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Original Research Article

MEASURING EQUIVALENT COHESION C_{EQ} OF THE FROZEN SOILS BY COMPRESSION STRENGTH USING KRIOLAB EQUIPMENT

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Abstract

Current paper presents the results of the experimental analysis on permafrost uppermost soil samples with various physical properties (moisture, porosity) tested with varied external pressure and time. The aim of this work is to test properties of the soil samples intended for the construction of buildings, railways and objects of civil infrastructure by modeled external pressure, data visualization and analysis. Variations in the soil samples were studied by analysis of the equivalent soil cohesion (C_{eq}) in frozen soil samples. Methods include integrated application of the laboratory experiments, methods of the statistical data analysis and 3D plotting performed by the selected LaTeX packages. Laboratory experiments were performed using KrioLab equipment 'Sharikovy Stamp PSH-1'. The 15 series of experiments have been tested. Models of the soil strength are graphically presented and statistically analyzed showing the results of the experiment.

Keywords: equivalent cohesion, modeling, deformation, moisture, pressure, soils, geotechnical engineering, frozen soil, mechanics, experiment, data visualization

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1. INTRODUCTION

Optimization of roads and buildings construction depends heavily on assessment of the bearing capacity of soils and their responses to the pressure across multiple tested areas in the region of construction. Therefore, study of physical and mechanical properties of soils remain challenging task due to the actuality of testing soil properties prior to the construction of buildings, infrastructure, roads and railways. Assessment of ground is especially actual for the regions of the permafrost areas with extreme climate conditions [1, 2]. In particular, the bearing capacity of the existing ground may have impact on the possibility of constructing stable roads and affect the economic value of the undertaken construction. Prior to construction works it is important to test and model primary controls on ground surface deformation and behavior of soils in various places of the study area to detected areas with low bearing capacity.

Methods of ground soil testing in engineering geology are described in the existing theoretical works [3] where various aspects of ground deformation are presented and explained. Further development of methods of testing surface ground deformation has been focused on modeling processes of the deformation properties of soft soils by testing compression strength [4, 5]. The soil capacity to resist external pressure has significant impact on the possibility of the road construction as well as on optimal methods and cost of potential construction which depend on soil deformation.

Therefore, new methods and devices for testing soil deformation and approaches to the technical geology and engineering surveys are constantly developing [6–10]. For instance, Di Matteo et al. [11] conducted four replications of the direct shear test by varied normal stresses (100, 150, 200 and 250 kPa) for 16 fine-grained soil specimens and obtained 256 pairs (44) of effective cohesion (c’) and effective friction angle (ϕ’), thus analyzing combinations of variables with geotechnical variability. These and others previously described methods present analysis of the mechanical properties of soils [12, 13] including combination of the computational and laboratory based methods for determining deformation characteristics of the soil samples [14]. Series of the investigations [15–18] presented general rules of the frost heave in finely dispersed soils, methods of heave measuring, effects of frozen soils on the quality of buildings constructed in the extreme environmental and climate conditions.

Current studies on soil deformation are largely supported by the advanced use of the information technologies (IT), programming languages and scripting. Such methods enable precise and speed data analysis, fine visualization, methods optimization through the computer-added software, machine learning techniques and development of geoscience engineering methods [19-22].

This paper examines a series of soil samples for equivalent cohesion that contains samples from the tested region using advanced computer based data analysis which assisted the laboratory based soil sampling. It presents a practical approach to evaluate correlation of the shear strength parameter C_{eq} (cohesion), obtained in shear tests. The research presented test experiments and results of the soil deformations in varies test conditions. The paper aimed to analyze the soil suitability for the road construction. Testing compressibility characteristics of the soils is important task in view of the development of northern territories and construction of infrastructure in the extreme climatic conditions.

The practical significance and importance of the present work is explained by the twofold reasons. The first aspect consists in the application of the machine learning techniques for geotechnical engineering is required for the advanced methods of data analysis. Correct and precise selection of the suitable areas for the proposed construction works ensures the safety of the roads which strongly depends on the condition of the soils. The second implication of this paper is to improve the techniques of data processing and methodology of soil testing aimed to improve our understanding and knowledge of how to test a clay frozen soil samples using sequential use of KrioLab equipment followed by LaTeX based data modeling, analysis and visualization. Advanced methods of data analysis ensure more precise and fast results on modeling which can be achieved during soil sampling and assessment and utilized in similar geotechnical studies.

Because soil samples can vary widely in composition, physical properties of the grounds may differ spatially in testing sites along the road. To achieve an improved planning of the roads constructions, areas of non-suitable soils must be avoided for the construction of stable roads. Therefore, precise assessment of soil properties is important task in geotechnical engineering. This especially concerns the extreme climate conditions [23] which require to ensure road stability and safety for industrial transportation that can be achieved through the improved methods of soil sampling and shear stress analysis. The analysis of soil properties provides data on strength characteristics of physical and mechanical properties in permafrost [24, 25].

