Patterns of Composite Soils Behavior under Shear and Compression

O V Dobud’ko¹, L I Aminova¹

¹ Branch FGBU ”TSNIIP Russian Ministry of Construction” DalNIIS, Vladivostok, Russia

E-mail: t.rusanova@dalniis.ru

Abstract. Clastic-silty-clayed (composite) soils of natural and artificial composition are the most widespread on construction sites in the Russian Far East, which makes the study of their strength and deformation properties relevant. Based on the results of laboratory and field studies, the relationship between the macrostructure and physical parameters of composite soil constituents and their mechanical properties was analyzed, and substantiation of patterns of composite soils behavior under shear and compression was made.

1. Introduction

Natural and artificial foundations of buildings and structures are often mixtures of rock fragments of various petrographic composition, degree of weathering and roundedness, and fine sand and clayed aggregate (hereinafter referred to as composite soils).

SP (Standard Specification) 22.13330.2016 [1] specifies the two limit state design of foundations: bearing capacity and deformations. The main parameters to determine the bearing capacity of the foundation and its deformations are \( \phi \), \( C \) and \( E \). Reliability of engineering and construction is determined by the correctness and reliability of the assessment of these parameters.

The leading institutes including NIIOSP, SoyuzDorNII, KhADI, VNIIG, VNIIVODGEO studied the strength and compressibility of composite soils for hydrotechnical engineering and road construction. They also designed the most suitable non-suffosion soil mixtures to ensure high strength and deformation characteristics of compacted soils. Researchers V.B. Shvets, E.M. Dobrov, O.N. Zhidkov, N.V. Kolomensky, G. B. Kulchitsky et al. studied the possibility of using composite soils for foundations in industrial and civil construction. They made a great contribution to the study of the strength and compressibility of these soils. The publication by L.A. Strokova [2] is of interest, since it presents the results of the study of the relationship between the physical and mechanical characteristics of clayed soils of Neogene-Quaternary sediments in the south of the Tomsk Region.

Integrated studies of physical and mechanical properties of composite soils, which were the most widespread on construction sites in the Russian Far East, were launched by Professor V.I. Fedorov [3] at DalNIIS. As a result, the composite soils were rated depending on their genesis; the main factors affecting \( \tau \), \( \phi \), \( C \) and \( E \) have been identified; main regularities of the relationship between the strength and deformation characteristics of composite soils and physical properties of their components, in particular, the strength (weathering) and roundness of debris, were determined; patterns of composite soils behavior under shear and compression were outlined.
Composite soils are natural mixtures of sharply different in physical and mechanical qualities components, such as rock fragments (uncemented particles of 2 mm and more) and silty-clayed aggregate (particles of 2 mm and less) with plastic properties. The mechanical properties of composite soils consisting of two dissimilar in properties components vary over a wide range and depend on the genesis of the soil, its grain composition (the ratio of silty-clayed aggregate \( P_L \) and plastic inclusions \( P_C \)), mechanical strength (abrasion coefficient \( k_s \) and shape (roundness \( O_k \)) of debris, variety (index of liquidity \( I_L \) and plasticity number \( I_p \)) and moisture content of the silty-clayed component \( W \), its mineral composition, and soil compaction density \( \rho_r \).

2. Patterns of composite soils behavior under shear

Many researchers [3-8] studied the relationship between the composition and condition of composite soils and their strength properties. Studies have shown that with the increase in the number of fragments, the total shear resistance \( \tau \) and \( \varphi \) also increases, while \( C \) decreases. An increase in quantity and moisture of clayed aggregate causes the decrease the strength of composite soils. The works [4-6] stated no sharp increase of \( \tau \) under the formation of a rigid macrofragmental skeleton. It was also found that crushed stone inclusions gave higher \( \varphi \) of composite soils than the pebble inclusions did. No significant difference in \( C \) with unrounded and rounded fragments was recorded in previous studies, except the experiments with “pure” debris. According to the studies, the total shear resistance \( \tau \) had practically no relationship with the moisture content of the clayed aggregate, when fragments in the soil exceeded 50%. It was found that in composite soils with soft- and very soft clayed component and with the debris content less than 20%-30% the degree of their influence practically dropped to zero. The shear parameters of composite soils significantly depended on the strength of the clastic material, which could be explained by the degree of weathering, the surface roughness of fragments and their shape. Thus, soils with stronger fragments had higher values of \( C \) and \( \varphi \). On the contrary, the decrease in debris strength caused a slight decrease in \( C \) and \( \varphi \). This, apparently, was a consequence of the varying degrees of cohesion of large fragments with each other, while stronger fragments had higher cohesion index, as a result of which the values of the total shear resistance \( \tau \) increased.

