Updated Technique for Forecasting Strength and Deformability of Composite (Clastic-Silty-Clayed) Soils

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Abstract. Clastic-silty-clayed soils are most common on construction sites of the Russian Far East. DalNIIS studies of the construction properties of these soils were launched by Professor V.I. Fedorov in 1968-1972 and ended with the development of a Technique of Assessing the Strength and Compressibility of the studied soils in 1991. This is the first in the global soil science Technique evaluating the mechanical characteristics of soil through its physical properties. In 2013-2014, the Technique was updated. As a result, a new modern edition of the Technique was developed as a Manual for Design and Construction of Foundations and Basements of Buildings and Structures in Watering out and Hazardous Heaving Soils of the southern Russian Far East with enclosed Charts of Standard Strength and Deformation Parameters of Clastic-Clayed Soils.

1. Introduction

SP (Standard Specification) 22.13330.2016 [1] specifies the two limit state design of building and structure foundations. The key parameters that determine the bearing capacity of the foundation and its deformation are the angle of internal friction $\phi$, specific cohesion $C$ and modulus of deformation $E$.

The SP [1] allows to determine standard and expected values $C$, $\phi$ and $E$ of soils depending on their physical characteristics for preliminary calculation of foundations of structures of the first and second levels of responsibility, as well as for final calculation of the foundations of structures of the third level of responsibility and power transmission line poles regardless of their level of responsibility. It is possible to use the data given in the charts of Appendix B for the final calculation of foundations of structures of the second level of responsibility with appropriate justification [1, Appendix B, charts B.2, B.3].

In 1981, Stroyizdat (Moscow) published the “Guidance on Making Regional Charts of Standard and Expected Values of Soil Properties” [2], which allowed to use specially developed regional charts of soil characteristics for certain areas with the engineering and geological specifics of these areas instead of the charts given at the Appendix to Chapter 2 of SNiP (Construction Codes and Regulations) II-15-74.

In the years 1970-1990, the leading institutes, like NIIOSP, SoyuzDorNII, KhADI, VNIIG, and VNII-VODGEO, studied the strength and compressibility of clastic-clayed 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. The use of clastic-clayed soils in artificial foundations for industrial and civil construction has been actively studied in the Ural Region. Researchers V.B. Shvets, E.M. Dobrov, O.N. Zhidkov, N.P. Lushnov, N.Ya. Halitov et al. [3-
[14] made a great contribution to the study of the strength and compressibility of clastic clayed soils. However, soil charts of the Ural Region have not been developed then.

And only in the last 10 years, L.A. Strokova [15] published 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. The study resulted in the development of a regional chart of standard property values of these soils. This was the first and only work on the development of regional charts of soil property values, which we found when researching the issue.

In accordance with [2], DalNIIS developed regional soil property charts that took due account of the engineering and geological features of the Russian Far Eastern regions. In 1972, the Charts of Standard Values of Russian Far East Clayed Soils of the Quaternary Period [16] were published. The charts were developed on the basis of laboratory and field tests of soils of the Primorye and Khabarovsk regions and Sakhalin Island found in the archives of PrimTISIZ and DalTISIZ.

Long-term studies launched by Professor V.I. Fedorov [17-20] at DalNIIS, showed the basic consistent relationship between the mechanical parameters of composite soils and the physical properties of their components. These patterns made it possible to develop charts for evaluation of strength and deformation parameters of composite soils on their physical properties.

In 1989, Stroyizdat published the “Technique ...” [17] with Charts of strength and deformation parameters of clastic-clayed soils of the Russian Far East regions in terms of their condition, composition and structure, that is, by physical properties. The Technique establishes the basic rules for determining the standard values $\phi$, $C$, and $E$ of clastic-clayed soils of eluvial, deluvial, proluvial, and alluvial origin of the Quaternary Period from the physical characteristics of their components. The Technique update is relevant and therefore in demand by design and survey organizations not only in the Russian Far East, but also in other areas with similar engineering and geological conditions.

In this regard, the NTS (Board for Research and Engineering) of DalNIIS RAASN (Russian Academy of Architecture and Construction Sciences) decided to update and publish the Technique [17]. The NTS also proposed to rename the coarse soils with dusty clayed aggregate and dusty clayed soils with coarse inclusions for shorter as composite soils. The qualitative behavior of mixed soil grounds under load, as it was confirmed by studies at MISI (Moscow Civil Engineering Institute) [13], corresponds to the mechanics of composite materials. Therefore, the new name of these soils - composite soils - does not contradict their properties.