This research is focused on the compression strength properties of frozen soils. The aim of the experiment is to determine creep deformations of the soil samples which happens during pore water dissipation and the compression stress transformation to the soil structure. Creep deformation in this experiment took place during the prolonged pressing of the ball stamp into the soil specimen, as well as the long value of the equivalent cohesion (C_{eq}). In a test series of the equivalent cohesion measurements the C_{eq} (MPa) was calculated over a period of 8 (eight) hours. The equivalent cohesion C_{eq} is a complex parameter that includes both the cohesion forces and friction and reflects the strength of the structural elements within the soil. It has been used to determine the computed values of the strength characteristics in the frozen soil samples. In this work the equivalent cohesion of the frozen soils was estimated using ball stamp method.

Soils located in the study area have high porosity, i.e. ratio of the volume of pores filled with water to the volume of heaving soil [26]. Clay soils, which include sandy loam, loam and clay, are difficult to use in geotechnical engineering and earthworks due to their water- and frost sensitivity. When frozen moisture transforms into ice and expands, it increases the volume of the soil, because clay soils well retains moisture. This process results in the frost heave, which happens as an upwards swelling of soil during freezing caused by the increased amount of ice in the soil. This brief description of the frozen soil degradation illustrates its negative impact on the road construction in the regions with frozen soils. Therefore, it is important to understand frozen soils properties and behavior not only at the point of sampling in the fieldwork but also using data modeling in the laboratory.

In this paper, two types of such soils were studied using compression method: sandy loam and loam. The compression coefficient d is the main indicator of the compressibility of ice-rich frozen soils determined by the stabilized longitudinal compression deformations of soil samples under stepwise increasing pressure. Deformation characteristics shows the process of soil compression as a result of its changes in volume. Soil compression is different from compaction, because compression excludes the possibility of lateral displacement of the soil sample. Therefore, this method has been selected for testing series of soil samples. The result from this study can be adopted to similar types of geotechnical research in cold regions with frozen soils which explains its applicability and actuality.

2. METHODS

In this work, the maximal long equivalent cohesion was measured by the immersion depth of the ball stamp in the soil sample by a given pressure (Fig. 1 and 2). The experiment temperature was set up at -5°C and lower by KrioLab equipment using available methods [27]. The ball stamp method was first proposed in 1979 and then developed in further studies [28]. This technique is very effective and remains scientifically and methodologically actual up to day. Using ball stamp method enables effectively determine the magnitude of the cohesion forces in a soil sample, assessing their variations over time. The method is effectively applicable for the viscous rocks and dispersed soils, such as loamy, silty, clayey and frozen soils aimed to measure properties of the clay soils with regard to weather and frost susceptibility. The ball stamp method has been hereto the most widely used in the assessment of the strength properties of the frozen soils. Pressure at the given soil sample at the last experiment stage is equal to the calculated soil resistance under the base of the foundation which is numerically set by the program. Statistical data processing and 3D visualization was performed in LaTeX package. Laboratory tests of the equivalent cohesion of the soil samples by the ball stamp method.

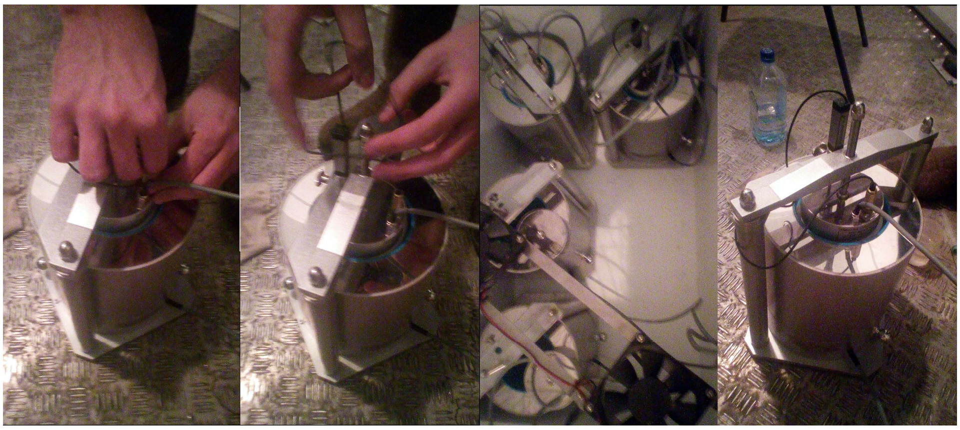


Fig. 1. Experiment setup. Container fixed in a frame (left); Placing soil sample in the lower area (center). Soil sample in cylinder (right). Photo: V.A. Lemenkov

According to the “Ball Stamp PSH-1” methodology developed by KrioLab and standards of soil measurements [29, 30], soil deformations were measured by the following parameters: 1) measured depth of the immersion of the ball stamp into the soil, which was determined at the end of the process (upon reaching the conditional stabilization of the deformation after 8 hours); 2) immediately measured soil cohesion when pressure was applied during 5-10 sec.

