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Investigating Mechanical Properties of Argillaceous Grounds in Order to Improve Safety of Development of Megalopolis Underground Space

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Abstract
This article discusses strength and deformation properties of argillaceous formations in megalopolis underground space. It is established that they are characterized by anisotropy of mechanical properties, which is directly related with the processes of generation of soil bodies. Rather frequently layered grounds are considered as transversal isotropic medium, the strength and deformation properties of which depends on direction of load application with regard to the stratification plane. On the basis of laboratory tests the values of strength and deformation properties have been obtained which could be used as parameters of transversal isotropic medium for mathematical and numerical simulation.

Keywords: deformation properties, bulk density, argillaceous grounds, anisotropy, minor deformations, tests.

INTRODUCTION

Construction of underground facilities is always related with modification of stressed state of rock mass, which leads to occurrence of various geomechanical processes. This is expressed in the form of deformations of rock mass which involves displacement of rock outline, generation of load onto casing of underground facility, settlement of ground, as well as other negative processes. Forecast of geomechanical processes should be performed in advance at designing stage, thus decreasing the risks upon construction of underground facilities, herewith, modern concept of ground deformation should be taken into account.

Nowadays the designing practice of underground facilities more and more frequently involves numerical analytical methods, which facilitate not only calculations with consideration for spatial configuration of underground facilities and sequence of their erection, but also accounting for various peculiarities of mechanical behavior of rocks, which was impossible previously. Despite the fact that the field of solution of practical engineering tasks has been significantly expanded after implementation of numerical methods and up-to-date models of mediums into the designing practice of underground facilities, the requirements to initial data also changed, in particular, to study into mechanical properties of grounds.

The main attention upon study into mechanical properties is paid to the aspects of estimation of pre-limiting stage of ground deformation, as well as ultimate strength indices, since the behavior of grounds at this stage determines mainly those geomechanical processes which occur in the vicinity of underground facilities. Study of mechanical behavior at super-limiting stage is also important for grounds, experiencing brittle destruction, however, these behavior peculiarities are not widely applied in the existing models of behavior of geomaterials. A peculiar feature of mechanical behavior of grounds is anisotropy, which makes significant contribution into those geomechanical processes, which occur in rock mass under the action of construction activities and should be accounted for in the calculations.

Natural anisotropy can be observed for numerous grounds and rocks. This related with sedimentation, grain shape, structure of porosity and, in the case of firm grounds or rocks, with jointing [1, 2]. It has been established experimentally that upon ground compression the particles tend to be arranged as basal plane in perpendicular to compressing pressure, herewith, the orientation extent increases with load. Upon displacement the area of oriented particle position is formed in parallel to the displacement direction. Similar results were reported later by Turovskaya, Shibakova, Bondarik, Osipov [3], Biarez, Matsuo and others. In these works it is mentioned that irrespective of arranged or chaotic pattern of initial texture the deformation processes (compaction, displacement) lead to arranged structure of the ground. In its turn, this determines the so called induced anisotropy of properties, obtained as a consequence of variation of initial stress strain state of ground.

The aspects of anisotropy was thoroughly studied by Fursa [4, 5], Rogatkina, Lukinskoi, Lushnikova and others. An example of laminar grounds is, in particular, bottom sedimentation of banded clays of Gulf of Finland in the vicinity of Leningrad. In the works by Fursa, Kagan [6, 7], Ivanov, Dashko [8], Lomtadze [9] these grounds are characterized by both deformation and strength anisotropy. The results of compression tests of glaciolacustrine deposits of basement of concrete flood prevention facilities of Leningrad are characterized by noticeable deformation and strength anisotropy [10]. The most common case of natural anisotropy of grounds of high and medium lithification extent is transversal isotropy [11-13].

Ward, Samuels, and Batler [14] reported about deformation and strength anisotropy of London clays, which are characterized by stratification and jointing. On the basis of experimental results by "squeezing" flowchart the authris present correlations between the modules $E_{\parallel}$ and $E_{\perp}$, obtained at the direction of stress σ_1 along and across stratification. In the case of loading the following relations took place: $E_{\parallel}/E_{\perp}$=1.2 – 1.95, in the case of unloading: $E_{\parallel}/E_{\perp}$=1.3–2.0. For the case of similar overpacked clays with integer structure Barden [15] reported: $E_{\parallel}/E_{\perp}$ = 1.5–4.

Therefore, anisotropy mechanical properties is an intrinsic property of grounds, and their structure determines only the rate of influence of this property on strength and deformability of grounds. This work discusses the study in mechanical behavior of Proterozoic clay as ground which is characterized by distinct anisotropy. This work does not consider for such important factor as structural disturbance of ground mass, which can make significant contribution into variation of mechanical properties of grounds, only the aspects of deformation of argillaceous grounds of undisturbed structure are considered.

There is a common trend to locate underground facilities in engineering and geological conditions of St. Petersburg in Proterozoic clays, which exist as a bulk of rather dense slightly wet clays with thing interlayers of cemented fine sand, with directed orientation of clay particles. Examples of such underground facilities are the sites of St. Petersburg metro system, sewer tunnels. There is a rather recent trend to consider Proterozoic clays as reliable medium for load accommodation from high buildings and facilities.

