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II. SMART CITIES, ROADS AND RAILWAYS
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ANALYSIS OF PHYSICAL AND MECHANICAL SOIL PROPERTIES DETERMINED USING PROBING DATA INTERPRETATIONS

Endijs VIRSIS*, Ainars PAEGLITIS

Department of Roads and Bridges, Faculty of Civil Engineering,
Riga Technical University, Riga, Latvia

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Abstract. Road design is a complex, time-consuming, and very responsible process. To develop a high-quality and viable road project, it is very important to start with an accurate geological investigation. In situ tests can provide a number of advantages over the traditional drilling, sampling and laboratory testing approach used in many geotechnical projects. However, like all tests, in situ tests also have a number of limitations. Although all probing methods are similar, each of them gives slightly different results. The aim of this work was to analyse and compare the interpretation results of soil layer physical-mechanical properties obtained with different in-situ test methods and to find out how the obtained results affect the development of constructive solutions from the safety point of view.

Keywords: Roads, road construction, soil properties, geotechnical investigation, static cone penetration test, dilatometric test, dynamic cone penetration test.

JEL Classification: L74, L92, Q24, Q26, R40, R41, R42.

Introduction

Geotechnical testing is conducted by site characterization, laboratory testing, and professional interpretation of data obtained to complete the design and construction of the site improvement. In situ testing methods include penetration tests such as Standard Penetration Tests, which penetrate via drilling, percussion-based investigation techniques, sonic vibratory drilling methods, and various static direct push Cone Penetrometer Testing (Vertek Team, 2021).

In situ testing provides the advantages of generating a more accurate assessment of subsurface conditions allowing for better data analysis and informed geotechnical design. The right test should be specified for the right situation or utilizing multiple tools to develop an accurate assessment of the subsurface strata. Understanding the different types of testing methods available and the advantages of each can significantly reduce uncertainties and future construction (Vertek Team, 2021).

Several studies have been performed in recent years comparing the correlations between Cone Penetration Test [CPT], Flat Dilatometer Test [DMT] and Dynamic Cone Penetration [DCP] tests (Poenaru, 2016; Grabar et al.,2022; Nepelski, 2019; Mulabdic, 2013; Zawrzykraj et al., 2017; Rabarijoely, 2018; McNulty & Harney, 2014; Robertson, 2009a; Benz-Navarrete, 2020; Schnaid et al., 2017).

Krzysztof Nepelski (2019) analysed the building – subsoil interaction. In his research he concluded, that DMT test interpretations showed higher constrained modulus of soil layers than CPT test interpretations. The same conclusion was made by Alexandru Poenaru (2016). The results of his investigation determined that DMT showed a stiffer response of the soil compared with the values obtained by laboratory investigations and CPT interpretations. McNulty and Harney (2014) in their research concluded that the DMT, not the CPT, should be used to estimate soil layer constrained modulus and be used for settlement design analyses. Mensur Mulabdic (2013) in his research compared CPT and DMT test interpretation results. He concluded that CPT and DMT tests showed remarkable repeatability and proved to be valuable aid in characterizing embankment quality, both in terms of inhomogeneity and physical and mechanical properties. In his investigation he determined that modulus of constrained deformation from oedometer (on submerged specimens) was much smaller than from CPT interpretation or even lower if compared to DMT standard interpretation values (performed on clay layers that were not submerged). In early 2022, a study on the correlation between CPT and DMT tests was published

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* Corresponding author. E-mail: *endijs.virsis@rtu.lv*

(Grabar et al., 2022). It was determined, that the general overlap of the constrained modulus was better at lower OCR values and in homogeneous soil intervals. In soil intervals with higher OCR values DMT test showed higher constrained modulus values. Miguel Angel Benz-Navarrete (2020) developed a linear model to predict qc CPT values from measurements of qd made with Panda DCP. Model is reliable if skin friction along the rods isn't detected during the test.

Taking into account all of previous researches and the relationship of small numbers of studies on the intercorrelations of DCP and other research methods it is clear that there are still many unknowns affecting the physical and mechanical soil properties determined using interpretations of DMT, CPT and DCP methods.

1. Objectives

Before the design of the project solutions, a geotechnical investigation is performed to ensure high-quality and safe solutions. Depending on the complexity and importance of the object, it is very important to choose the right research methods. Probing studies are used to determine the physical and mechanical properties of soil layers. Different test procedure, necessary equipment and obtained data interpretation formulas / approaches have been developed for each geotechnical probing investigation method.