Because in geotechnical engineering including soil sampling practical work is often performed under varying nature conditions, methods used must be robust simulating prevailing conditions of the soils in normal environment. Following settings may vary at in situ measurements: soil particle size, water content in samples, mineral content of soil. Technical settings of this experiment were as follows. The salinity in all samples is 0 (zero). For the correctness of the experiment the temperature was taken at 3.7°C which allowed to determine the correlation in equivalent cohesion with density and humidity of soil samples. After data sampling in ‘Ball Stamp PSH-1’ by KrioLab, the statistical analysis of the tested data and graphical visualization were carried out using LaTeX markup language. The statistical analysis has been employed to evaluate and visualize different soil behavior at treatment experiments in the laboratory for various soil samples. The TikZ library provided coordinate transformation styles for 3D plots defining 3D frames to plot in TikZ as demonstrated (Fig. 3 and 4). The tikz-3dplot provided efficient tool to draw the 3D coordinate system as variable of the three components enabling to draw diagrams and plots (Fig. 3 and Fig. 4).

Fig. 2. Soil samples after the experimental test. Photo: V.A. Lemenkov

In order to design a high-quality experiment, the controlling factors for the soil settings should be defined. Therefore, the preliminary experimental planning has been defined and performed as important step for the quality of the experiment. Preliminary research step included sampling of the undisturbed soil which was clipped out of the vertical slice of the soil monolith by cutting ring method using cylindrical shape. Then testing device equipment was used with samples placed in the freezer. The 15 tests of the soil samples have been tested in total. Each test included a set of measurements of the equivalent cohesion (MPa): standard (C_{eq}.8n), maximum (C_{eq}.8max) and minimum (C_{eq}.8min). During these tests, the conditions were determined as follows: pressure at the given soil sample at the first loading stage is equal to the pressure by its own weight at the sampling horizon. The experiments have been performed using general principles of the experimental design in geotechnical engineering.

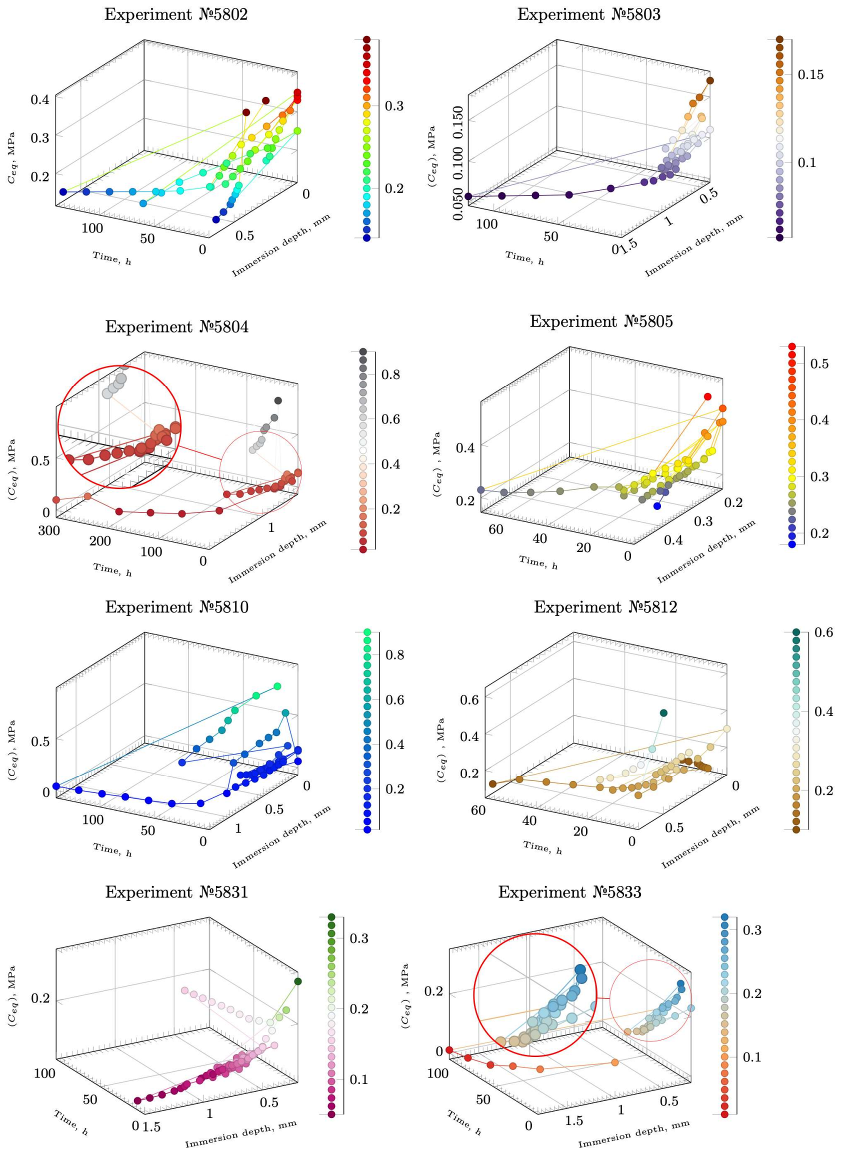
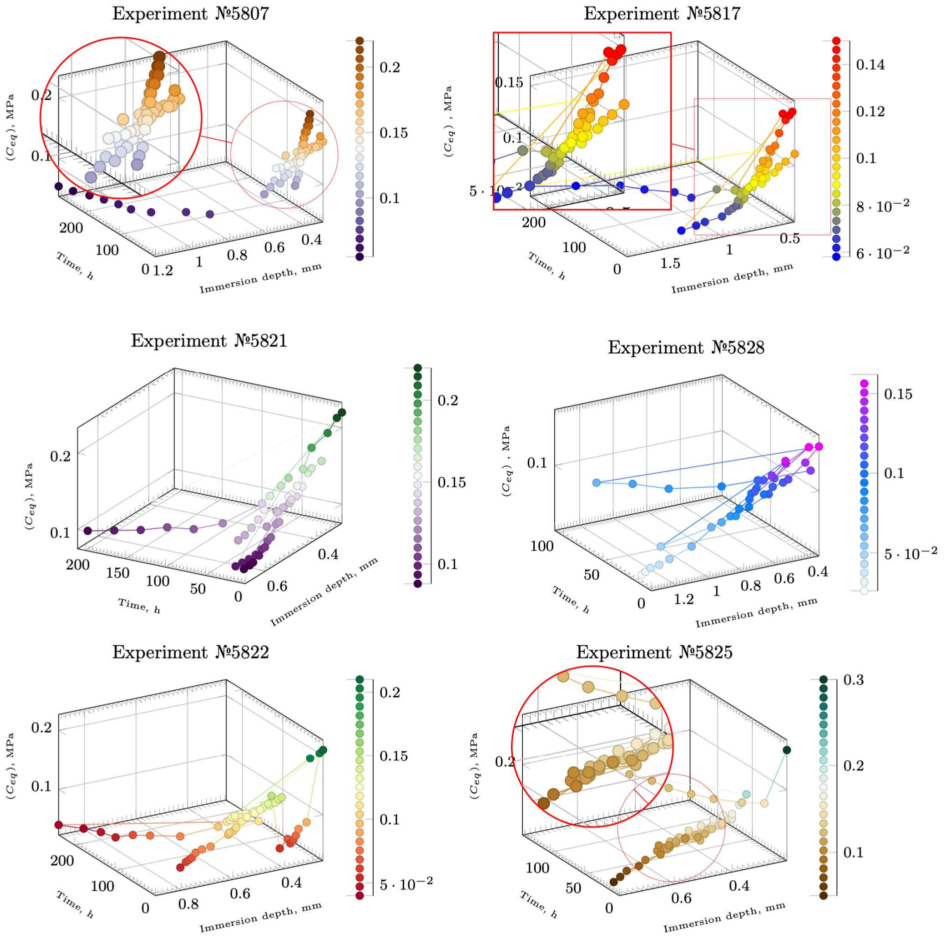