EXPERIMENTAL

Analysis of prior art studies into strength and deformation properties of Proterozoic clays

Proterozoic clay, which is the subject of this work, presents a prominent pattern of grounds with distinct anisotropy of strength and deformation propeties. Peculiar features of mechanical behavior of Proterozoic clays was studied by Dashko [16], Podakov [17, 18], Bezrodnyi [19, 20], Kartashov [21, 22] and others.

The researches by Podakov (Table 1) revealed that the properties of transient clay layer in the upper portion of Proterozoic mass differ significantly from those of primary rocks. The clays of transient layer are in dislocated state, they includes impurities of quaternary deposits, boulders and gravel, they are flooded and fractured. The deformation and strength properties of Proterozoic clays increase with depth.

Table 1. Physicomechanical properties of clays

Values	Ground		
	Proterozoic broken clays	Proterozoic clays in upper layers	Proterozoic clays in deep layers
Mositure, %	18 - 23	14 – 16	12 – 13
Bulk weight, kN/m^3	20.0	21.5	22 -22.5
Coefficient of porosity	0.6	0.5	0.45
Resistance against uniaxial compression in perpendicular to stratification, MPa	0.7	1.5	3.0
Resistance against uniaxial compression in parallel to stratification, MPa	-	1.0	2.0
Young modulus, MPa	30 – 50	100 – 250	250 – 500

The study into physicomechanical properties of Proterozoic clays performed by Podakov and Nezrodnyi in cooperation with the laboratory of mechanical properties, VNIMI, indicates at difference in the properties along in perpendicular to rock stratification. It is revealed that the ultimate strength upon uniaxial compression in perpendicular to stratification is 3.2 – 3.6 MPa, and in parallel to stratification is 1.0–2.0 MPa. The Young modulus upon loading in perpendicular to stratification is 270 – 280 MPa, in parallel to stratification 710 – 770 MPa, the coefficient of transversal deformation is 0.09 – 0.2.

In the work by Kartashov the strength properties were studied in perpendicular and in parallel to stratification. The considered results demonstrated that the strength envelope of Proterozoic clay is curvilinear, simplified in the work by broken curve with two linear sections (Table 2).

Table 2. Strength properties of Proterozoic clay according to data by Kartashov Yu. M.

	Parameters at various sites of strength certificate					
	Site I			Site II		
	c_1, MPa	φ_1, MPa	$\sigma_1 = v + w\sigma_3$	c_1, MPa	φ_1, MPa	$\sigma_1 = v + w\sigma_3$
Compression in parallel to stratification	1.75	36.86	$70.0 + 4.0\sigma_3$	3.17	15.32	$82.9 + 1.7\sigma_3$
Compression in perpendicular to stratification	1.89	32.86	$69.5 + 3.4\sigma_3$	3.30	15.17	$86.2 + 1.7\sigma_3$

Analysis of the obtained data made it possible to establish that the strength values of Proterozoic clay differ insignificantly in perpendicular and in parallel directions to stratification. Herewith, with increase in confined pressure there is observed decrease in the difference between strength properties as a function of direction of load accommodation. Therefore, the coefficient of anisotropy is 1.08.

The work by Zhukova [23] highlights interrelation between deformation properties and value of confined pressure as follows:

$$E_0 = 183.4\sigma_3 + 155.0, \qquad (1) \qquad (1)$$

In conclusion of this brief analysis of previous studies it should be mentioned that the studies into mechanical behavior of Proterozoic clays were sufficiently considered, both anisotropy and strength, as well as deformation properties were analyzed, including the influence of stress state on deformation properties. However, the mentioned works paid attention mainly to one aspect of mechanical behavior of Proterozoic clay and did not analyze the influence of layered structures of such clays on deformation of argillaceous grounds in wide range of deformation variations, as well as did not pay attention to the aspects of destruction of argillaceous grounds in various stress strain state. These and some other issues will be considered upon study into mechanical behavior of layered argillaceous grounds.

Test procedure applied to argillaceous grounds

Up-to-date methods of calculation of geomechanical processes in the vicinity of underground facilities make it possible to account for numerous features peculiar to mechanical behavior of grounds, thus increasing reliability of the performed calculations. Existing and newly developed models of geomaterials enable consideration for non-linear behavior of grounds, their strengthening at pre-limiting stage of deformation and weakening at super-limiting stage, non-linear elasticity in the range of extremely low to low deformations, non-linear variation of ground strength as a function of achieved value of average stresses, natural and forced anisotropy, as well sa other peculiarities of their mechanical behavior. In its turn, this expands the spectrum of active tasks in the field of forecasted variations of stress strain state cause by construction of underground facilities. Therefore, the aim of laboratory tests was to study mechanical behavior of Proterozoic clays in wide range of variation of stresses and strains, which can be subsequently used for substantiation of parameters of selected model of geomaterials.

