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ANALYSIS OF PHYSICAL AND MECHANICAL SOIL PROPERTIES DETERMINED USING INTERPRETATIONS OF DILATOMETRIC TEST (DMT) AND CONE PENETRATION TEST (CPT) METHODS

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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 survey in order to define the best road layout. Moreover, the geotechnical characterisation of foundation soils and construction materials as well as the analysis and assessment of geotechnical works are mandatory. Laboratory and in situ investigations are complementary and should be carried out by defining a cost-effective investigation campaign. Most often, Dynamic Cone Penetrometer (DCP) or Cone (static) Penetration Test (CPT) are performed because they are economic and quick. In addition, it is also possible to perform the Marchetti Dilatometer Test (DMT). From the obtained test results, the data are interpreted by determining the properties of the soil

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layers. Although all probing methods are similar, each of them gives slightly different results. The aim of this study is to analyse and compare the results of the probing test, to determine the difference between the obtained data and to find out how the obtained results affect the development of constructive solutions from the safety and economic point of view.

Keywords: dilatometric test, geotechnical investigation, in-situ test, roads, road bearing capacity, road construction, soil properties, static cone penetration test.

Introduction

The geotechnical engineer's task is to explore the subsurface conditions at a project site, determine the capacity of the soil to carry the load without collapsing or experiencing intolerable movement and to recommend appropriate foundation alternatives (Weber, 2010). Geotechnical investigations are performed to obtain information on the physical/mechanical characteristics of soil and rock around at a given site to design earth retaining systems and foundations for proposed structures and for repair of distress to earthworks and structures caused by subsurface conditions. Site investigations have acquired substantial importance in preventing human and material damage due to the earthquakes, foundation cracks and other catastrophes. Geotechnical investigations can be as simple as conducting only a visual assessment of the site or as detailed as a computer-aided study of the soil.

Several studies have been performed in recent years comparing the correlations between Cone Penetration Test (CPT) and Marchetti Dilatometer Test (DMT) (Poenaru, 2016; Grabar et al., 2022; Nepelski, 2019; Mulabdic, 2013; Zawrzykraj et al., 2017; Rabarijoely, 2018). Krzysztof Nepelski (Nepelski, 2019) analysed the building – subsoil interaction in 2019. He concluded that DMT test interpretations showed higher constrained modulus of soil layers than CPT test interpretations. Same conclusion was made by Alexandru Poenaru (Poenaru, 2016) in 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. Mensur Mulabdic (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 a valuable aid in characterising embankment quality, both in terms of inhomogeneity and physical and mechanical properties. In his investigation, he determined that modulus of vertical constrained deformation from oedometer (on submerged specimens) was much smaller than that 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 (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. Taking into account all the previous studies it is clear that there are still many unknowns affecting the physical and mechanical soil properties determined using interpretations of DMT and CPT methods.

1. Objectives

Before the design of the construction site begins, 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. Considering these facts, the accuracy of the results obtained for each method has been assessed, see Table 1.

The aim of this study is to analyse and compare the results of the probing test, to determine the difference between the obtained data and to find out how the obtained results affect the development of constructive solutions from the safety and economic point of view. As part of this study, the data of geotechnical investigation of the motorways P32 49.58 – 49.97 km section were analysed.

2. Static Cone Penetration Test method

The cone penetration test is a method used to determine the geotechnical engineering properties of soils and delineating soil stratigraphy. It was initially developed in the 1950s at the Dutch Laboratory for Soil Mechanics in Delft to investigate soft soils. The cone penetration test has become internationally one of the most widely used and accepted test methods for determining geotechnical soil properties (Lunne et al., 1997).

The test method consists of pushing an instrumented cone, with the tip facing down, into the ground at a controlled rate (controlled between 1.5–2.5 cm/s accepted). The resolution of the CPT in delineating stratigraphic layers is related to the size of the cone tip, with typical cone

Table 1. In situ test parameter accuracy (Robertson, 2012)