Fig. 3. Time series analysis of the variations of the long-term equivalent cohesion of soils (C_{eq}) in increasing immersion depth of samples. Series-II (№1-8). 3D visualization: LaTeX. Source: authors

These include i) replication; ii) randomization; iii) blocking [31, 32]


Experiment №5807

Experiment №5817

Experiment №5821

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Experiment №5825

Fig. 4. Time series analysis of the variations of the long-term equivalent cohesion of soils (C_{eq}) in increasing depth of the samples. Enlarged: graphs of the 8-hours equivalent cohesion of soils. Series-II (№9-16). 3D: visualization: LaTeX. Source: authors

Replication defines the amount of tested soil specimens treated using identical procedures (here: 15 specimen replicates of soil tests). Randomization is a crucial statistical parameter to data modeling and simulating, which controls random data distribution (here: randomly taken soil species to ensure their statistical independence). Blocking is a technique achieved through selecting a homogeneous set of material to make a representative block of the soil portion

3. RESULTS

Dry hard soil with high density (1.85 g/cm^3) and low humidity (29.4%) has equivalent cohesion in range of 0.115–0.132. The drying of the soil resulted in changes in the soil structure in case of the clay-size fraction of the soil. One of these effects is caused by the very low water contents and the lack of water which makes the soil cohesion low [33]. Loose moist soil with low density (1.65 g/cm^3) and high humidity (49.3%) demonstrated equivalent cohesion fluctuating between the 0.163–0.082. Hence, here the cohesion process is intense. The accuracy index (ρ_α) varies within the following values: from 0.06 to 0.40 with an average value of 1.11

