Comparative Analysis of Different Methods for Determining the Strength of Coarse-grained Fractions of Composite Soils

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Abstract. The analysis and comparison of various methods for evaluating the strength of coarse clastic fractions of composite soils, one of the main physical characteristics involved in the evaluation of the mechanical parameters of coarse clastic soils with a silty-clay aggregate and silty-clay soils with coarse clastic inclusions, had been made. New methods for assessing the strength of fragments corresponding to the nature of the loading impact on the bases, made of composite (coarse-clastic) soils, are proposed.

1. Introduction
Natural and artificial bases of buildings and structures are often made of heterogeneous soil that is, according to GOST (State Standard) 25100-2011 (Soils. Classification), a mixture of two varieties of dispersed soils: coarse clastic and silty-clayey. As the researches conducted under the guidance of Professor S.V. Ukhov [1] at the MISI showed, qualitative behavior of heterogeneous soil grounds under load corresponds to the mechanics of composite materials. In this regard, the new name of coarse clastic soils with a silty-clay aggregate - composite soils - does not contradict the properties of these soils.

Composite soils are complex multicomponent systems. Studies by DalNIIS [2, 3, 4] have shown that the formal classification of soils as coarse clastic ones (the granulometric composition has more than 50 percent of particles larger than 2 mm) in accordance with GOST 25100-2011 is not at the same time the boundary of the qualitative change in their mechanical properties. Based on the common factors of variability of mechanical properties, composite soils with 20 percent of debris and those with 90 percent of debris should be considered as soils of the same type. On the other hand, separate rock fragments (unconsolidated particles larger than 2 mm) and a silty-clay aggregate (particles less than 2 mm) are fundamentally different both in size of fractions and in mechanical properties.

From this prospective, composite soils can be considered as mixtures of such sharply different in physical and mechanical properties components as rock fragments and clay aggregates with plastic properties.

This division has a physical meaning. Macrofragmental dispersive soils (with particles larger than 2 mm) have considerable porosity with the advantage of large pores, which makes them more water-permeable. These soils have considerable internal friction, they weakly compact under statistical loads and, on the contrary, are strongly compacted under dynamic impact. Coarse clastic dispersive soils can resist load in both dry and wet conditions. Depending on the petrographic composition of the initial rock, the degree of its weathering and genesis, rock fragments contained in composite soils may have different strength and roundness.

The most characteristic feature of silty-clayey soils is their sharp change in strength when interacting with water: in a dry state, the cohesive soils have high strength, with increasing moisture, it...
decreases, and at high water content, the soil can completely lose its strength and turn into a fluid state. The porosity of cohesive soils, as a rule, is high, but the permeability is insignificant, because micropores predominate among the pores.

The strength properties of composite soils, combining these two components dissimilar in properties, vary over a wide range and, according to the studies [2, 4-7, 16, 17] depend on many factors. Such factors include the genesis of soils, their mineral composition, granulometric (grain) soil composition, natural moisture and the plasticity limits of a silty-clay aggregate, the mechanical strength and degree of roundness of large fragments, and the density of soil formation.

The decisive factor affecting the mechanical properties of composite soils is the relation between the mass of the silty-clay component and the mass of the debris [2, 4-11].

Almost all researchers agree that the next most significant factor, along with the variety and moisture content of the aggregate, is the mechanical strength of the clastic material, i.e. its ability to resist external destructive influences.

At present, the strength of rocks is estimated in accordance with GOST 21153.2-84 (Rock Types. Methods for Determining the Uniaxial Compressive Strength) and GOST 8269.0-97 ( Crushed Stone and Gravel from Dense Rocks and Industrial Waste for Construction Works. Methods of Physical and Mechanical Testing). Samples of rocks are tested in a cylinder with a diameter and height of 40-50 mm or in a cube with an edge of 40-50 mm. Size of coarse clastic fractions of composite soils often do not permit to make such samples.

The strength of crushed stone for construction works is estimated in accordance with GOST 8269.0 97. Testing of crushed stone for abrasion is carried out in an abrasion testing machine with removable shelves (shelf drum) with metal balls, which have an additional destructive effect on crushed stone. Large clastic inclusions in composite soils are not affected by this factor.