Group	In-situ test	Geotechnical Parameter												Ground Type					
		Soil type	Profile	U_0	*OCR*	D_R–ψ	Φ'	S_u	G_0–E	σ–ε	M–C_c	k	C_v	Hard rock	Soft rock	Gravel	Sand	Silt/clay	Peat-organic
Penetro-meter/ Direct Push	Dy. Probing (DP)	C	B	–	C	C	C	C	C	–	–	–	–	–	C	B	A	B	B
	SPT	B	B	–	C	B	C	C	C	–	–	–	–	–	C	B	A	B	B
	CPT	B	A	–	B	B	B	B	B	C	C	C	–	–	B	B	A	A	A
	CPTu	A	A	A	B	A	B	A	B	C	B	A	A	–	B	B	A	A	A
	SCPTu	A	A	A	A	A	B	A	A	B	B	A	A	–	B	B	A	A	A
	DMT	B	B	B	B	C	B	B	B	C	B	C	B	–	C	C	A	A	A
	SDMT	B	B	B	A	B	B	B	A	B	B	C	B	–	C	C	A	A	A
	Full-flow (T/ball)	C	B	B	B	C	C	A	C	C	C	C	C	–	–	–	C	B	A
	Field vane (FVT)	B	C	–	B	–	–	A	–	–	–	–	–	–	–	–	–	A	B
Pressure-meter	Pre-bored	B	B	–	C	C	C	B	B	C	C	–	C	A	A	B	B	B	B
	Self-bored	B	B	A[1]	B	B	B	B	A	A	B	B	A[1]	–	C	–	B	A	B
	Full-displacement	B	B	B	C	C	C	B	A	A	B	B	A	–	C	–	B	A	A
Other	Screw/plate load	C	–	–	B	C	C	B	B	B	B	C	C	C	A	B	B	B	B
	Borehole shear	C	–	–	–	–	B	C	–	–	–	–	–	C	B	C	C	C	–
	Permeameter	C	–	A	–	–	–	–	–	–	–	A	B	A	A	A	A	A	B
	Borehole seismic	C	C	–	B	C	–	–	A	C	–	–	–	A	A	A	A	A	B
	Surface seismic	–	C	–	B	C	–	–	A	C	–	–	–	A	A	A	A	A	A
	Hydraulic fracture	–	–	B	–	–	–	–	–	–	–	C	C	B	B	–	–	B	C

Applicability: A = high, B = moderate, C = low, – = none
Geotechnical parameters: U_0 = in-situ static pore pressure, *OCR* = over-consolidation ratio, D_R–ψ = relative density and/or state parameter, Φ' = peak friction angle, S_u = undrained shear strength (peak and/or remolded), G_0–E = small strain shear and/or Young's modulus, σ–ε = stress-strain relationship, M–C_c = constrained modulus and/or compression index, k = permeability, C_v = coefficient of consolidation.

tips having a cross-sectional area of either 10 or 15 cm^2, corresponding to diameters of 3.6 and 4.4 cm (Robertson & Cabal, 2010).

The cone penetration resistance values can be then correlated to shear strength parameters using proposed empirical curves. There are also some design methods associated with CPT results, which directly use the CPT results to estimate the settlement in soils under a given pressure. Major research works have been carried on by Robertson (Robertson & Cabal, 2015). Notable interpretations of the CPT have been published by Lunne (Lunne et al., 1997).

Many empirical and theoretical CPT interpretation methods are broadly accepted and used in practice. These approaches tend to consider whether the cone penetration is drained or undrained, and then consider the soil as either "sand" or "clay". 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 behaviour (Been et al., 2010).

In 1983, Robertson and Campanella published two major papers on the interpretation of the CPT (Robertson & Campanella 1983a, 1983b). Since 1983, there have been several major publications on the interpretation of the CPT (Lunne et al., 1997; Mayne, 2007). Table 2 shows an estimate of the perceived applicability of the CPTU to estimate soil parameters.

3. DMT (Dilatometric Test) method

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, 2021).

Table 2. Perceived applicability of CPTU for deriving soil parameters (Robertson & Cabal, 2010)

Soil Type	D_r	ψ	K_0	OCR	S_t	S_u	Φ	E, G	M	G_0	k	C_h
Sand	2–3	2–3		5			2–3	3–4		2–3	3	3–4
Clay			2	1	2	1–2	4	3–4	4	3–4	2–3	2–3

1 = high; 2 = high to moderate; 3 = moderate; 4 = moderate to low; 5 = low reliability; Blank = no applicability, where:

D_r – Relative density,
φ – Friction angle,
Ψ – State parameter,
E, G – Young's and Shear moduli,
K_0 – In-situ stress ratio,
M (or mv) – Compressibility (in work used designation Eed),
OCR – Over Consolidation Ratio,
G_0 – Small strain shear moduli,
S_t – Sensitivity,
k – Permeability,
S_u – Undrained shear strength,
C_h – Coefficient of consolidation.