The aim of this work was to analyse and compare the interpretation results of soil layer physical-mechanical properties obtained with different in-situ test methods and to find out how the obtained results affect the development of constructive solutions from the safety point of view. As part of this work a test area was created, field test studies were carried out and data of geotechnical research were analysed.

2. In-situ test methods

In situ tests can provide a number of advantages over the traditional drilling, sampling and laboratory testing approach used in many geotechnical projects. However, like all tests, in situ tests also have a number of limitations. It is important that engineers understand both the advantages and the limitations of in situ tests. In order to correctly use the results obtained from in situ tests, the understanding of limitations is important. Limitations of in situ test include – 1) boundary conditions are poorly defined; 2) drainage conditions are unknown; 3) the level of soil disturbance is unknown; 4) strain rates are usually higher than in laboratory tests; 5) the specific nature of soil being tested is unknown; 6) effect of environmental changes on soil behavior are difficult to assess (Lutenegger, 2021).

The cone penetration test has been in use for over 40 years. The CPT has major advantages over traditional methods, such as drilling and sampling, because it is fast, repeatable and economical. In addition, it provides near-continuous data and has a strong theoretical background (Robertson, 2009b). Many empirical and theoretical interpretation methods are broadly accepted and used in practice. These approaches tend to consider whether the cone penetration is drained or undrained, and then will consider the soil as either "sand" or "clay," respectively. Most fundamental research into the CPT and its interpretation considers penetration through sands or clays separately and includes verification tests in materials with close to ideal sand or clay behavior (Been et al., 2010).

The Flat Dilatometer Test is an in-situ testing method used to determine the strength and deformation characteristics of fine-grained soils. Test is performed by using a dilatometric, which operates on the principle of verification of values by using the displacements of the inductive sensors (with a sensitivity of up to 0.001 mm). The advantage of these tests is a more accurate description of the displacement and deformation of foundation soil. The corrected DMT results are used to obtain information on soil stratigraphy, in situ state of stress, shear strength and deformation properties (Marchetti, 2022). The Flat Dilatometer Test (DMT) is a push-in type in situ test quick, simple, economical, highly reproducible. It is executable with a variety of field equipment. It provides estimates of various design parameters/information (M, cu, soil stratigraphy, deposit history). One of the most fitting applications is investigating the in-situ soil compressibility for settlements prediction (TC16 DMT Report, 2001).

The dynamic cone penetration test was developed by Scala (1956). The current model was developed by the Transvaal Roads Department in South Africa. The mechanics of the DCP shows features of both the CPT and SPT. The DCP is performed by dropping a hammer from a certain fall height measuring penetration depth per blow for a certain depth. Therefore, it is quite similar to the procedure of obtaining the blow count N using the soil sampler in the SPT. In the DCP, however, a cone is used to obtain the penetration depth instead of using the split spoon soil sampler. In this respect, there is some resemblance with the CPT in the fact that both tests create a cavity during penetration and generate a cavity expansion resistance (Salgado & Yoon, 2003). Many empirical and theoretical DCP interpretation methods are broadly accepted and used in practice. These approaches tend to consider whether the cone penetration is drained or undrained, and then will consider the soil as either "sand" or "clay," respectively. Geotechnical engineer needs to choose the best fit correlation method/formula taking into account the litho types actually encountered. Results of correlations for cohesionless terrains are certainly more reliable than those for cohesive ones as these latter ones are influenced by drainage to a greater extent, while the rapid test occurs in saturated state with consequent lesser reliability (Salgado & Yoon, 2003).

3. Comparison of in-situ test methods using geotechnical investigation data

During the development of road, building or other structure reconstruction or construction projects geotechnical investigation of the existing soil is always performed. Depending on the road category and the traffic intensity of the vehicles, the design task defines the minimum requirements for geotechnical investigation, which includes soil drilling, various soil in situ tests, static loading plate, laboratory tests of soil samples and other studies.

As part of the research, a test field was prepared and different in-situ test methods (CPT, DMT, DCP – light, medium and super heavy) were duplicated at five points. In addition to field studies, several odometer and direct shear laboratory tests were performed. The obtained results were compared with the interpreted soil properties during the research.