GOST 25100-2011 and SP (Set of Rules) 22.13330.2011 (Bases of Buildings and Structures) suggest evaluating the strength of coarse clastic and residual soils by the coefficients of weathering $K_{wrt}$ and abrasion $K_{fr}$ based on the results of their tests in the abrasion testing machine, though they do not give test guidelines.

GOST 5180-2015 (Soils. Methods for Determining Physical Characteristics) also does not have guidelines for evaluating the strength of coarse clastic fractions of soil.

Taking into account all the above, the objective of the present research was to develop a guideline for assessing the strength of coarse clastic fractions of composite soils, which reflects the nature of the external load impact on the foundation of structures.

2. Guideline for assessing mechanical strength of rock fragments

Authors of previous studies proposed various methods for assessing the mechanical strength of fragmental material: coefficient of weathering describing the state of a rock by weathering as a whole, - Yu.V. Syrokomsy [11], coefficient of weathering against the rock density – V.F. Bezrukov [12], degree of weathering depending on uniaxial compressive resistance in water-saturated state - A. Khamrol [13] and others.

These developments formed the basis for the methodology of estimating coefficients of weathering $K_{wrt}$ and abrasion $K_{fr}$ of coarse clastic soils in accordance with GOST 25100-2011 and the degree of weathering and the relative strength of residual soils according to SP 22.13330.2011. According to GOST 25100-2011, coefficient of weathering of coarse clastic soil $K_{wrt}$ is determined by formula (A.3):

$$K_{wrt} = \frac{(K_1 - K_0)}{K_1}$$  \hspace{1cm} (1)

where $K_1$ is the ratio of the mass of particles smaller than 2 mm to the mass of particles greater than 2 mm after testing the soil for abrasion in a shelf drum;

$K_0$ is the ratio of the mass of particles smaller than 2 mm to the mass of particles larger than 2 mm of the soil in native state.

This formula determines the weathering coefficient for the composite soil $K_{wrt}$ for the soil as a whole, but not separately for clastic fractions.
SP 22.13330 requires setting for residual coarse clastic soils the degree of their weathering characterized by coefficient of weathering $K_{wrt}$, and the relative strength of fragments characterized by coefficient of abrasion $K_f$.

Coefficient of weathering $K_{wrt}$ is determined by formula (6.20), which is similar to formula (A.3) GOST 25100-2011.

Coefficient of abrasion of large fragments (particles larger than 2 mm) of residual coarse clastic soils is determined by abrasion tests of these particles in a rotating shelf drum and calculated by formula:

\[ K_f = \frac{m_1}{m_0} \]  

where $m_1$ is the mass of particles smaller than 2 mm after the abrasion test; $m_0$ is the initial mass of a sample of large fragments.

Formula (6.20) of SP 22.13330 suggests that only coarse clastic fractions of soil are subjected to the abrasion test.

Long-year studies of construction properties of composite soils had been conducted in DalNIIS under the supervision of Doctor of Technical Sciences, Professor V.I. Fedorov. The goal was to determine the main regularities and to create a methodology for assessing the strength and compressibility of these soils by their physical characteristics.

Particular attention was paid to the evaluation of the mechanical strength of coarse-fragment fractions of the soil. Guidelines for abrasion tests in a shelf drum and shearing tests in a standard box shear apparatus have been developed.

**Abrasion tests in a shelf drum** allowed us to determine coefficient of abrasion $k_e$ of fragments. In our experiments, we used a shelf drum without the use of steel balls developed at the DalNIIS.

Coefficient of abrasion of fragments $k_e$ by the DalNIIS method was determined by formula:

\[ k_e = \frac{(m_0 - m_e)}{m_0} \]  

where $m_0$ is the initial mass of a sample of coarse clastic fractions of the soil (before an abrasion test in the shelf drum); $m_e$ is mass of sieve residue of 2 mm in size after testing the sample in the shelf drum to the point of failure.

The principal difference in the determination of coefficient of abrasion of fragments $k_e$ from coefficient of weathering $K_{wrt}$ is that not all of the soil, but only its coarse clastic fractions, i.e. particles larger than 2 mm, are subjected to an abrasion test. In addition, the yield of fine soil in a 2-minute treatment cycle in the drum, equal to 0.5 percent of the initial mass of the test sample of large clastic fractions, is taken as an abrasion failure.