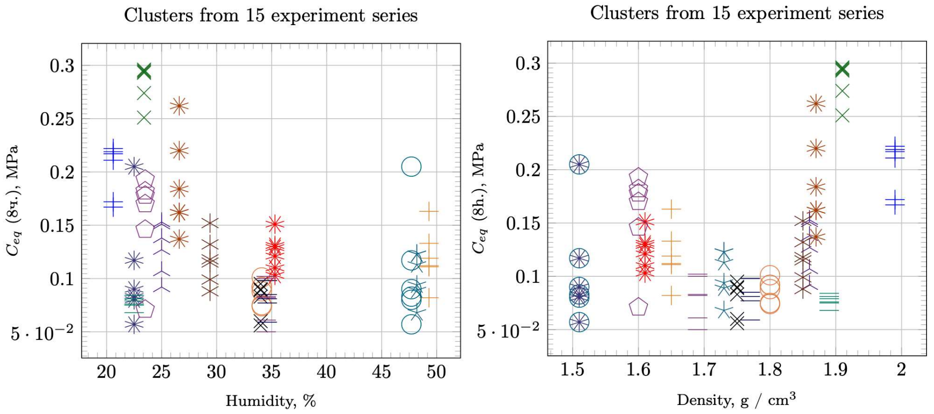

Fig. 5. Scatter plot of the variations of the 8-hours equivalent cohesion of soil samples under changed humidity (left) and density (right) conditions. Source: authors

The reliability coefficient for soil (γ_g) was set up depending on the variability of the strength characteristics when calculating following values: equivalent cohesion and tensile strength on the uniaxial compression of soils [34], soil density, number of determinations (in this case: 6), confidence values ($\alpha = 0.9$) and varied in the following values: 1.11; 1.20; 1.05; 1.18; 1.21, 1.24; 1.17; 1.12; 1.18, 1.22; 1.26; 1.66; 1.06 and 1.30. Ultimate tensile strength is the maximum stress that a soil sample can withstand during the experimental pressure. The tensile test was performed in connection to the test series with aim to test how the time of pressure affected the certain type of soil, that is, to record the engineering stress against strain. For other soil characteristics, confidence value is assumed to be 1.0, since a value within 1.0 is acceptable depending on the nature of strength characteristics, which indicates the reliability of the experiments by 'Ball Stamp PSH-1'. According to the results of the experiments, the equivalent cohesion in soil samples largely depends on the temperature of the soil and the time duration of the pressure (Fig. 3 and Fig. 4)

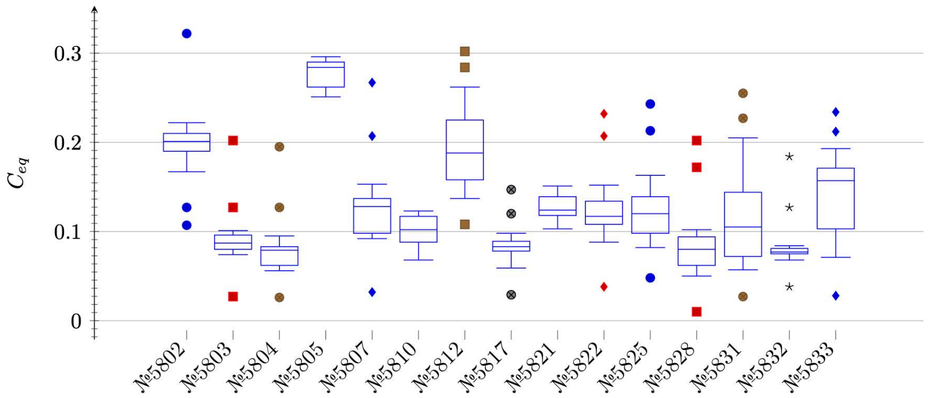

Fig. 6. Statistical boxplot of the variations of distributions for the 8-hours equivalent cohesion of the soil samples in 15 experimental sets (C_{eq}). Source: authors

The values of the equivalent cohesion of the frozen soil C_{eq}, MPa, were determined with an accuracy of 0.01 MPa according to the formula [35]:

$$C_{eq} = 0.06k \cdot \left(\frac{F}{dbSb} \right) \tag{3.1}$$

where following abbreviations are used:
F – pressure on the ball stamp, kH;
d – diameter of a ball stamp, cm;
S – immersion depth of the ball stamp in the soil at the end of the test, cm;
k – dimensionless coefficient equal to 1 when tested until conditionally stabilized deformation and 0.8 by accelerated (speed-up) regime.

The equivalent cohesion calculated by the eight-hour pressure (8-hour equivalent cohesion) exceeded values received by the long-term pressure by 1.4 times. For example, according to the test results, text No. 5804, (C_{eq}.8r) with 0.066MPa versus (C_{eq}.dlr): 0.046MPa; test result No. 585, (C_{eq}.8p): 0.269MPa versus (C_{eq}.dlr): 0.223MPa; test results No. 587, (C_{eq}.8p): 0.109MPa versus (C_{eq}.dlr): 0.071MPa, etc. (Fig. 3 and Fig. 4).