The soil is a material characterized by high heterogeneity and variability of its parameters. In order to provide a safe, economic and environmentally friendly design, the main parameters, obtained from Geotechnical research, were compared, in order to evaluate the reliability of each investigation. The overall data analysis was used as input data for a geotechnical model.

Based on published relationships, several calculated, correlated soil parameters were determined as part of the data interpretation. The published correlations are generally based on a combination of theoretical and semi-empirical concepts. The interpretation methods of constrained modulus and related parameters are presented in Table 1.

Table 1. Interpretation methods used

Parameter		CPT	DMT	DCP
Constrained modulus	M	Robertson (2009a, b)	S. Marchetti (1980)	Stroud
Undrained shear strength	Su	Moon (2018)	S. Marchetti (1980)	Schmertmann (1975)
Friction angle	Φ	Mayne (2006)	S. Marchetti (1980)	Sowers (1961)
Unit weight	γ	Robertson (2009a, b)	Marchetti, S. and Crapps, D. K. (1981)	Meyerhof (1956)

3.1. The interpretations of the results obtained in the study points

The interpretations of the results obtained in the first study point are summarized and plotted to make the comparison of soil parameters easy to understand, see Figure 1–4.

Comparing the obtained results, it can be seen that the research of the CPT shows highest strength values of constrained modulus. In sand soils CPT values are on

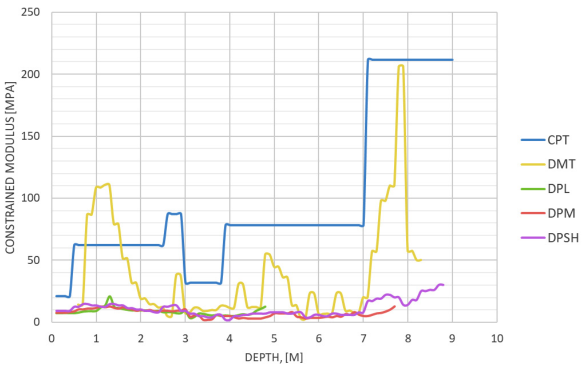


Figure 1. Constrained modulus in the first study point

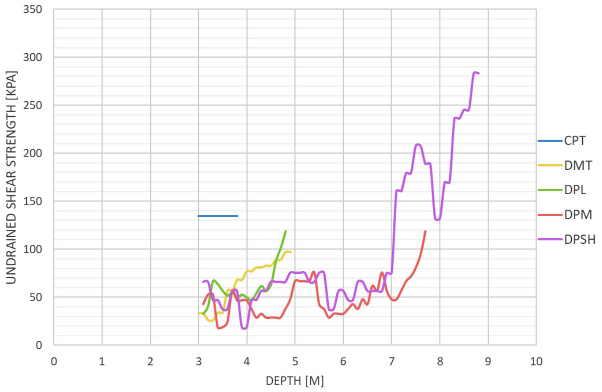


Figure 2. Undrained shear strength

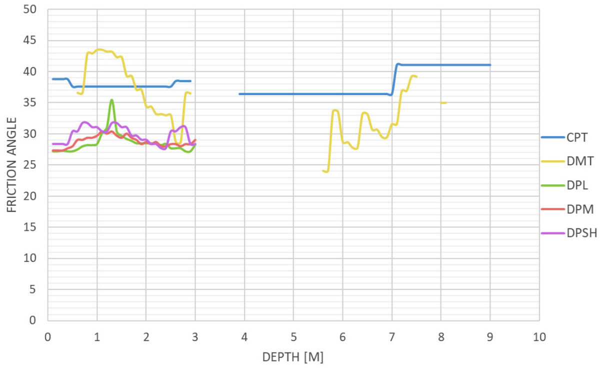


Figure 3. Friction angle in the first study point

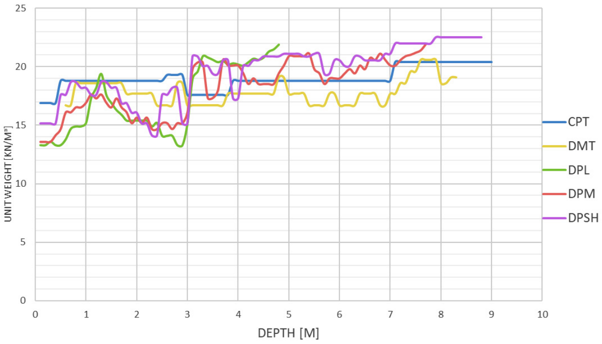


Figure 4. Unit weight in the first study point

average 428% higher than DMT and 825% higher than DCP. In clayey soils CPT values are on average 315% higher than DMT and 1145% higher than DCP.