The flat dilatometer test (DMT) uses pressure readings from an inserted flat plate to obtain estimates of soil type and various soil parameters. The flat dilatometer test (DMT) was developed in Italy by Silvano Marchetti (Marchetti et al., 2001). The flat dilatometer is a stainless-steel blade having a flat, circular steel membrane mounted flush on one side. 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.

The blade is connected to a control unit on the ground surface by a pneumatic-electrical tube (transmitting gas pressure and electrical continuity) running through the insertion rods. A gas tank, connected to the control unit by a pneumatic cable, supplies the gas pressure required to expand the membrane. The control unit is equipped with a pressure regulator, pressure gage(s), an audio-visual signal and vent valves. The pressure required to initiate the movement of the membrane against the soil is recorded and is called "A-pressure". The inflation continues until the centre of the membrane is moved 1.1 mm against the soil. The required pressure to achieve that is called "B-pressure". If the required depth is below the water table, the membrane can be slowly deflated to record "C-pressure", which represents the pore pressure acting on the membrane (Marchetti et al., 2001).

The original correlations (Marchetti, 1980) were obtained by calibrating DMT results versus high quality parameters obtained by traditional methods. Many of these correlations form the basis of today interpretation have been generally confirmed by subsequent research.

4. Comparison of CPT and DMT using geotechnical investigation data of road P32

During road reinforcement and reconstruction projects, geotechnical investigation of the existing soil and road surface 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.

Geotechnical investigation on the Latvian regional road P32 Augsligatne – Skriveri 49.58–49.97 km section was performed. In the section 49.66–49.93 under the road, as well as next to the road embankment, organic sediments were detected – peat and sludge. The thickness of the layer of organic sediments under the road embankment in the mentioned section was uneven and varied within 0.9–5.7 m, on average – 3.0 m. Organic soils (peat, sludge) lying under the road embankment have low load-bearing capacity and high deformation properties, as a result of which this stratum is not suitable as a road construction foundation. During the geotechnical investigation, a total of 44 research points were carried out, placing them in 12 cross-sections, evenly covering the design area. The average distance between cross sections was 30 m. In order to determine the conditions of artificial and natural soil deposition, as well as the physical and mechanical properties of soil, 22 static probing points (CPTu) were performed at a depth of 2.6–12.4 m from the ground surface and 8 flat dilatometer tests (DMT) at a depth of 6.0–11.0 m.

The location of the geotechnical survey points was planned to be as efficient as possible to cover the entire survey area, so the CPT and DMT surveys were not carried out in the same location. However, to perform investigation quality control, the probing points were duplicated in two locations. Using the interpretations of the obtained data, the analysis and comparison of the results were performed. The interpretation of the data was performed by a geotechnical investigation engineer using specially developed computer programs. A comparison of four soil parameters was also performed in the study – undrained shear strength (*Cu*), constrained modulus (for one-dimensional consolidation/compressibility the designation Eed is used in the study), friction angle (φ), unit weight (γ).

4.1. The interpretations of the results obtained in the study point 497+20D

The interpretations of the results obtained in the first study point (497+20D) are summarised and plotted to make the comparison of soil parameters easy to understand (see Figure 1). Various correlations and formulas have been developed for expressing CPT and DMT data in physical-mechanical parameters. Soils are divided into soil types. Initially, the type of soil and the thickness of the layers are determined from the obtained probe parameters. Different correlations and formulas have been developed for each soil type; therefore, it is important to accurately determine the soil type.

The graph shows the first difference between the CPT and DMT test results. The data obtained during the CPT study are divided into broader sections, taking into account the identified material types and the correlated soil properties for a thicker stratum. The results of the DMT test are interpreted in each test area (in this case for 20 cm thick layers) and, thus, a soil characteristic is obtained every 20 cm.