As a result of studies by Professor V.I. Fedorov [3] at DalNIIS, four specific patterns of composite soils behavior under shear were determined. The soils with very strong unrounded debris were studied. But, as already noted, the strength and shape of the debris were the main factors affecting \( C \) and \( \varphi \) of composite soils.

To assess the relationship between the composition and condition of composite soils and their strength properties, the authors used model mixtures composed of packing clay and debris of various strengths and roundness, as well as the field tests results and the archival data [9-10]. The artificially prepared mixtures were selected because they allowed to widely vary the properties of composite soils, which was almost impossible when working with real soils. The use of model mixtures allowed to obtain certain soils based on the specified properties for every particular case, which made it possible to objectively study the influence of each factor.

The mass content \( P_f \) of fragments in model mixtures varied from 20% to 90%. We used very strong sharp-edged fragments of irregular shape, fragments of medium strength and soft fragments, as well as strong medium rounded and perfectly rounded fragments. Quantitatively, the strength of the fragments was expressed through the coefficient of abrasion \( k_s \), the roundness \( O_k \) – in points on Khabakov scale. The density of dry soil \( \rho_c \) in the samples varied from 1.7 to 2.3 g/cm\(^3\). Clays with \( I_p \) from 18.4 to 21.5, clay loams with \( I_p \), from 9.5 to 10.3 and clayey sands with \( I_p \) from 3.3 to 4.4 were used as an aggregate. The index of liquidity of the aggregate \( I_L \) ranged from 0 to 1. Depending on the change in \( I_L \) and the type of debris, the tests were divided into four cycles.

*In the first cycle*, we used sharp-edged fragments of various strengths and hard aggregates \( I_L \leq 0 \), medium hard aggregates \( 0 < I_L \leq 0.25 \), and low-plasticity aggregates \( 0.25 < I_L \leq 0.50 \). *In the second cycle*, we used sharp-edged fragments of various strengths and high-plastic aggregates \( 0.50 < I_L \leq 0.75 \),...
extremely high liquid limit aggregates $0.75 < I_L \leq 1.00$, and fluid $I_L > 1.0$. In the third cycle, we used fragments of different roundedness and hard aggregates $I_L \leq 0$, medium hard aggregates $0 < I_L \leq 0.25$ and low-plasticity aggregates $0.25 < I_L \leq 0.50$. In the fourth cycle, we used fragments of different roundedness and high-plastic aggregates $0.50 < I_L \leq 0.75$, extremely high liquid limit aggregates $0.75 < I_L \leq 1.00$, and fluid $I_L > 1.0$.

In each cycle of experiments, we performed 270 shears on a small standard shear testing machine and 27 shears on a large shear testing machine of the DalNIIIS design. The method of shear testing on a fixed surface was taken as the simplest and most reliable. The tests were carried out on the pattern “accelerated shear under the conditions of complete consolidation” of GOST 12248-2010 [11]. We dried each sample of soil after shear and determined $\rho_d$.

The complex experimental studies that we conducted allowed us to give a more precise definition of the theoretical aspects of the composite soils behavior under the shear, as well as to supplement the classification patterns of the behavior of these soils. Taking into account the mechanical strength and roundness of the debris supplemented the existing patterns and made them more general.