From Figure 2, it can be seen that probing methods determined the clay soils in different intervals and depths. According to the borehole data, the clayey soil was found from 3 to 9 m deep. CPT undrained shear strength values were 2 times higher than those determined by the other research methods. DMT and DCP studies determined approximately equal undrained shear strength values.

The research of the CPT and DMT test shows highest friction angle values in the first three meters of research. In deeper soil layers, the highest values were shown by CPT research. By comparing the interpreted friction angle values, it was established that CPT research method determined 10% higher values than DMT and 25% higher than DCP.

According to the data of Figure 4, the unit weight of the soil layers throughout the depth of the borehole is very variable for all research methods, but considering the average indicators, all methods provide relatively similar parameters.

In order to better reflect the values of soil parameters and their mutual differences, obtained by all research methods, all processed data are presented in Table 2. For the dynamic probe, average values are collected taking into account all three device variations.

Table 2. Average values of soil layers

Research point	Parameter	CPT	DMT	DCP
1	M [MPa]	97.4	38.8	9.5
	Su [kPa]	134.5	64.5	71
	Φ [angle]	38.1	34.8	29.2
	γ [kN/m^3]	18.97	17.85	18.32
2	M [MPa]	52.7	25.5	9.5
	Su [kPa]	94.8	55.6	80.9
	Φ [angle]	38.9	39.8	29.3
	γ [kN/m^3]	18.11	17.14	19.19
3	M [MPa]	43.9	14.0	7.8
	Su [kPa]	33.3	20.0	14.4
	Φ [angle]	36.3	33.3	31.0
	γ [kN/m^3]	16.14	16.8	17.2
4	M [MPa]	36.1	22.4	14.3
	Su [kPa]	252.7	72.3	147.8
	Φ [angle]	35.6	40.6	28.4
	γ [kN/m^3]	17.9	17.4	17.4
5	M [MPa]	43.9	59.1	14.0
	Su [kPa]	164.4	70	143.5
	Φ [angle]	38.4	41.4	30.6
	γ [kN/m^3]	18.03	18.07	18.82

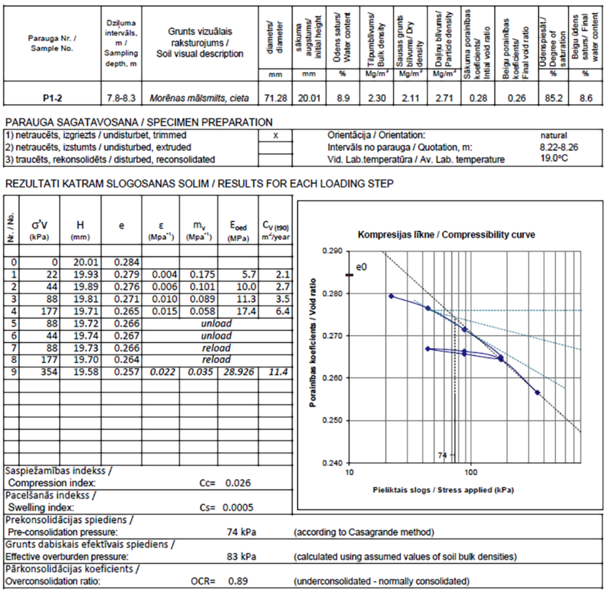
Analyzing the data in Table 2, it was concluded that the CPT method showed the highest average values of the constrained modulus of the soil layers in all research points, except for point 5. Therefore, the least expected structural deformations will be determined using CPT interpretations. In order to verify this within the scope of the study, in Chapter 3.3., a settlement/consolidation calculation was developed for each research point.

Also, when comparing the undrained shear strength, significant differences in the parameters of the soil layers were determined, which could affect the stability of the slopes. CPT interpretations showed the highest undrained shear strength. In order to verify the impact on the stability of the slopes caused by the different interpretation values of the soil layers the calculation of slope stability was carried out in the Chapter 3.4.

3.2. Comparison of laboratory and in-situ interpretation data

The constrained deformation modulus provides an essential characteristic of the compressibility of the soil. Detecting low constrained modulus values, the engineer can immediately conclude that without additional soil strength analysis, geotechnical calculations or specific solutions, it is not possible to develop a safe, long-lasting construction solution.