Comparative parallel tests of soil samples with the determination of the values of $k_e$ and $k_{e,10}$ were carried out. Abrasion coefficient of $k_{e,10}$ was determined by a shortened cycle: the soil sample was processed in the drum once for 10 minutes. The tests showed a good correlation between $k_e$ and $k_{e,10}$.

The DalNIIS development for determination of coefficient of abrasion of fragments $k_e$ in the shelf drum (1977-1989) was used as the basis for determining coefficient of abrasion of coarse clastic soils $K_f$ in GOST 25100-2011 and SP 22.13330.2011.

It should be noted that the method of abrasion of debris in the shelf drum does not reflect the operation of coarse clay soil under load (vertical or horizontal). In addition, testing clastic material of low density (0.8-1.0 g / cm$^3$) by this method gives results that do not correspond to the actual strength of the fragments. For example, testing of debris from the Pavlovskiy coal mine in Primorye (density of fragments 0.87 g/cm$^3$) in the shelf drum showed high strength of the material, while the fragments were easily broken by hands (low strength). This discrepancy arises from the fact that abrasion occurs in the drum under the influence of the own weight of debris. At a low density, the fragments only slightly collide and there is no destruction of the material there.

The method of estimating the mechanical strength of broken pieces of irregular shape by shear testing in a small standard shear device is the closest in terms of the nature of the external load impact on soil.

The test method is as follows. Samples of coarse clastic fractions of soil are selected by sieving through sieves of 10 mm and 2 mm, and a mixture of fragmental material is made. The rings of a small
standard shear device are loaded with debris with compaction up to \( r = 1.65 - 1.70 \text{ g/cm}^3 \). Then the shearing at normal pressures of 0.1, 0.2 and 0.3 MPa are carried out according to GOST 12248-2010 (Soils. Methods of Laboratory Determination of Strength and Deformability Characteristics) and the normative values of the specific adhesion \( \sigma_{sd} \) and the angle of internal friction \( j \) are determined.

In 2013-2017, the studies were updated based on the analysis of modern works [14, 15, 18-22] and supplemented with new developments of DalNIIS. A method for evaluating the mechanical strength of debris by *squeezing in a cylinder* was developed.

The strength of coarse clastic fractions of the soil was estimated by the pressure \( \sigma_{sd} \) on the sample placed under the press in a steel thick-walled cylinder. Fragment fractions of 20-40 mm in size were put into a cylinder with a diameter of 150 mm up to the mark of 20 mm from the upper edge of the cylinder. At the same time, the filling of fractions of crushed stone into the cylinder was carried out in two steps \( s \) of 0.5 volume of the prepared for testing crushed stone with leveling by tapping on the wall of the cylinder. Then the punch was put into the cylinder so that the edges of the cylinder coincided with the mark of 20 mm from the bottom of the punch.

The soil sample was squeezed at 0.5 mm/s speed of punch. The effort of \( P_{sd} \), kN corresponding to plunging of the punch to the second mark at 20 mm from the first mark was fixed.

When the soil sample was squeezed on the press, the pressure on the sample \( \sigma_{sd} \), MPa was determined by formula:

\[
\sigma_{sd} = 10 \frac{P_{sd}}{F}, \tag{4}
\]

where \( P_{sd} \) is the compression force corresponding to plunging the punch by 20 mm, kN and \( F \) is the cross-sectional area of the cylinder (177 cm²).