The study into mechanical behavior of Proterozoic clay were performed on laboratory scale using various pressing equipment. Initial materials for fabrication of samples were monoliths of Proterozoic clay, taken from bottom of central tunnel of Bukharestkaya metro station and Prospekt Slavy metro station in St. Petersburg, as well as some data obtained upon study into mechanical properties of Proterozoic samples taken from the bottom of Mezhdunarodnaya metro station, delivered by experts of Lenmetrogiprotrans Institute. The depth of sampling site was about 60 m from terrain level. The sampled monoliths were comprised of Proterozoic clay (Bukharestkaya metro station) and Proterozoic clay with inclusion of sandstone interlayers (Prospekt Slavy metro station). Monoliths, comprised mainly of sandstone, were rejected, no samples on the basis of such lumps were prepared for subsequent laboratory tests.

Mechanical behavior of Proterozoic clays were studied using regular laboratory tests, which included uniaxial compression, indirect tests in order to determine strength upon uniaxial tension, shear tests and tests on bulk stress state. The obtained laboratory results were supplemented by the results of study into mechanical properties obtained by us previously upon study into mechanical properties of Proterozoic clays on the samples from other sites.

The tests were performed upon bulk compression according to consolidated undrained layout. The test schedule of Proterozoic clay upon bulk compression included testing of 12 samples in perpendicular direction to stratification and 12 samples in parallel direction to stratification. The tests were performed upon lateral pressure of 0.5 MPa, 1.0 MPa, 2.5 MPa, and 5.0 MPa, which enabled covering of nearly total stress range for construction conditions of underground facilities in St. Petersburg. The tests were performed in two stages. At the first stage a sample with hydrostatically loaded at the rate of 0.5 MPa/h. Then the value of confined pressure was maintained constant yp to complete stabilization of deformations. At this stage a chance of liquid filtration from sample was allowed. At the second stage deviator loading of sample was performed. Axial load was transferred according to the schedule of preset deformations. In the range of variation of relative longitudinal deformation from $1\cdot10^{-5}$ to $1\cdot10^{-3}$ three loading cycles of subsequent unloading were performed. Longitudinal and transversal deformations were measured at the increment of $1\cdot10^{-5}$, both upon loading and unloading. The rate of deviator loading was 10^{-6} s^{-1}. Then, the stress deviator $q = \sigma_1 - \sigma_3$ was increased to 2 MPa, further unloading was performed to q of 0.5 MPa. Subsequent loading was performed up to achievement of residual strength. Limiting deformation is the value of deformation curve when it reaches the section of residual strength. In the course of tests axial and transversal deformations are measured. At this stage the liquid filtration from sample pores is not allowed.

RESULTS

Proterozoic clay: Experimental results under uniaxial compression

Laboratory tests under uniaxial compression were performed in sufficient quantities only on the samles taken from the bottom of Prospekt Slavy metro station, overall subsequent analysis covers only these grounds.

Analysis of laboratory results of Proterozoic clays under uniaxial compression revealed the following. Non-linear interaction between stresses and strains was determined at the stage of sample deformation (Fig. 1,b), in the range of minor deformations, and at final section of pre-limiting stage of deformation (Fig. 1,a). Average modulus of deformation after processing of 16 tests equaled to 277 MPa in perpendicular to stratification and 567 MPa in paralle to stratification. Average elasticity modulus obtained by unloading curves equaled to 610 in perpendicular to stratification and 1393 in parallel to stratification. The coefficient of transversal deformations is 0.1 and 0.2 in perpendicular to and in parallel to stratification, respectively. Average uniaxial compression strength equaled to 2.7 MPa in perpendicular to stratification and to 3.0 MPa in parallel to stratification.

Therefore, the coefficient of anisotropy of deformation properties expressed as the ratio of the modulus of deformation in parallel to stratification to the modulus of deformation in perpendicular to stratification is 2.05. The coefficient of anisotropy of deformation properties expressed as the ratio of the modulus of elasticity in parallel to stratification to the modulus of elasticity in perpendicular to stratification is 1.91. The coefficient of anisotropy of deformation properties expressed as the ratio of rock uniaxial compression strength in parallel to stratification to the uniaxial compression strength in perpendicular to stratification is 1.12. The ratio of the elasticity modulus to the modulus of deformation of Proterozoic clay in perpendicular to and in parallel to stratification is 2.20 and 2.06, respectively.

The obtained results correlate sufficiently well with the previous studies. However, the value of anisotropy of deformation properties is slightly lower, which can be attributed to significant inclusions of sandstones into the body of Proterozoic clay.

Estimation of error demonstrated that more stable results (lower scattering) are obtained upon testing of Proterozoic clay in parallel to stratification with respect to rock testing in perpendicular to stratification.

It should be mentioned that during testing of Proterozoic clays destruction quite often occurred in the form of cleavage of sample due to formation of longitudinal planes of rupture. However, the formation of longitudinal planes of rupture did not resulted in achievement of ultimate strength of rock and further stresses still increased in sample. This effect is well distinguished by growth of transversal deformations, their rate from certain time sharply increased, the sample volume also increased. Such sharp volume increase cannot be attributed only to dilatancy processes, mainly this is related with formation of rupture cracks and defragmentation of sample, which was recorded by sensors of transversal deformations. Hence, study into variation of spatial deformations upon uniaxial stress state is incorrect in the frames of the considered experimental procedure.