As part of the study, undisturbed laboratory samples were taken at several research points. Odometer and direct shear laboratory tests were performed, see Figure 5.



Parauga Nr. / Sample No.	Dziļuma intervāls, m / Sampling depth, m	Grunts vizuālais raksturojums / Soil visual description	diametrs/ diameter mm	sākuma augstums/ initial height mm	Ūdens saturs/ Water content %	Tilpumblīvums/ Bulk density Mg/m^3	Sausas grunts blīvums/ Dry density Mg/m^3	Daļiņu blīvums/ Particle density Mg/m^3	Sākuma porainības koeficients/ Intial void ratio	Beigu porainības koeficients/ Final void ratio	Ūdenspiesāt./ Degree of saturation %	Beigu ūdens saturs/ Final water content %
P1-2	7.8-8.3	*Morēnas mālsmilts, cieta*	71.28	20.01	8.9	2.30	2.11	2.71	0.28	0.26	85.2	8.6

PARAUGA SAGATAVOSANA / SPECIMEN PREPARATION

1) netraucēts, izgriezts / undisturbet, trimmed	x	Orientācija / Orientation:	natural
2) netraucēts, izstumts / undisturbed, extruded		Intervāls no parauga / Quotation, m:	8.22-8.26
3) traucēts, rekonsolidēts / disturbed, reconsolidated		Vid. Lab.temperatūra / Av. Lab. temperature	19.0°C

REZULTATI KATRAM SLOGOSANAS SOLIM / RESULTS FOR EACH LOADING STEP

Nr. / No.	σ'V (kPa)	H (mm)	e	ε (Mpa^{-1})	m$_v$ (Mpa^{-1})	E$_{oed}$ (MPa)	C$_{V (t90)}$ m^2/year
0	0	20.01	0.284				
1	22	19.93	0.279	0.004	0.175	5.7	2.1
2	44	19.89	0.276	0.006	0.101	10.0	2.7
3	88	19.81	0.271	0.010	0.089	11.3	3.5
4	177	19.71	0.265	0.015	0.058	17.4	6.4
5	88	19.72	0.266	*unload*			
6	44	19.74	0.267	*unload*			
7	88	19.73	0.266	*reload*			
8	177	19.70	0.264	*reload*			
9	354	19.58	0.257	*0.022*	*0.035*	*28.926*	*11.4*

Saspiežamības indekss / Compression index:	Cc=	0.026	
Pacelšanās indekss / Swelling index:	Cs=	0.0005	
Prekonsolidācijas spiediens / Pre-consolidation pressure:		74 kPa	(according to Casagrande method)
Grunts dabiskais efektīvais spiediens / Effective overburden pressure:		83 kPa	(calculated using assumed values of soil bulk densities)
Pārkonsolidācijas koeficients / Overconsolidation ratio:	OCR=	0.89	(underconsolidated - normally consolidated)

Figure 5. Odometer test results in first study point

At the first research point oedometer laboratory test was performed, the sample was taken in the depth interval from 8.22 to 8.26 m. According to the odometer test, the effective overburden pressure was 83 kPa, thus it was determined that the constrained modulus of the soil was 11.1 MPa. Comparing the laboratory test results with the CPT, DMT and DCP interpretations, it can be concluded that in the specific range the CPT test has determined M = 211.5 MPa; the DMT test has determined M = 50.1 MPa and DCP test has determined M = 18.2 MPa. The differences in values are significant and can affect the safety of the designed structures.

At second research point two direct shear tests was made. The shallowest sample was taken in the depth interval from 5.77 to 5.92 m. According to the odometer test data, the effective overburden pressure was 64 kPa, thus it was determined that the shear strength of the soil was 73 kPa.

Comparing the laboratory test results with the probing interpretations, it was concluded that in the specific depth the CPT test has determined Su = 94.8 kPa; DMT test Su = 61 kPa and DCP test Su = 52 kPa. CPT determined a higher undrained shear strength compared to direct shear tests.

All processed data, obtained by laboratory and in-situ tests, are presented in Table 3. For the dynamic probe, average values are collected taking into account all three device variations.