The updated Technique was enriched with studies that have not been conducted before. Thus, the previous Technique did not take into consideration the direct debris strength when evaluating soil properties. Reliable relationship between the mechanical parameters of composite soils and their physical properties were given only for very strong debris, and the mechanical properties of composite soils containing debris of different strengths were adjusted with appropriate coefficients. The objective of this research was to obtain the correct relationship between the mechanical parameters of composite soils and the strength and shape of the debris.

To assess the effect of the composition and condition of the studied soils on their strength properties, laboratory studies were performed using sample mixtures composed of packing clay and debris of various strength and roundness, as well as the results of semi-natural and field tests and archive data.

The obtained correlation dependences made it possible to justify the working patterns of composite soils and to develop Charts of standard values of strength characteristics depending on the physical properties of composite soils. A sample chart of strength characteristics of composite soils with strong debris (Table 1) is presented in the article.

To study the deformation characteristics of composite soils, we used materials from stamp tests of composite soils performed by PrimorTISIZ, DalTISIZ (Khabarovsk, Sakhalinsk and Komsomolsk-on-Amur branches), PromstroINIIproekt, and DalmorNIIproekt in 1936-1976. 186 records of stamp tests of composite soils with sand and clay aggregate were selected in various regions of the Russian Far East, including 63 stamp tests made in Primorye, 41 in the Khabarovsk Krai, 31 in Sakhalin, 20 in the city of Amursk, and 33 in Komsomolsk-on-Amur. Of the selected records, 170 tests were made of
composite soils with clayed aggregate and 18 - with sand. The tests were carried out both with a standard stamp of an area of 5,000 cm², and with a rope-and-lever unit with a round metal stamp of 600 cm² in area. In 2013, these data were enriched with the results of 98 stamp tests and pressiometry. The deformation modulus was determined based on the findings of field tests by the Schleich formula:

\[ E = (1 - \mu^2) \omega \sqrt{F} \frac{AP}{AS} \]

where \( \mu \) – Poisson’s ratio,
\( F \) – area of stamp,
\( \omega \) - coefficient depending on the shape of the stamp area, for a round stamp \( \omega = 0.89, \)
\( AP \) – rise of pressure on stamp, MPa,
\( AS \) - increment of stamp settlement, fitting in with \( AP \).

The linearization of the relationship \( S = f(P) \) included all stages of the load up to the critical one, in which the increment of settlement was twice as much as in the previous stage of loading. The natural pressure \( P_0 \) was taken as an initial load. The physical and mechanical properties of the soils of the site were averaged according to the widely used formulas of GOST 20522-2012 [5]. In this case, the coefficient of property variation should not exceed 0.15 for the coefficient of porosity \( e \) and humidity \( W \) and 0.30 - for \( E \).

Composite soils with over 25% of debris were included in the mathematic processing. In total, we had 76 stamps for mathematical processing.

Analyzing the results of stamp tests, we regretfully found that the strength of the debris was not evaluated during the survey and field testing of composite soils, and only an approximate visual assessment of the degree of weathering was given. And only the petrographic composition along with the visual description of weathering made it possible to very roughly evaluate the strength of the debris contained in the soil.

| Index of Liquidity | Content of particles larger than 2 mm (% by mass) |
|------------------|-----------------------------------------------|
|                  | \( C_n \) | \( p_n \) | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 95 | 100 |
| Clayey Sand \( I_L \leq 7 \% \) | 0,00 ≤ \( I_L \) ≤ 0,25 | 28 | 28 | 24 | 21 | 19 | 15 | 14 | 12 | 12 | 12 | 12 |
| Clay Loam \( I_L \leq 7 \% \) | 0,25 ≤ \( I_L \) ≤ 0,75 | 15 | 15 | 14 | 14 | 13 | 13 | 12 | 12 | 12 | 12 | 12 |
| Clay \( I_L \geq 17 \% \) | 0,50 ≤ \( I_L \) ≤ 0,75 | 16 | 16 | 15 | 15 | 14 | 13 | 13 | 12 | 12 | 12 | 12 | 12 |
| Clay \( I_L \geq 17 \% \) | 0 ≤ \( I_L \) ≤ 0,25 | 45 | 44 | 38 | 34 | 32 | 28 | 27 | 22 | 20 | 12 | 12 | 12 |
| Clay \( I_L \geq 17 \% \) | 0,25 ≤ \( I_L \) ≤ 0,50 | 34 | 32 | 29 | 26 | 23 | 20 | 18 | 17 | 13 | 12 | 12 | 12 |
| Clay \( I_L \geq 17 \% \) | 0,50 ≤ \( I_L \) ≤ 0,75 | 24 | 19 | 17 | 17 | 15 | 15 | 14 | 14 | 12 | 12 | 12 | 12 |

