending on the percentage of large fragments. With their insignificant content (up to 30%), the load is mainly perceived by the aggregate, since large fragments do not contact each other, but rather “float”. With a debris content of more than 30%, a gradual increase of coarse soil elastic modulus begins.
4. They determined the estimated values of the deformation and shear characteristics of some varieties of coarse soil for the design of pavement.

References
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