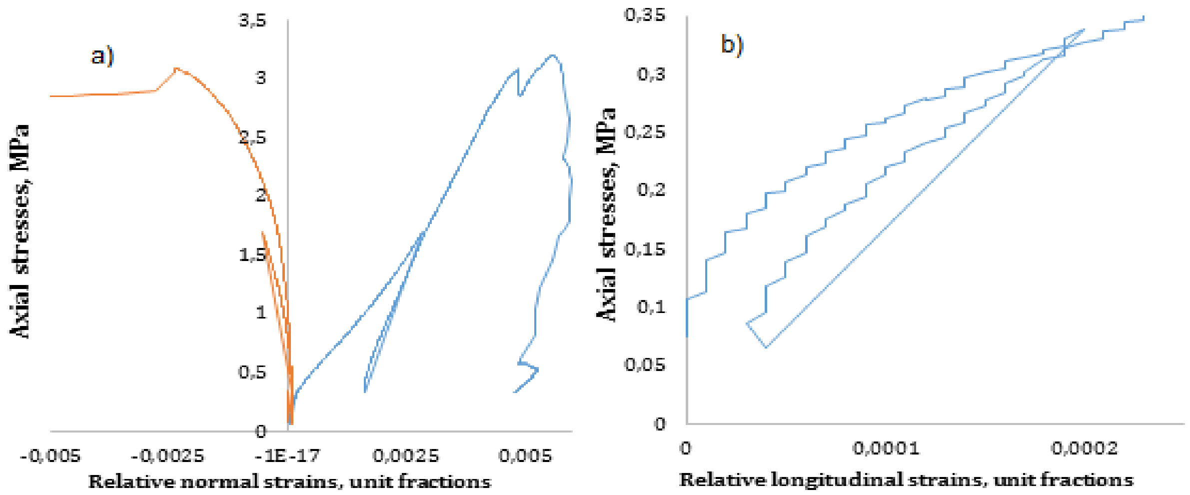

Fig. 1. Typical deformation pattern of Proterozoic clay: a – total deformation diagram; b – interaction between axial stresses and longitudinal strains in the range of minor stains

Non-linear behavior of clay was determined in the range of minor strains (Fig. 1, b), which can be conveniently presented as tangent modulus of deformation as a function of achieved longitudinal deformations (Fig. 2). The value of tangent modulus of deformation has its maximum at initial stage of deformation with its gradual decrease to constant value corresponding to the modulus of deformation at stresses equaling to 50% of ultimate strength. Such results were obtained upon testing of all 16 samples of Proterozoic clay both in perpendicular to stratification and in parallel to stratification, which confirms regularity of this effect and peculiarity of behavior of this rock. Herewith, initial value of the module of deformation differs from the modulus of deformation at 50% of ultimate strength by about 4-7 times. Limiting value of deformations, after which the tangent modulus in the range of minor deformations is not varied, equals approximately to 0.02-0.025 unit fractions. Maximum value of the initial modulus of deformation cannot be detected by local sensors of deformation, since it is beyond the accuracy range of local sensors, it should be detected by a dynamic method. Such tests were not considered in the frames of this work.

Experimental results under bulk compression

Qualitative analysis of laboratory results under conditions of volumetric compression revealed that the pattern of sample destruction does not depend on the direction of its loading. Thus, in the samples, loaded in the direction coinciding with the direction of stratification, mainly vertical rupture cracks were formed in the layers. Upon testing in perpendicular to stratification the destruction was accompanied by formation of shear cracks. In this and in that testing variants the destruction pattern was brittle. With increase in lateral pressure plastic properties of argillaceous ground became more obvious, and the destruction was more and more accompanied by development of shear cracks.

Characteristic dependences of deformation of Proterozoic clay under the conditions of uniaxial and volumetric stress state from the bottom of Bukharestskaya metro station, St. Petersburg are illustrated in Figs. 3a, b. During the tests only the value of longitudinal deformations was measured, the sensors of transversal deformations were not installed. As can be seen in the presented dependences, clearly defined anisotropy of deformation properties is observed. The modulus of deformation in parallel to stratification is higher than that in perpendicular to stratification. Anisotropy of strength properties is insignificant, it is in agreement with the results of other researchers.