Comparing the obtained results, it can be seen that the research of the static probe (CPT) shows higher strength values in all the considered positions. Comparing the results of CPT and DMT, CPT shows on average 8% higher value of friction angle and 87% higher value of constrained deformation modulus in sand soils, 130% higher undrained shear strength and 60% higher value of constrained deformation modulus in clayey soils, 300% higher undrained shear strength and 360% higher value of constrained deformation modulus in low baring capacity soils (peat, organic layers). Both methods give equivalent material density values. Soil deformation and slope stability are most significantly affected by material bond, deformation modulus and friction angle. The biggest differences in the obtained results are observed in the strength properties of the soil constrained deformation modulus and undrained shear strength; therefore, these parameters will be analysed in more detail in this investigation point. It is very important to make sure which of the methods (CPT or DMT) more accurately reflects the true

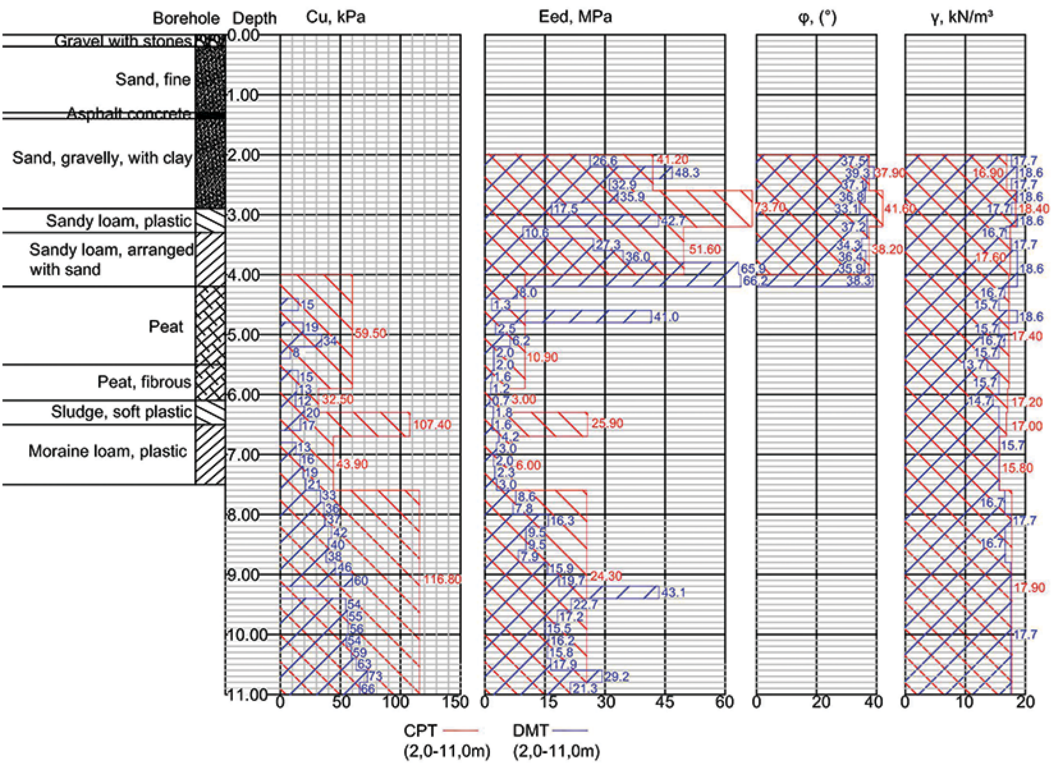

Figure 1. Results obtained in the study point 497+20D

properties of the soil layers. Therefore, it is necessary to compare the obtained results with another test of geotechnical investigation.

Comparing the obtained data, the most significant differences are observed in the results of material undrained shear strength. Undrained shear strength (*Cu*) values obtained with CPT are averagely by 180% higher than values obtained with DMT. In sites with slope stability problems, it is very important to determine the exact parameters of the clayey, bound soils, as undrained shear strength is one of the most important properties of these soil types. In order to determine which of the geotechnical investigation methods more accurately reflects the true undrained shear strength of the soil, it is necessary to compare the results with another research method. Although only DMT and CPT studies were duplicated at this point, CPT and Field Vane (FVT) tests were duplicated at the base of road slope 12 m sideway (see Figure 2), so it was possible to compare the results at investigation point 497+20B