**Pattern I.** $90 \leq P_2 \leq 100 \%$. The debris were in direct contact with each other. The strength of the debris was the main factor affecting the construction properties of the soil, and the clayed aggregate had no actual effect. The vertical load fell on a rigid skeleton of soil made of large fragments. Fragments moved, rolled over and slipped in relation to one another during the shear. Depending on the vertical load and the compaction density of the soil, the debris remained undisturbed or had slight chipping of their sharp edges. The total soil resistance to shear $\tau$ consisted mainly of the cohesion force, engagement force and friction force of the debris ($\varphi$). The value $C$ was negligible and amounted to about 1.0-4.0 kPa. The granulometric composition of the samples before and after the shear was almost the same. The debris of medium strength were destroyed to a greater extent. When the soils with low-strength and fragile debris sheared, the debris sheared and destroyed in the shear plane in addition to moving of the debris in relation to one another and chipping of sharp edges, due to which $C$ increased significantly (up to 40 kPa), and $\varphi$ and $r$ were decreasing. After shearing, the granulometric composition of the samples changed significantly upwards the percentage increase of smaller fractions of debris.

**Pattern II.** $70 \leq P_2 < 90 \%$. The direct contact of the fragments with each other still took place. With the increase in the quantity of the aggregate, the contacts were decreasing, but the rigid clastic skeleton of soil remained. The vertical load fell only on the rigid skeleton and the clayed aggregate was not compressed. The clayed aggregate played the role of a lubricant, so even a slight increase in the percentage of aggregate caused a noticeable decrease of $\varphi$. Specific cohesion $C$, on the contrary, increased, since the shearing force of the soil with very hard debris was spent not only on moving the debris in relation to one another and chipping edges, but also on shearing the aggregate. At a given debris strength, an increase $I_L$ of the aggregate led to a decrease in $C$. The granulometric composition of the samples before and after the shear was almost the same, as it was in Pattern I. In the soils containing low-strength and fragile debris, $C$ also increased with an increase in the amount of the aggregate. However, an increase $I_L$ of the aggregate caused an increase $C$ rather than a decrease. This was due to the increase of the aggregate moisture caused by moisture exchange that led to an increase of moisture in the debris and a decrease in their strength compared to the air-dry state. Therefore, the shear of the fragments themselves occurs more often, which increases the value of $C$, but $\tau$ is significantly lower than in soils with strong fragments. The granulometric composition of the samples before and after the shear changes similar to the Pattern I.

**Pattern III.** $50 \leq P_2 < 70 \%$. Contacts of fragments with each other decreased with the increasing quantity of aggregate. The clayed aggregate behaving as a contact layer turned into a viscous substance with concretions of debris. At the initial moment, the vertical load fell to the entire mass of the soil, but as soon as the debris came into contact with each other, the aggregate switched out of use and the vertical pressure fell only on the rigid debris skeleton. In the soils with debris of high and medium strength, $\tau$ consisted of the friction of rolling and slipping large debris, the force of chipping of sharp edges, the friction and cohesion in the aggregate at the compression load of first level. As
soon as large fragments made the skeleton, an increase in τ occurred due to the increment of friction caused by rolling and slipping large fragments. The increasing mass of the aggregate caused a decrease of ϕ and an increase of C. With an increase of I_L in the aggregate, C decreased. In the soils with low-strength and fragile debris, τ consisted of the friction of rolling and slipping large debris, the force of chipping of sharp edges, the friction and cohesion in the clayed aggregate at the compression load of first level. As soon as large fragments made the skeleton, an increase in τ occurred due to the destruction and shearing of the fragments themselves. Similar to Pattern II, an increase of I_L in the aggregate first caused a slight increase of C, which then decreased. Since the mass of the aggregate in the soil was large (up to 50%) and it played a significant role, an increase in C due to the destruction of fragments was less in contrast to its decrease due to an increase in I_L of the aggregate. The significance of the mechanical strength of the debris became less important, and the nature of the relationships approached to the relationships of the debris of high strength.

Pattern IV. 20 ≤ P_z < 50%. The number of contacts between the fragments was insignificant. A rigid skeleton was not formed. The debris, sort of, “floated” in the aggregate. When the soil sheared, the fragments slipped and rotated in relation to one another, the fragments rotated in the aggregate, and the aggregate sheared between the fragments. The rotation of the fragments in the aggregate was actually a shear of the aggregate along the surface of rotation of the fragments. The total value of τ in the clayed soil with inclusions of high and medium strength consisted of the friction of fragments, the friction of the fragments at the rotation in the aggregate, and the friction of the aggregate in spaces between the fragments. The cohesion of clayed soil with coarse inclusions was composed of aggregate cohesion at its shearing by the fragments surfaces in rotation and cohesion at the shearing of the aggregate in spaces between the fragments. The soils with low-strength and fragile debris had the total friction magnitude τ similar to that one in the soils with debris of high and medium strength, and the debris shear force added to the value C. But the quantity of debris falling on the shearing surface was very small, and with their content of 30% or lower, the strength of the debris had no relationship with the construction properties of the soils. Thus, I_L and I_F of the aggregate became the main factors affecting the strength characteristics of soils.