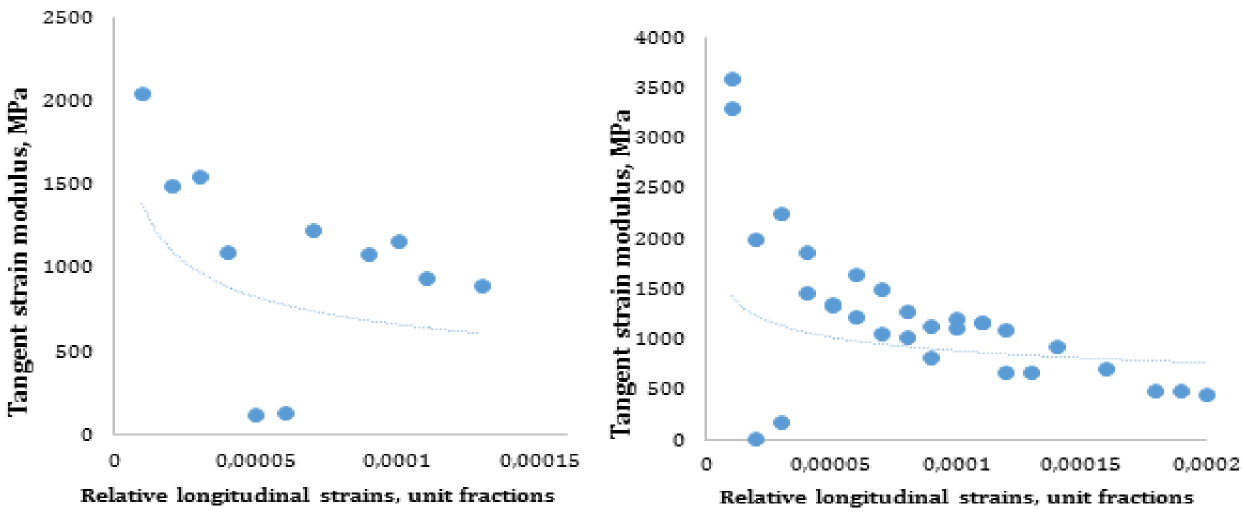

Fig. 2. Variation of tangent strain modulus of Proterozoic clay as a function of achieved value of relative longitudinal strains (typical dependences).

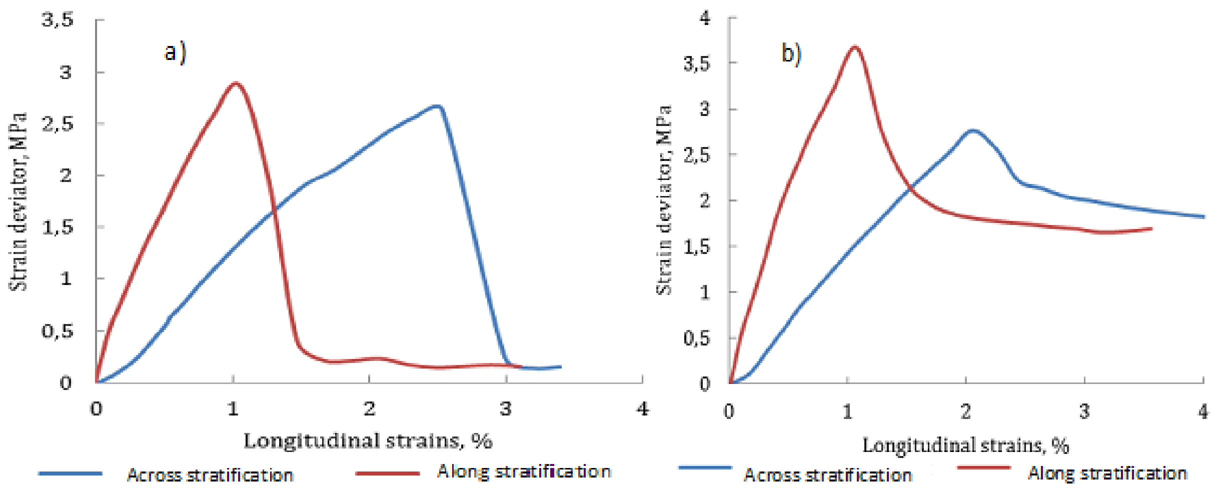

Fig. 3. Characteristic behavior of Proterozoic clay in parallel and perpendicular to stratification: a – lateral pressure $\sigma_3 = 0$; b – lateral pressure $\sigma_3 = 0.5$.

Therefore, on the basis of the performed study it is possible to arrive at the conclusion of existence of pronounced deformation mad strength anisotropy of Proterozoic clays. Difference in deformation properties along directions is more pronounced, and $E_{0\parallel}/E_{0\perp}$ as a function of lateral pressure equals to 1.6–2.62. The ratio of strenfth in longitudinal and transversal directions $C_{u\parallel}/C_{u\perp}$ is 1.08–1.37. Low amount of laboratory tests of Proterozoic clays does not allow determination of variation of the coefficient of anisotropy of deformation and strength properties as a function of type of stress state. It could be mentioned that rigidity of Proterozoic clay along stratification is higher than that in perpendicular to stratification.

More comprehensive study under volumetric compression was performed with clay samples taken from the bottom of Prospekt Slavy metro station. The tests were performed both under triaxial compression and isotropic compression. Typical deformation diagrams of Proterozoic clay upon triaxial compression are illustrated in Fig. 4.

Data processing results of tests of Proterozoic ground are presented in the form of deformation modulus as a function of minimum main stresses (Fig. 5). In the presented curves it can be seen that upon increase in stresses promoting rock compaction the deformation properties increase. This effect is characteristic both for tests in perpendicular to stratification

and for tests in parallel to stratification.
More obviously the increase in deformation properties can be observed upon testing in perpendicular to stratification. Thus, increase in minimum main stresses from 0.5 MPa to 5.0 MPa increases the modulus of deformation from 500 MPa to 1100 MPa, that is, by 2.2 times. In the considered range of variation of minimum main stresses the modulus of deformation in parallel to stratification increased by 1.35 times from 1200 MPa to 1620 MPa. Similar results were obtained upon data processing of tests with Proterozoic clay sampled from Bukharestskaya and Mezhdunarodnaya metro stations.