Six samples have been tested and tied to the standard - the ultimate strength of the rock under uniaxial compression in accordance with GOST 8269.0-97 and GOST 21153.2-84. Under a root-mean-square deviation of 4.97 MPa, the compression strength of the original rock is determined by the formula:

\[
R_c = 18.19 \sigma_{sd} - 22.06 \text{ MPa} \tag{5}
\]

The results of the tests carried out by three methods developed in DalNIIS including test for abrasion in a shelf drum, test for shearing in a standard shear device and test compression in a cylinder on a press are presented in the table 1.

| Varieties of clastic soils in strength | Ultimate strength for uniaxial compression, \( R_c \), MPa | Coefficient of abrasion \( k_u \), u.f. | Values of \( C \) and \( j \) when clastic material is subjected to shear | Pressure at compression \( \sigma_{sd} \), MPa |
|---------------------------------------|---------------------------------|-----------------|-----------------|-----------------|
| High strength                         | \( R_c > 120 \)                  | \( k_u < 0,05 \) | \( k_{s10} < 0,02 \) | \( 0 \leq C \leq 5 \) | \( j > 50 \) | \( \sigma_{sd} > 8,0 \) |
| Strong                                | \( 50 < R_c \leq 120 \)         | \( 0,05 \leq k_u \leq 0,10 \) | \( 0,02 \leq k_{s10} < 5 < C \leq 30 \) | \( 50 < j \leq 45 \) | \( 4,0 \leq \sigma_{sd} \leq 8,0 \) |
| Moderate strength                     | \( 15 < R_c \leq 50 \)          | \( 0,10 \leq k_u \leq 0,20 \) | \( 0,04 \leq k_{s10} < 30 < C \leq 40 \) | \( 45 < j \leq 35 \) | \( 2,5 \leq \sigma_{sd} \leq 4,0 \) |
| Soft                                  | \( 5 \leq R_c \leq 15 \)        | \( 0,20 \leq k_u \leq 0,40 \) | \( 0,12 \leq k_{s10} < 40 < C \leq 45 \) | \( 35 < j \leq 30 \) | \( 2,5 \leq \sigma_{sd} \leq 1,0 \) |
| Low strength                          | \( 3 \leq R_c < 5 \)            | \( k_u > 0,40 \) | \( k_{s10} > 0,28 \) | \( C > 45 \) | \( j < 30 \) |

**Conclusion**

Analysis of methods for assessing the strength of debris in residual and coarse clastic soils regulated by GOST 25100.2011 and SP 22.13330.2011 showed the shortcomings of the method of
testing debris and soil in the shelf drum. In particular, the abrasion method in the shelf drum does not reflect the work of the soil under load and does not always reflect the true mechanical strength of debris (low density fragments).

Two new methods have been developed at DalNIIS - the shearing method in the shear device and the method of compression in the cylinder by the press, which directly reflect the mechanical strength of the debris in the composite soil.

When it is possible to cut out samples of the required shape and size from rock fragments of the coarse clastic soil, the mechanical strength of such fragments forming the composite soils can be estimated by the direct characteristic of the strength of the original rock, which is regulated by GOST 8269.0-97 and GOST 21153.2-84, namely, ultimate uniaxial compression strength of rock $R_c$.

Methods for assessing the strength of rock fragments in composite soils, developed in DalNIIS, determine the strength of debris by such indicators as:

- coefficients of abrasion $k_e$ and $k_{e10}$;
- specific cohesion $C$ and angle of internal friction $\phi$;
- pressure when compressing crushed stone in the cylinder $\sigma_{cb}$.

These characteristics are linked to the standard - the strength characteristic of the original rock $R_c$.

When considering mechanical properties of large fragments of soils in terms of their resistance to applied mechanical forces, the first two characteristics describe the resistance of the fragments to weathering or abrasion. They do not have a direct connection with the strength of clastic inclusions, while the latter two characteristics reflect the resistance of the fragments to compressive loads and shear.

When considering the mechanical strength of debris in terms of the complexity of testing, then we can say the following.

Tests for estimating coefficient of abrasion $k_e$ are laborious since the weighing and dispersion of a sample should be repeated 6 to 15 times. Less time-consuming is the test for estimating coefficient of abrasion $k_{e10}$, which can be determined by single dispersion and weighing.

Specific adhesion $C$ and the angle of internal friction $\phi$ can be estimated by the results of nine shears. Thus, this method is also rather laborious.

Squeezing the debris in a cylinder on a hydraulic press requires the use of large-sized equipment. The positive aspect of this method is that the dispersion and weighting of fractions are excluded from the experiment, though the fractionation of the debris is added.

The carried out parallel mechanical strength tests of rock fragments by different methods gave comparable results allowing to assess the strength of debris. Researchers can select the most accessible and convenient test method.

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