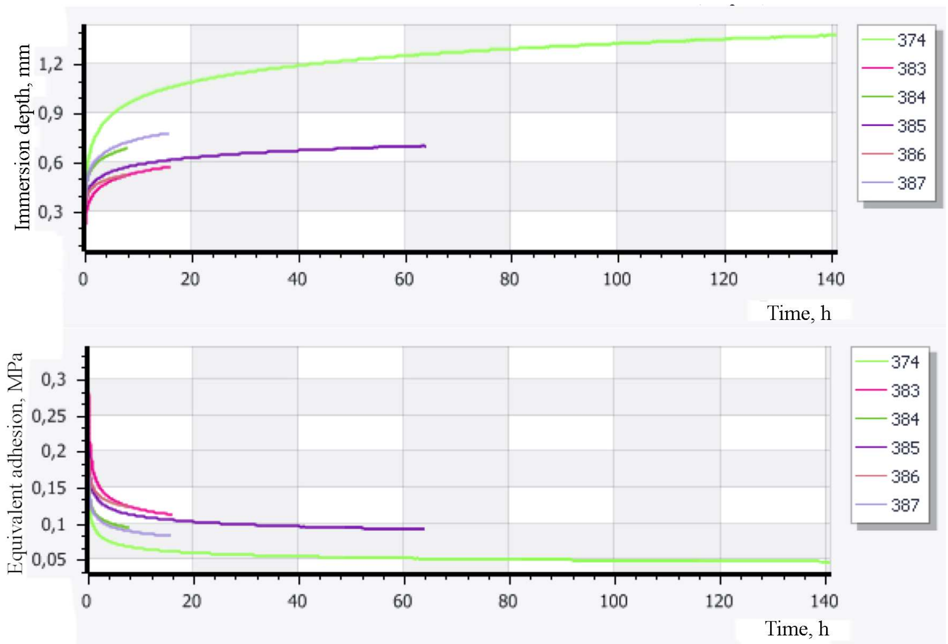

Fig. 7. Plot of the variations of the equivalent cohesion and Immersion depth over the time of the experiment, Visualization: “Ball Stamp PSH-1” by KrioLab, ball stamp method. Source: authors

In Fig. 5 the equivalent cohesion (C_{eq}) of the tested sample soils is plotted against the humidity (moisture content) and density of the samples. The results show that there is a clear difference between the density and cohesion in the tested soil. For a moisture content of 25% the soil has an equivalent cohesion of approximately 0.3 MPa whereas the humidity of soils at 35% has a cohesion of ca. 1.5 MPa (Fig. 5).

Furthermore, the correlation between the immersion depth of the soil sample and the test time demonstrated following results. Logarithmic curve reaches its peak (i.e., maximum immersion depth of the soil: 1.00 mm) at 24-30 hours from the start of the experiment. Afterwards soil gradually starts sinking, but the speed of immersion is significantly slower (Fig. 3. and Fig. 4). Thus, the optimal time for the experiment to receive representative values of the soil deformations is determined as 24-48 hours. The observed behavior of the soil samples will not change significantly by longer experiment, so the period of 24-48 hours for the experiment is recommended as proved and tested. A total of 47 tests were conducted of which 15 were representative and visualized (Fig. 3 and 4).

Table 1. The results of experimental tests of frozen soil sampling and computer calculations, “Ball Stamp PSH-1” by KrioLab. Source: authors

Statistical processing of tests by ball stamp No 5810	
Number of Completed Definitions	6
The number of definitions in the calculation (n)	6
Standard equivalent clutch ($C_{eq.8n}$)	0.102MPa
Maximum Equivalent Grip ($C_{eq.8max}$)	0.123MPa
Minimum equivalent clutch ($C_{eq.8min}$)	0.068MPa
Confidence Probability (α)	0.95
Statistical Criterion (ν)	2.07
Unbiased standard deviation (S)	0.02
Coefficient of Variation (V)	0.22
Accuracy Rate (ρ_α)	0.17
Reliability Ratio for Soil (γ_g)	1.21
Estimated Eight-Hour Equivalent Coupling ($C_{eq.8r}$)	0.084MPa
Transition Coefficient (K)	0.76
Estimated Continuous Equivalent Grip ($C_{eq.dl}$)	0.064MPa

Frozen soil was tested with a ball stamp to determine the deformation of the clay soils with organic matter content of less than 10%. Samples of frozen soil of the undisturbed composition with natural humidity and ice content have been used. The thickness of the ice layers in the samples was <2 mm, ice content <0.4 mm. The impact of the testing time on the equivalent soil cohesion is visualized on Fig. 3 and Fig. 4 and can be summarized as follows: the equivalent cohesion decreases sharply along with increase of the experiment duration. Hereby the peak of a sharp decrease in the values of the equivalent cohesion from 0.25 to 0.1 MPa is reached at 24 hours after the start of the experiment. After that the value of the equivalent cohesion decreases only insignificantly. The plot in Fig. 7 shows the decreased equivalent cohesion and increased immersion depth over the time of the experiment using ball stamp method which shows the significant difference for the period of 10 hours. The graph further shows that there is no major difference in equivalent cohesion for the clay soils stabilized after 20 hours of experimental time processing.