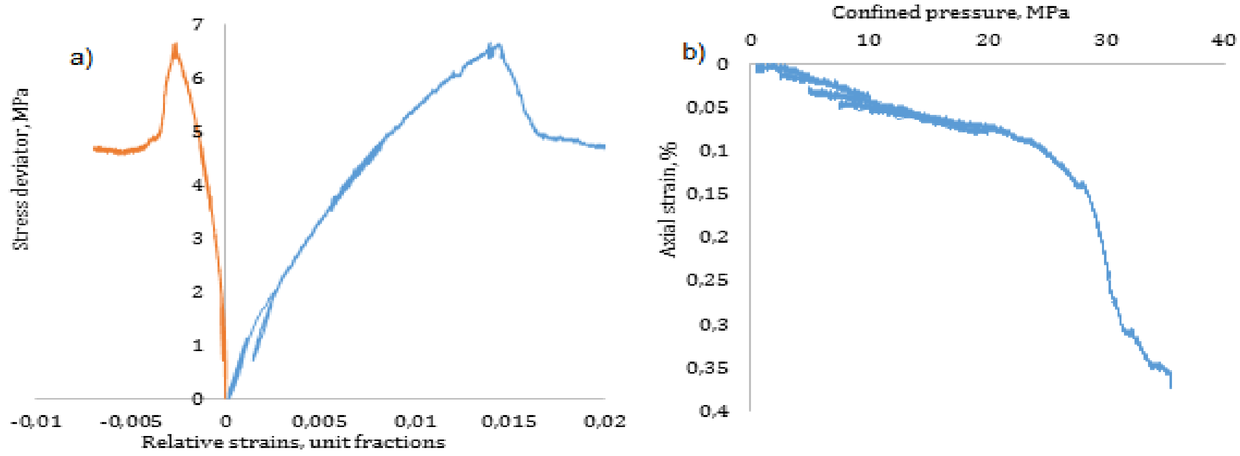

Fig. 4. Typical strain diagram of Proterozoic clay upon volumetric compression: a – triaxial compression; b – isotropic compression.

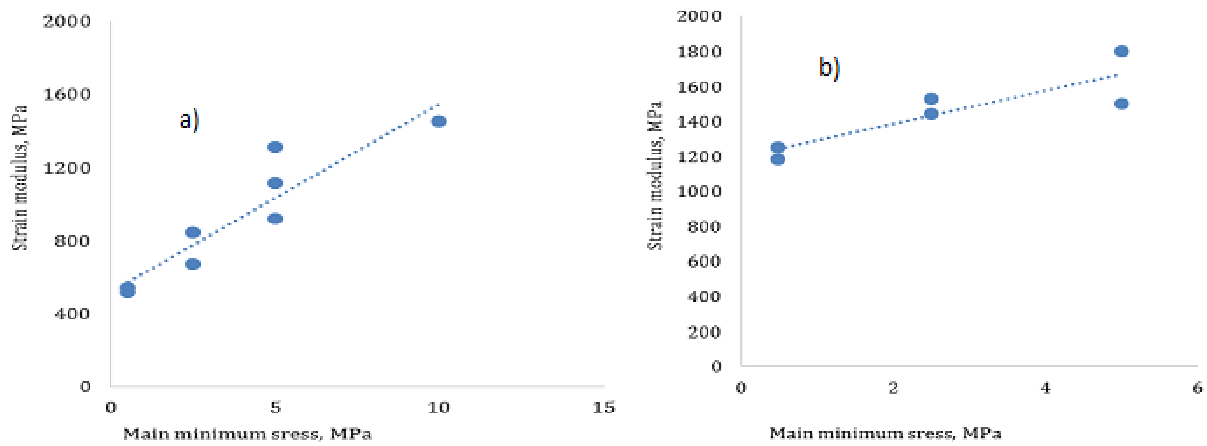

Fig. 5. Rock strain modulus as a function of confined compression ("Prospekt Slavy" Metro Station: a – tests in perpendicular to stratification; b – in parallel to stratification.

While generalizing the above results, it is possible to mention that the interrelation between the value of average stresses and the modulus of deformation of Proterozoic clays can be sufficiently well described by the following common analytical equation:

$$E_0 = E_0^{ref}\left(\frac{c\cos\varphi - \sigma_3 \sin\varphi}{c\cos\varphi + p^{ref}\sin\varphi}\right)^n, \quad (2)$$

where E_0^{ref} is the value of modulus of deformation obtained at average effective stresses of p^{ref}; c is the cohesion; φ is the angle of internal attrition; n is the exponent, which characterizes the interrelation between average stresses and the modulus of deformation. The exponent n for Proterozoic grounds in perpendicular to stratification varies from 0.70 to 0.75, and 0.30-0.35 – in parallel to stratification.
Therefore, it can be mentioned that characteristic feature to increase rigidity with increase in average stresses is also peculiar for Proterozoic clay. Parameters of analytical dependence obtained in this work should be verified in the course of further laboratory tests.