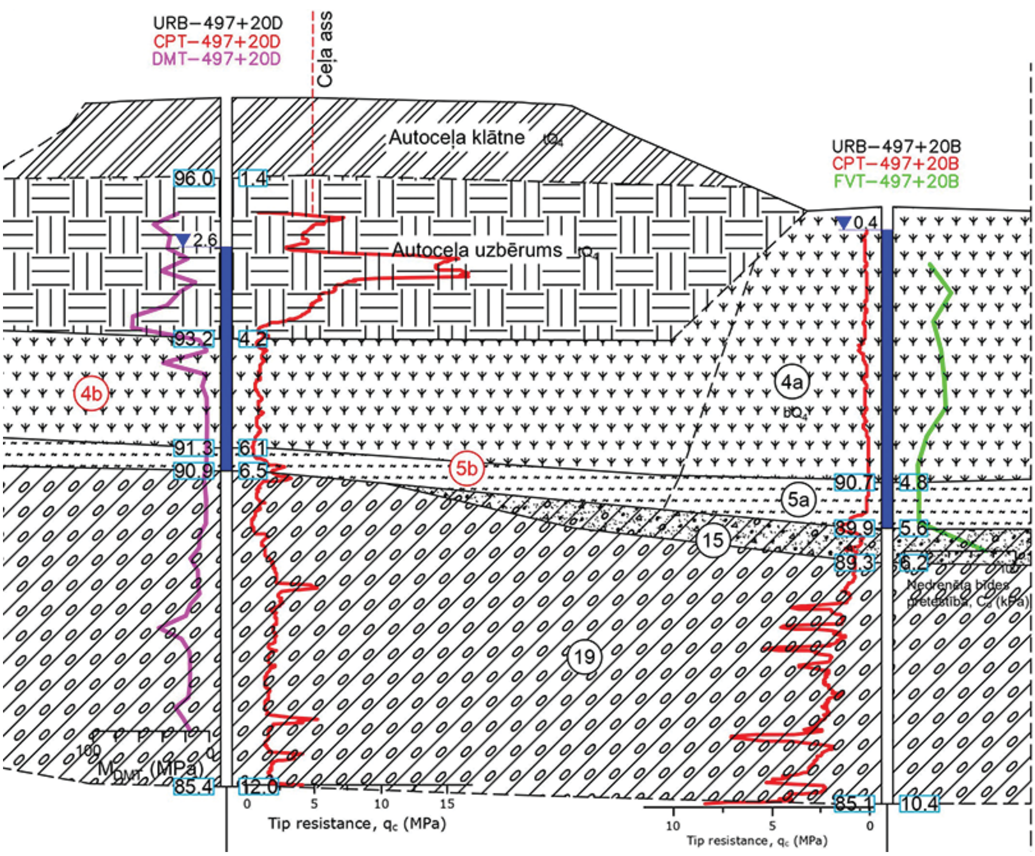

Figure 2. Geotechnical cross-section of the road

and determine, whether the CPT study showed higher/lower undrained shear strength. According to Table 1, the FVT test gives higher accuracy than the CPT in determining the undrained shear strength of soil layers.

The shear vane test is a method of measuring the undrained shear strength of a cohesive soil. The test is carried out with equipment consisting of a rod with vanes mounted to it that is inserted into the ground and rotated. A gauge on the top of the rod measures the torque required to cause failure of the soil and provides a conversion to shear strength. Obtained FVT and CPT test results are summarised in Figure 3.

As can be seen from the results obtained, the FVT test shows a higher strength of soil undrained shear strength than the CPT study. Therefore, it can be concluded that the interpreted results of CPT and DMT at study point 497+20D show a lower strength of the soil bond than it is actually. The correlation of DMT test data provides a greater margin of strength, which, when developing design solutions, would force the engineer to develop more complex and expensive design solutions, but at the same time it would increase the reliability of the construction.

The constrained deformation modulus provides an essential characteristic of the compressibility / deformation of the soil. When detecting low E_{oed} values during the project design, the designer can immediately conclude that without the additional soil strength analysis, geotechnical calculations or specific building solutions, it is not possible to develop a safe and long-lasting construction solution. The results of the CPT study showed an average of 85% higher modulus of soil constrained deformation than DMT. In this investigation point 497+20D a soil sample was taken at a depth of 6.35 m to perform consolidation test in the laboratory. From the results of the consolidation test performed in the laboratory (see Figure 4), it is possible to determine the value of the