The calculated indicators, such as number of the laboratory tests, sample origins, depth, temperature, humidity, density and salinity are illustrated in Fig. 7. Technical settings of the experiment are presented in Tab. 1. The impact of humidity and density on the soil samples as important factors in the deformation of the clay soils is visualized in Fig. 5. The plot shows variations in changes in the soil density and moisture characteristics during the experiment for each cluster of the sample groups. The results of the experimental measurement revealed following pattern. To a large extent, the value of the pressure depended on the soil temperature as well as the duration and value of the pressure: $C_{eq}=f(T, t, P)$ as the equivalent cohesion is a function depending on values of temperature, pressure and density of the soil samples. Because the temperature was set as constant in this series of experiment, the results shown correlation of the equivalent cohesion with soil density, humidity and pressure over time.

As can be seen from Fig. 5, in most cases, variability in density of soil samples during its dehydration is <0.03 g/cm^3 which corresponds to the 2% of its density (the accuracy of density measurement is ± 0.01 g/cm^3). Besides, changes in density of the sample mass caused by soil shrinkage gradually increases with the decreasing humidity reflecting the decline in soil moisture content. The time series of the performed tests of 8-hour and long-term equivalent cohesion are presented in Fig. 3 and Fig. 4. The statistical boxplot of the variations in distributions of the 8-hours equivalent cohesion of the soil samples in 15 experimental sets (C_{eq}) is presented on Fig. 6.

The analysis of the time series includes the decomposition of the experiment series into three components: i) general trend; ii) seasonality effect; iii) random component. Since the tests have been carried out during the time period of less than 300 hours, the effect of seasonality was excluded as an unnecessary factor n this particular case. The depth for all measurements has been taken as 3,9 m. The temperature is set as -3,7°C, humidity is 48,2%, density is 1,73g/cm^3, salinity is 0,0, Well No ZP44-2, Lab No 05810. C_{eq} (MPa) for the measurements shown on Fig. 7 are as follows: experiment No. 374 – 0,068, No. 383 –0,123, No. 384 – 0,094, No. 385 – 0,113, No. 386 – 0,123, No. 387 – 0,089. In this research, the long-term equivalent cohesion coefficient was determined by the immersion depth of the ball stamp into the soil sample by a given load pressure at a test temperature -3,7°C.

Therefore, the presented work analyzed the general trend of the soil behavior under the impact of the external pressure. With the removal of trend component, the residual noise was obvious. After the noise data were excluded, the periodic component in the model of soil behavior under varied pressure over time was assessed. The results of the statistical data processing by the computed-based methods have been presented in Fig. 3 – 7. In particular, a diagram of the one-dimensional distribution of the statistical probabilities by clusters of sample series from 15 measurements determining 8-hour and long equivalent cohesion is presented, respectively. The impact factors affecting equivalent soil cohesion are determined and the statistical models of the C_{eq} soil samples are plotted.

4. DISCUSSION

The compression strength tests in this study have been performed on clay soil sample specimens. The accuracy of the tests has been checked by the following indicators. The confidence probability in all experimental tests is $\alpha=0.9$, which proves the accuracy and reliability of the experiments. Since the concept of confidence probabilities follows from the principle that unlikely events are considered almost impossible, and events whose probability is close to 1 are taken as almost reliable, the probabilities P1=0.95, P2=0.99, P3=0.999 are used as confidence probabilities.

Certain probability values correspond to the significance levels, which are taken as the difference in the formula $\alpha=1-P$ where the α-value is an index of the reliability of a result. In this case, a probability of 0.95 corresponds to the significance level of α1=0.05 (5%), a probability of 0.99–α2=0.01 (1%), a probability of 0.999–α3=0.001 (0.1%), which proves the accuracy of the tests. Here the higher the probability, the higher is the expectation that the observed relation between soil properties and measured variables in the sample is a reliable indicator of the reaction on external pressure as a relation between the variables and settings in the soil sampling. The statistical criterion for the tests performed is $\nu=2.07$; unbiased standard deviation (S): 0.01–0.05; coefficient of variation (V): 0.06–0.26. Accuracy Index (ρ_α): 0.05–0.21; soil reliability coefficient (γ_g) ranged from 1.05 to 1.24.

The analysis of the obtained results indicated that patterns of curves are varying in the equivalent cohesion of the assessed soil samples with increasing moisture and period of pressure on the given sample varies for different clusters of soil sample series. This is explained both by varied environmental conditions and by the differed duration of the formation of structural connections in the clay soils. It is also possible that in this case the effect of various additional factors takes place: type of structure in the soil samples, number and strength of elements in the soil structure which are different in nature for various soil types [36] caused by environmental conditions affecting their physical and mechanical settings.

Analyzing the correlation between the equivalent cohesion of the soil samples and its physical and mechanical properties (density and humidity), following conclusions are obvious (Fig. 5). The density of the soil mass is statistically the most significant factor, since this parameter takes into account the type of internal contacts between the soil elements, pore volumes and voids. Moreover, the void ratio for the compacted soil specimens directly affects the shear strength of soils.

Certain difference exist for the coarse and fine-grained clay soils regarding the pore volumes pressure reaction from the compaction and pressure.