Estimation of strength of Proterozoic clay

According to testing results of Proterozoic clay by indirect methods the uniaxial tension strength of Proterozoic clay in parallel to and in perpendicular to stratification equals to 0.29 MPa and 0.64 MPa, respectively; uniaxial compression: 1.89 MPa and 3.74 MPa, respectively; and pure shear: 0.48 MPa and 1.00 MPa, respectively. Combining the results obtained by indirect methods and the results of triaxial tests, the strength certificate was obtained (Fig. 6) in perpendicular to and in parallel to stratification.

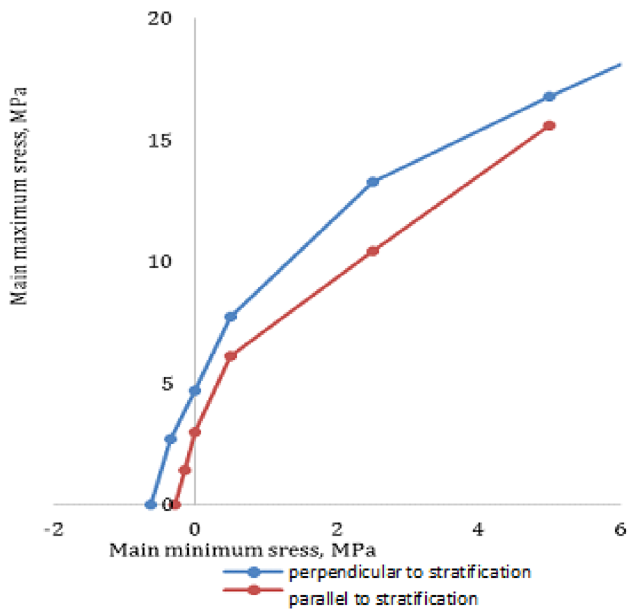

Fig. 6. Strength certificate of Proterozoic clay in the axes of main stresses (specimen taken from bottom of "Prospekt Slavy" Metro Station).

While analyzing the plotted strength curves of Proterozoic clay it could be mentioned that independent on loading direction the strength envelope is non-linear function, the interrelation between ultimate strength and active normal stresses is non-linear. The strength of Proterozoic clay in perpendicular to and in parallel to stratification is different, herewith, maximum difference in strength characterized by the coefficient of anisotropy is peculiar for action of only tension stresses, it decreases gradually with increase in normal compressing stresses. Thus, the coefficient of anisotropy of strength properties upon uniaxial compression is 2.2 and upon uniaxial compression it is 1.9. The coefficient of anisotropy of strength properties upon volumetric compression in the range of variation of main minimum stresses (confined pressure) from 0.5 MPa to 5.0 MPa varies from 1.27 to 1.08, herewith, the higher value corresponds to the lower values of minimum main stresses. That is, with increase in the value of minimum main stresses the influence of layers structure of Proterozoic clays decreases, possibly, subsequent increase in minimum main stresses would allow to consider Proterozoic clay as isotropic medium under such conditions. However, such high values of minimum main stresses are not characteristic for solution of actual tasks in forecasting of areas of limiting state in the vicinity of tunnels and underground facilities of St. Petersburg metro system.

DISCUSSION

Complex study into mechanical behavior of Proterozoic clays on laboratory scale made it possible to analyze deformation of Proterozoic clay in wide range of achieved strains and stresses. In particular, deformation dependences of Proterozoic clays have been established in the range of minor deformation, where non-linear pattern of clay deformation is observed. Similar dependences have been obtained both in perpendicular to and in parallel to stratification. The plotted diagrams of tangent modulus of deformations in the range of minor deformations as a function of achieved value of longitudinal deformations evidence its step-by-step decrease with increase in deformations, up to reaching constant value.

The performed complex of laboratory studies, including loading of clays by coaxial indentors, cleaving along generators, testing upon uniaxial and volumetric compression, made it possible to obtain strength indices of Proterozoic clay upon various types of stress state. Generalization of the obtained data enabled development of strength certificate of Proterozoic clay in parallel to and in perpendicular to its stratification. The influence of structure of Proterozoic clay on its strength properties was mentioned.

The study into deformation of Proterozoic clay under conditions of uniaxial and volumetric compression made it possible to establish the influence of minimum main stresses on its deformation properties. Thus, increase in minimum main stresses leads to increase in the Young modulus and elasticity modulus of Proterozoic clay. Herewith, this effect was observed both at initial deformation stage of Proterozoic clay and with increase in the achieved deformation.

Anisotropy of deformation properties is higher at low values of triaxial compression, it decreases gradually with increase in lateral compression. That is, while minimum main stresses increase the deformation properties of Proterozoic clay in various directions became closer and the rock transfers to isotropic pattern of deformation.

Non-linear variation of strength in the area of tension stresses and at minor values of compressing stresses leads to conclusion that destruction of Proterozoic clay in the considered stress range was caused not only by formation of shear cracks or slip planes but also by formation of planes of rupture, which is peculiar not only for rocks with microstructural fracturing or heterogeneous mineral composition, thus leading to such type of destruction. At significant values of lateral compression the main mechanism of rock destruction is formation of single or several main shear cracks. Thus, upon consideration of simulation of geomechanical processes in Proterozoic clay the surface of plastic flow of model of ground behavior should take this aspect into account.