Table 3. Comparison of laboratory and in-situ test results

Research point	Parameter	Laboratory	CPT	DMT	DCP
P1-2	M [MPa]	11.1	211.5	50.1	18.2
P2-2	M [MPa]	5.5	25.8	4.3	6.1
P2-4	M [MPa]	6.7	25.8	5.9	6.6
P3-3	M [MPa]	0.6	5.4	3.7	2
P2-2	Su [kPa]	73	94.8	61	52
P2-6	Su [kPa]	79	94.8	51	110
P3-3	Su [kPa]	44	28.3	28	20

Comparing laboratory and in-situ test results, it was concluded that the CPT method determined higher parameters of soil layers compared to laboratory test data. The results of the DMT and DCP methods were equivalent and slightly different from the laboratory data. It can be concluded that interpretations of CPT data overestimated soil parameters. In order to avoid such problems in the course of project development, it is necessary to carry out laboratory tests in addition to probing, to verify the obtained results of interpretations and, if necessary, perform data correction.

3.3. Construction settlement calculations using interpreted values

For settlement calculations, specially developed calculation software has been used, in which it is possible to precisely define all input parameters, as well as to take into account partial factors. For the calculation of settlement, the same constructive solution has been adopted for all calculations. It was assumed that the place where the probing was started is the existing ground surface and a 2 m high road embankment has been built on it. In addition to the backfill load, a distributed transport load of 50 kPa has been applied. The embankment was built with a slope of 1:2. The calculations use partial factors of Eurocode 7 – design approach 1, combination 2.

The results of calculation at first investigation point are shown in the Figures 6–8.

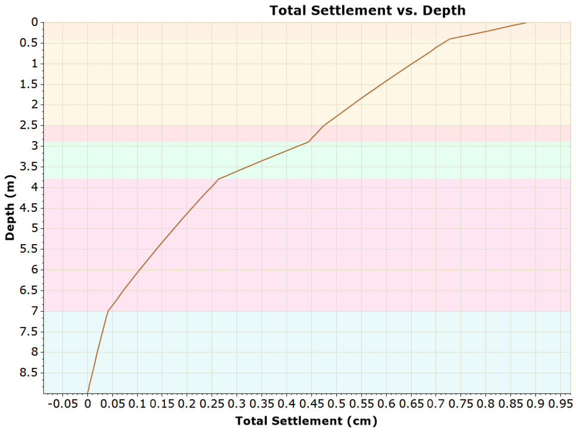


Figure 6. Settlement results using CPT interpretations

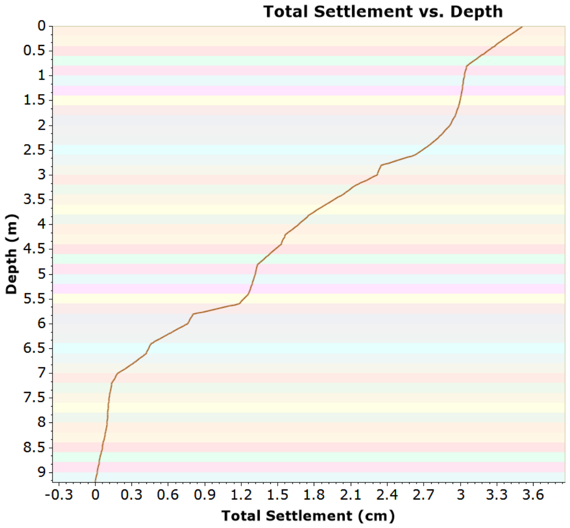


Figure 7. Settlement results using DMT interpretations

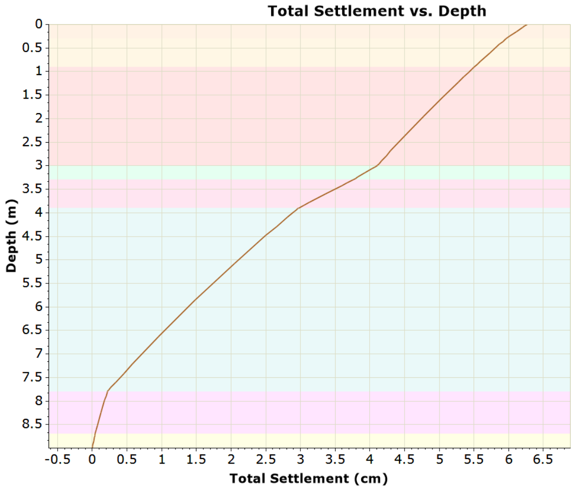


Figure 8. Settlement results using DCP interpretations

According to the obtained results of all three calculations, the greatest deformations occur using DCP interpretation values. The settlement of the structure was determined to be 0,88 cm from CPT data, 3,51 cm from DMT data and 6,26 cm from DCP data. The difference between obtained CPT and DCP results was 5,38 cm or approximately 7,1 times, but between obtained CPT and DMT results was 2,63 cm or approximately 4 times.