Thus, for coarse soils there are no significance with pore pressure during soil compaction, due to the high air and water permeability of the soil. However, in a fine-grained moist clay soil, compaction is gradually compensated by the pore pressure till the reached limits of densification of the soils. In turn, the mechanical properties of soil such as pore volumes and voids, affect their physical characteristics. Lesser influence of the humidity on the variations in the equivalent cohesion can be explained by the fact that all moisture values lie in the range from the maximal hygroscopic to the maximal molecular moisture capacity [37], while it is exactly in this interval that the humidity has relatively small effect on the physical and mechanical properties of the soil.

The performed experiments have been made on the weak loams using ball stamp method. As a special feature of the experiment was the fact that during iterated samplings with the same sample data for 5-10 minutes at the beginning of the test, there were observed significant differences in the results of the equivalent cohesion at different points of the frozen samples. However, during the experiment, the discrepancies gradually leveled, and in most cases the final results of the long-term strength were identical. The disadvantage of the ball stamp method is that soil strength is determined only at the place of the pressure application. The results were improved when the sample was tested at several points, that is, in this case, there was observed certain subjectivity factor in technical capabilities of the 'Ball Stamp PSH-1' hard/software.

The presented experiments can be successfully used and re-applied in other cases to determine the long-term strength of the frozen soils in further similar research using example of the experimental series and methodology presented in this work. The analysis of the correlation between physical and mechanical properties of soils and their resistance towards deformations is effective for a large number of samples of different soil species. An approach for inverse problem can also be tested: interpreting data response to the strength for modelling soil structure in technical engineering works of soil testing prior to the road construction

5. CONCLUSION

With integrated use of advanced data analysis and developed technical tools of soil sampling it is possible to predict and verify the properties of the clay fine-grained soil and assess the suitability of the region for road construction. The paper presented the results of a series of the experimental tests on soil shear stress and deformation depending on frozen soil properties. It revealed the correlation between the indicators of the deformation and external factors (such as humidity, density, immersion depth) of the clay soil by laboratory engineering methods of the geotechnical sampling and statistical data modeling. The data visualization was made using selected packages of LaTeX, a high-level macro language. The experiments demonstrated that increasing humidity affects the cohesion of the contacts of the individual soil particles which are constantly decreasing. It can be explained by the continuously decreasing rigidity of pores of the soil and soil aggregation.

The actuality of this study is explained by the geotechnical needs for soil testing prior to road construction planning. The analysis of the soil compaction is essential for engineering construction works. The content of the compacted water in soils must be within an acceptable range in order to have the capacity of resistance to external pressure. Besides, the densification of the fine-grained soils should overcome the cohesion of soil [38]. Using LaTeX macro language presented an effective method of data visualization, as shown in this paper. Various plotting commands were used to visualize facetted plot by spherical polar coordinates with three variables (equivalent cohesion, immersion depth and time). Coordinate transformation commands allowed calculation of a coordinate in 3D view depending on three variables in one frame based on its values in another frame. Presented advanced method of data visualization can be re-used for visualizing bearing capacity for the displacement in soils under pressure. Applying high level tools for data modeling and visualization is a key tool for assessment of the soils acceptability for road construction using criteria of resistivity of soil strength to the pressure.

The importance of the undertaken research is explained by the necessity of the civil engineering geotechnical works for constructing infrastructure and roads, as also well demonstrated in various geotechnical research [39–43] and papers on statistical analysis application in geosciences [44–50]. The soil acceptability for construction can be defined using various criteria: water content, compaction, shear strength, degree of saturation, to mention a few of them. Compared to other types of soil, frozen soil is more sensitive to the climate and environmental effects and difficult to use in the construction which explained the need for advanced methods of soil analysis, testing and modeling. The susceptibility of the frozen soil towards temperature fluctuation is one of the major concern in road construction due to its adverse effect on the long-term functionality of roads and railways. The question of measurements of frozen soils remains challenging as discussed in literature [51–53]. Further reading on geotechnical tests of the shear strength and deformation of soils types is given in publications [54–66].

To conclude, demonstrated research is made using combination of methods that included use of standard geological equipment (by KrioLab), methods of data analysis and 3D computer-based data visualization showing results of modeling. The integration of the KrioLab technical equipment for soil testing with high-level LaTeX language for consequent data modeling has been proven to be efficient and accurate methodological workflow for soil testing as a tool for evaluating its acceptability for road construction. The application of various approaches and methods enables effective workflow designed for the soil studies, enabling reliable and proper assessment of the physical-mechanical properties of soils. Besides, it facilitates decisions on the suitability of various soil types for possible construction of roads and buildings in cold conditions.

To summarize, the values of the strain in tested soil samples were determined using ball stamp method (long and 8-hour indentation). According to the received results on soil deformation and the dynamics of its change, temporal variations in the equivalent cohesion of the soil samples were calculated. Correlations of the equivalent cohesion with soil density and humidity were determined, modeled and visualized. The presented study shown experimental tests of soil deformations and its dependence with humidity. Correlations between the physical and mechanical parameters of the soil settings and deformation of samples are visualized in view of a time series as 3D plots. Additional soil characteristics are calculated, modeled and analyzed. The presented method is applicable in geotechnical studies on frozen soil testing

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