CONCLUSIONS

This work has analyzed the requirements to laboratory results aiming at detection of mechanical properties of rocks in order to perform geomechanical calculations using up-to-date analytical methods and models of medium behavior. Peculiar features of rock (ground) deformation have been studied as well as their behavior as a function of various factors. The issues of generation of Proterozoic clays have been considered. On the basis of analysis of published work and our own experience we present analytical data on deformation and strength properties of Proterozoic clays.

It should be mentioned that layered structure of Proterozoic clay influences on all its mechanical properties. The highest anisotropy of both strength and deformation properties becomes apparent at low values of minimum main stresses, the influence of structure obviously decreases with their increase. The coefficient of anisotropy of deformation properties is higher than that of strength properties, that is, the influence of structure of Proterozoic clay in pre-limiting stage of deformation is higher than in limiting and super-limiting stages.

The obtained laboratory results make it possible to achieve more detailed information about deformation and destruction of Proterozoic clays and can be applied in investigations into its behavior, development of new or adaptation of existing equations of material state, as well as at the designing stage of underground facilities in the considered clays.

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REFERENCES

[1] Oda M. & H. Nakayama, Yield function for soil with anisotropic fabric. J. Eng. Mech. ASCE, No. 115 (1) pp. 89–104, 1989.

[2] Duveau G., Shao J.F., and J. P. Henry, Assesment of some failure criteria for strongly anisotropic geomaterials. Mech. Cohes-Frict. Mater, No. 3, pp. 1–26, 1998.

[3] Osipov Yu. B. & A. I. Vaitekunene, Anisotropy of mechanical properties of argillaceous grounds. " Inzh. Geol.," No. 4, pp. 106-112, 1979.

[4] Fursa V. M. Structural Properties of Grounds near Leningrad. Leningrad: Stroiizdat, 1975.

[5] Fursa V. M. On Investigation into Physicomechanical Propeteis of Postglacial Banded Deposits. In: Ground Science and Engineering Geology. Leningrad: Publishing House of Leningrad University, 1964.

[6] Kogan A. A. Calculated Physicomechanical Properties of Grounds. Leningrad: Stroiizdat, 1973.

[7] Kogan A. A. Physicomechanical Properties of Banded Clays of late Glacial Lakes. Gidroproekt, Proceedings, 1974.

[8] DashkoR. E. & A. A. Kagan, Mechanics of Grounds in Engineering Geological Practice. Moscow: Nedra, 1977.

[9] Lomtadze V. D. Engineering Geology. Engineering Geodynamics. Leningrad: Nedra 1977.

[10] Bugrov A. K. & A. I. Golubev, Anisotropic Grounds and Basements of Structures. St. Petersburg: Nedra, 1993.

[11] Kirkgard M.M. & P. V. Lade, Anisotropic three-dimensional behavior of a normally consolidated Clay. Can. Geotech, No. 30 (4), pp. 848–858, 1993.

[12] Abelev A. & P. V. Lade, Characterization of failure in cross-anisotropic soils. J. Eng. Mech. ASCE, No. 130 (5), pp. 599–606, 2004.

[13] Niandou H., Shao J.F., Henry J.P., and D. Fourmaintraux, Laboratory investigation of the behaviour of Tournemire shale. Int. J. RockMech. Min. Sci., No. 34 (1), pp. 3–16, 1997.

[14] Ward W. H., Samuels S.G., and E. Batler, Studies of Properties of London Clay. Geotechnique, No. 9, pp. 33-58, 1959.

[15] Barden L. The influence of Structure on Deformation and Failure in Clay Soil. Journal Engineering Geology, No. 5, pp. 159-163, 1972.

[16] Dashko R. E. Geotechnical diagnostics of basic clays of St. Petersburg region (case study of Low Cambrian formation). Rekonstr. Gorodov Geotekh. Stroit. No. 1, pp. 24-28, 2000.

[17] Podakov V. F. Study into deformation of terrain on Moscow–Petrograd direction. "Metrostroi." No. 3 – 4, 1963.

[18] Podakov V. F. Study into the Influence of Terrain Deformation on Building upon Arrangement of Metro Tunnels in Cambrian Clays. Candidate Thesis. VNIMI, Leningrad, 1969.

[19] Bezrodnyi K. P., Sil'vestrov S. N., and Yu. M. Kartashov, Peculiar features of deformation of Proterozoic clays. "Metrostroi," No. 6, pp. 16-17, 1982.

[20] Bezrodnyi K. P. “Studies into static operation peculiarities of structural elements of single-vault Metro stations in Proterozoic clays”. Candidate Thesis. Leningrad, TsNIIS, 1977.

[21] Bazhin N. P., Petrov V. A., Kartashov Yu. M., and A. I. Bazhenov, “Experimental results of study into physicomechanical properties of Cambrian clays”. Rock pressure, Displacement of rocks and Surveying Procedures: VNIMI, Proceedings. – Leningrad, Issue. LIII, pp. 49-63, 1964.

[22] Kartashov Yu. M.,. Mikheev G. V., and A. B. Fadeev, “Strength and Deformability of Rocks”., Moscow: Nedra, 1979.

[23] Zhukova A. M. “Engineering geological feasibility study of high building construction in St. Petersburg. Candidate Thesis”, St. Petersburg, Saint-Petersburg State Mining University. 2011.