3. Patterns of composite soils behavior under compression
Deformation properties of composite soils depend on their macrostructure. The classification proposed by SoyuzDorNII [4, 12] specifies three macrostructures of composite soils: frameless, with incomplete frame and skeleton framed. The frameless structure has a low content of debris in clayed soil (up to 20-25%). Being at a considerable distance from each other, fragments “are floating” in clayed soil. A structure with an incomplete frame has a higher content of debris (from 20-25% to 55-60%) in the clayed soil. The fragments are brought together; a more compact fine-earth structure is created in the clusters areas. This macrostructure creates a continuous skeleton that behaves as a single system. The skeleton framed structure has a maximum content of debris in the soil (over 60%). Under compression, the fragments come together, get locked and make tight coupling.

To study the deformation characteristics of composite soils, we used materials from stamp tests of composite soils performed by PrimorTISIZ, DalTISIZ, PromstroiNIiproekt, and DalmorNIiproekt.

We conducted laboratory and semi-natural studies of the deformation patterns of composite soils. For testing, we used igdantine patterns with inclusions [13, 14] and samples of composite soil. Clay loam was used as an aggregate, and strong andesite rotted rocks - as large inclusions. Clastic-clayed mixtures were tested on standard compression testing machines and on a large-scale compression testing machine of the DalNIIS design. The compression rate of the mixture in the machines was 0.95 [15].

In particular, we researched the influence of the following factors: the content of debris in the sample, the shape of the debris, the roughness of the debris, the location of the debris in the sample. As a result of the research, the following was observed.

Depending on the content of inclusions, the behavior of composite soil samples can be divided into three pattern.
Pattern I. The content of inclusions is up to 40% by mass, the compressibility of the sample is determined by the aggregate properties and the number of inclusions, the deformation modulus $E$ is slightly higher than that of clayed mixtures without inclusions (“pure” aggregates).

Pattern II. The content of inclusions is from 40 to 60% by weight, the influence of the aggregate on the compressibility of the sample is reduced, the deformation modulus $E$ is much higher than that one of the “pure” aggregate.

Pattern III. The content of fragments is over 60% by weight, the compressibility of the samples is determined by the properties of inclusions and the content of aggregate. A skeleton is formed of large fragments with a different packing density. We specified three subgroups in this pattern. In the first subgroup — with inclusions from 60 to 70% by mass — a skeleton is formed, but the influence of the aggregate is significant. In the second subgroup — with inclusions from 70 to 80% by mass — the packing density of inclusions is unstable, the influence of the aggregate properties is still noticeable. In the third subgroup — with inclusions over 80% by mass — the packing density of inclusions is high, the influence of the aggregate properties on the compressibility is negligible. The deformation modulus $E$ tends to the deformation modulus of “clean” coarse soil without an aggregate.

4. Conclusion

Our studies have shown that the main factor determining the deformability of a composite soil is the content of debris, while their shape, roughness and location in the massif are not significant. The consistency of the aggregate affects the compressibility of the soil directly: the higher its consistency is, the higher the compressibility of the composite soil will be.

The tests also proved that a waste in the secondary cohesion of a clayed aggregate in soil mixtures results in a significant increase in the deformability of the composite soil. The influence of the structural damage of the aggregate on the deformation properties of the composite soil increases more significantly, when the index of liquidity of the clayed aggregate or its plasticity number grows.

The laboratory and semi-natural tests on ignantine patterns with inclusions and on clastic-clayed mixtures under compression allowed to substantiate the factors that determine the deformability of composite soils and establish patterns of the relationship between the mechanical properties of the soil and physical and mechanical properties of its components.

So, through the experiments, we have identified the factors that determine the strength and compressibility of composite soils, which made it possible to forecast the values of $C$, $\phi$ and $E$ from the physical and mechanical properties of its components.

5. References

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