The construction settlement calculations were made in all research points. The calculation results are summarized in Table 4.

Table 4. Comparison of settlement results

Research point	Parameter	CPT	DMT	DCP
1	Settlement [cm]	0.88	3.51	6.26
2	Settlement [cm]	1.43	6.68	5.64
3	Settlement [cm]	5.67	14.20	30.20
4	Settlement [cm]	1.96	4.87	11.10
5	Settlement [cm]	1.36	2.10	5.38

Analyzing the data in Table 4, it was concluded that the CPT method determined the smallest settlement of the structure. According to the obtained results of all calculations, the greatest deformations occur using DCP interpretation values.

The largest settlement was determined at the 3rd research point using dynamic probe data interpretations and it was 20 cm. The differences between obtained CPT and DCP results were approximately 5,2 times, between obtained CPT and DMT results were approximately 2,8 times and between obtained DMT and DCP results were approximately 1,9 times. Taking into account the results obtained in the third research point, it can be seen that the differences in the amount of total deformations are large. Given that we have previously determined that deformation values for the CPT method determined higher parameters of soil layers compared to laboratory test data it can be concluded that the calculation using CPT test data interpretations gives a more optimistic structural settling result than actually expected. This may create the risk of unexpected structural deformations occurring after the completion of the construction works, which could not be determined by calculations due to the imprecisely determined properties of the soil layers.

3.4. Slope stability calculations using interpreted values

Civil engineering projects such as buildings, bridges, earthen dams, and roadways require detailed subsurface information as part of the design process. The ground below us ultimately supports all structures and to be successful, the ground must not fail under the applied structural load. The type of material encountered is important because it provides an indication of how the soil will react under load and whether or not the material is even sufficient to support foundations.

For analytical slope stability calculation, the Bishop method has been found to be adequately accurate providing minor variances from the actual Factor of safety of slopes. The main assumption of slope stability is that the resisting forces are greater than the driving forces.

For the calculation of slope stability, the same constructive solutions and partial factors as described in Chapter 3.3. were adopted. The results of calculation at first investigation point using the CPT interpretations are shown in the Figure 9, calculation using the DMT interpretations are shown in the Figure 10 and calculation using the DCP interpretations are shown in the Figure 11.

The stability of slopes is most significantly affected by the shear resistance of the soil layers and the angle of internal friction. As was concluded in Chapter 3.1. the CPT interpretations showed the highest undrained shear strength.

After the calculation, the slip surface with the lowest safety factor is determined and plotted. Comparing all calculations in first study point, it can be seen that the difference between the safety factors is minimal. The calculated slope stability safety factor using CPT and DMT