The formula:

\[ E = (1 - \mu^2) \omega \sqrt{F} \frac{AP}{AS} \]

where \( \mu \) – Poisson’s ratio,
\( F \) – area of stamp,
\( \omega \) - coefficient depending on the shape of the stamp area, for a round stamp \( \omega = 0.89, \)
\( AP \) – rise of pressure on stamp, MPa,
\( AS \) - increment of stamp settlement, fitting in with \( AP \).
Therefore, we used the deformation module to divide the samples into separate geotechnical groups according to the strength of the debris. So, the group of soils with strong debris included composite soils with deformation modules of 50-100 MPa. Soils with \( E = 38-70 \) MPa were put to the group with debris of medium strength. The group of soils with reduced debris strength included soils with \( E = 36-55 \) MPa. Composite soils with \( E = 23-35 \) MPa were included in the group with fragile inclusions. The strength of the debris was determined by the coefficient of abrasiveness \( k_e \) according to the DalNIIS method.

We performed correlation-regression analysis of the results of stamp tests of composite soils in order to select the optimal forecasting equation - the basis for constructing charts of standard values for the modulus of deformation of composite soils. We examined the multiple correlation between the deformation modulus of composite soils and their physical characteristics, namely, the plasticity index \( I_p \) of the clay aggregate, index of liquidity \( I_L \), and the content of large inclusions in soil \( P_2 \).

Studies of multiple correlation relationships were carried out for four samples of composite soil containing strong inclusions, inclusions of medium strength, soft and low strength, for the relationship \( \ln E = f (I_p, I_L, P_2) \). Two types of the equation of constraints were considered: polynomials of the first and second degrees. The results of multiple correlation analysis are given in table 2. The data in the chart show that the second degree equation gives higher correlation ratios for all samples. It was chosen as a forecasting equation for compiling charts of standard values for the modulus of deformation of composite soils by field tests.

**Table 2. Results of Multiple Correlation Analysis of Relationships.**

| Type of Equation of Constraint | Soil with strong inclusions, n=10 | Soil with medium strength, n=20 | Soil with low strength, n=21 |
|--------------------------------|---------------------------------|--------------------------------|---------------------------|
| \( y=a_0+bI_p+cI_L+dP_2 \)   | 0.842 0.211 0.955 0.096 0.924 0.121 | 0.989 0.058 0.977 0.069 0.944 0.103 |
| \( y=a_0+b_1I_p+c_1I_L+d_1P_2^2 \) |                                |                                |                          |

**Table 3. Standard Values of the Deformation Modulus of Composite Soils \( E'' \) in MPa with Strong Debris \( (k_e < 0.10) \).**

| Types of Aggregate | Index of Liquidity Of Aggregate | Content of Large Size Debris \( (d > 2 \) mm), % |
|--------------------|--------------------------------|-----------------------------------------------|
| Clayey Sand | 0 ≤ \( I_L \), \( I_L \) ≤ 0,25 | 58 67 74 79 83 86 89 |
|                  | 0,25 < \( I_L \) ≤ 0,75 | 35 40 45 52 64 72 77 |
|                  | \( I_L \) < 0 | 33 43 52 61 69 77 80 |
|                  | 0 ≤ \( I_L \) ≤ 0,25 | 31 40 50 59 67 76 79 |
| Clay Loam | 0,25 < \( I_L \) ≤ 0,50 | 24 32 40 48 57 65 73 |
|                  | 0,50 < \( I_L \) ≤ 0,75 | 22 30 38 47 56 64 75 |
|                  | 0,75 < \( I_L \) ≤ 1,0 | 15 21 27 34 41 49 56 |
|                  | \( I_L \) < 0 | 28 36 44 52 64 76 79 |
|                  | 0 ≤ \( I_L \) ≤ 0,25 | 27 35 43 51 58 66 74 |
| Clay | 0,25 < \( I_L \) ≤ 0,50 | 24 32 40 48 57 65 73 |
|                  | 0,50 < \( I_L \) ≤ 0,75 | 18 27 36 42 50 54 70 |
|                  | 0,75 < \( I_L \) ≤ 1,0 | 14 19 25 31 40 51 68 |
For greater certainty in the deformation characteristics of composite soils, we compared these characteristics with the results of field tests and correlation analysis. As it turned out, the deformation moduli of composite soil [12] with strong debris were 25% to 62% lower in contrast to field results and correlation analysis data; for composite soil with medium strength debris, soft and low strength, the largest differences were from 26% to 48%. Therefore, the need to correct chart values of $E$ is obvious. The adjusted standard values of the deformation modulus of composite soils with debris of different strengths are selectively presented in Chart 3.

2. Conclusion
Thus, due to the current research, we have developed updated charts of standard values of strength and deformation characteristics of composite soils.

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