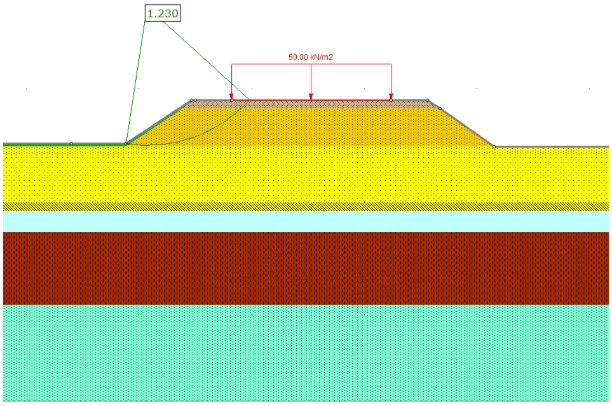


Figure 9. Slope stability using CPT interpretations

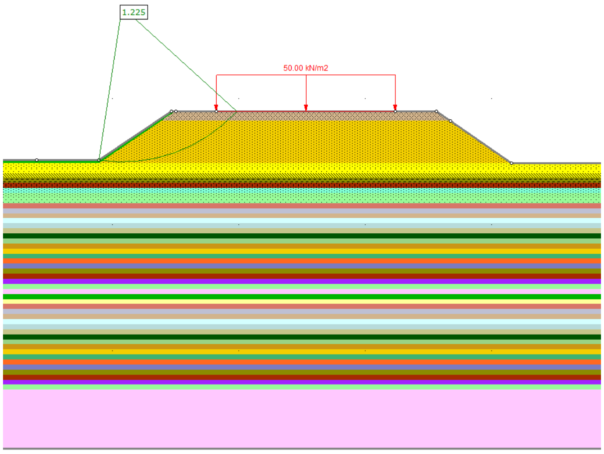


Figure 10. Slope stability using DMT interpretations

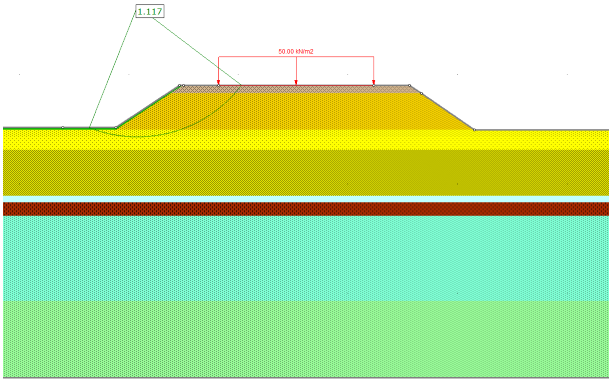


Figure 11. Slope stability using DCP interpretations

interpretation values is the same. The result difference between CPT, DMT and DCP is 10% (DMT – Fsafety = 1,225; CPT – Fsafety = 1,230; DCP – Fsafety = 1,117).

The construction slope stability calculations were made in all research points. The calculation results are summarized in Table 5.

Table 5. Comparison of slope stability safety factor results

Research point	Parameter	CPT	DMT	DCP
1	Safety factor	1.23	1.225	1.117
2	Safety factor	1.23	1.22	1.121
3	Safety factor	1.239	0.766	0.519
4	Safety factor	1.23	0.834	0.704
5	Safety factor	1.24	1.25	1.06

Analyzing the data in Table 5, it was determined that slope stability, using the CPT interpretation data, was ensured in all five investigation points. Given that we have previously determined that undrained shear strength values for the CPT method determined higher parameters of soil layers compared to laboratory test data it can be concluded that the calculation using CPT test data interpretations gives a more optimistic slope stability results than actually expected.

The dynamic probe method showed the lowest interpretations of soil parameters, as well as the largest settlement deformations, so it was natural that the greatest slope stability problems were determined when performing calculations using DCP interpretations. In the third and fourth research points, the stability of the slopes was not ensured using the data of the DMT and DCP methods.

DMT and DCP calculations confirmed that vertical structural deformations are closely related to slope stability. At the research points, where the largest amount of settlement was determined, the stability of the slopes was not ensured.

Conclusions

The static cone penetration test method showed the highest average values of the constrained modulus and undrained shear resistance of the soil layers in all research points.

The CPT method interpretations determined higher soil parameters than laboratory tests and other field tests. In order to avoid such problems in the course of project development, it is necessary to carry out laboratory tests in addition to probing, to verify the obtained results of interpretations and, if necessary, perform data correction.

CPT test data interpretations gives a more optimistic structural settling result and more optimistic slope stability than actually expected. This may create the risk of unexpected structural deformations occurring after the completion of the construction works, which could not be determined by calculations due to the imprecisely determined properties of the soil layers.

The dynamic probe method showed the lowest interpretations of soil parameters, as well as the largest settlement deformations and the greatest slope stability problems. Geotechnical solutions developed based on DCP interpretations provides greater structural safety compared to the CPT and DMT, but also increases construction costs.

Interpreted soil layer parameter values using DMT method were equivalent and only slightly different from the laboratory data. Therefore, we can conclude that the DMT method provided the most accurate initial data for calculations. The CPT method showed too good soil properties, while the DCP method gave conservative data.

Vertical deformations are closely related to slope stability. At the research points, where the largest amount of settlement was determined, the stability of the slopes was not ensured.

The CPT investigation method requires in-depth research to verify that the interpretations developed are appropriate for the soil in our climatic and geographic conditions. The major studies on CPT correlations have been carried out mainly in the USA, so it is necessary to ascertain whether the methods developed for the interpretation of the CPT are appropriate or whether it is necessary to use the soil parameter factors offered by the Eurocodes.

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