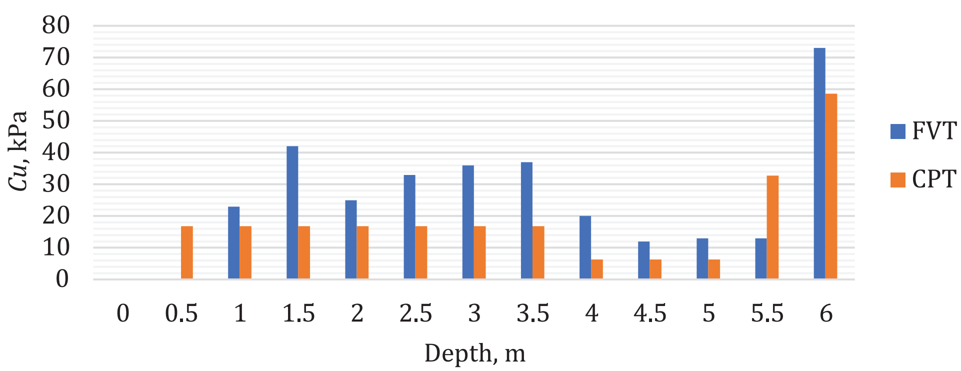

Figure 3. Soil undrained shear strength in investigation point 497+20B

soil constrained deformation modulus. Thus, it is possible to compare the values obtained with DMT and CPT research data.

Consolidation test is used to determine the rate and magnitude of soil consolidation when the soil is restrained laterally and loaded axially. The consolidation test is also referred to as a standard odometer test or one-dimensional compression test. During the consolidation test, a load is applied to the sample and is increased with each subsequent loading step. The situation at the site is similar, because the existing soil layers are subjected to the backfill load (the load caused by the soil layers above the layer under consideration). Taking into account the densities of the soil layers determined during the geotechnical investigation and the height of the groundwater, it has been determined that the existing embankment load at a depth of 6.35 m reaches a load of approximately 82 kPa. By

Saspiežamība - kalkulācija Consolidation test - calculation			
Objekts / Location		**Līguma Nr.** / Job ref.	
Valsts reģionālā autoceļa P32 Augšlīgatne - Skrīveri posma km 47,20 - 60,29 ģeotehniskās projektēšanas risinājumu izstrāde		**Lab. Nr.** / Lab. no.	124C333
		Urbuma Nr. / Borehole no.	-
Grunts apraksts / Soil description		**Parauga Nr.** / Sample no.	P497+20D-2
Putekļi ar vidēju organisko savienojumu saturu		**Dziļums** / Depth	6,35
Medium-organic silt		**Datums** / Date	04.04.18-13.04.18
Testēšanas metode / Test method	LVS CEN ISO/TS 17892-5		
Aparāta Nr. / Machine no. I	**Parauga diametrs** / Specimen diameter 71,7 mm	Augstums / Height Ho	34,67
Blīvums / Density ρ Mg/m³ 1,45	**Daļiņu augstums** / Height of solids 11,58 mm	**Minerāldaļiņu blīvums** / Particle density Mg/m³	2,528
Mitrums / Moisture w % 71,2	**Sakuma porainības koeficients** / Initial voids ratio e_o 1,994		

PORAINĪBAS KOEFICIENTS / VOIDS RATIO						**SASPIEŽAMĪBA** / COMPRESSIBILITY				**KONSOLIDACIJAS KOEFICIENTS**/COEFFIC. OF CONSOLID.				
Pakāpes Nr. Increment no.	**Spiediens** Pressure P, kPa	**Summāra saspiede** Cumulative compression (ΔH - y), mm	**Relatīvā deformācija** Relative deformation ε	**Konsolidēta parauga augstums** Consolidated height $H=H_o-(\Delta H-y)$	**Porainības koeficients** Voids ratio $e=\frac{H-Hs}{Hs}$	**Pakāpes** / Incremental **augstuma izmaiņas** height change δH, mm	**spiediena izmaiņas** pressure change δp, kPa	$m_v=\frac{\delta H}{H_1}\cdot\frac{1000}{\delta p}$ m²/MN	$E_{oed}=\delta P_v/\delta\varepsilon_v$ MPa	h_{90} mm	t_{90} min	$L=(H_1+H_2)/2$ mm	$C_v=\frac{0.848 \cdot H^2}{t_{90}}$ m²/gadā m²/year	**Sekundārās saspiežamības koeficients** c_α
0	0	0	0	34,67	1,994	0	0	-	-	-	-	-	-	-
1	79	5,510	0,159	29,16	1,518	5,510	79	**2,012**	**0,5**	3,670	100,00	31,92	**4,54**	-
2	25	4,970	0,143	29,70	1,565	-0,54	-54	-	-	-	-	-	-	
3	50	5,402	0,156	29,27	1,528	0,432	25	**0,582**	**2,0**	5,275	81,00	29,48	**4,78**	**3,8E-04**
4	100	6,665	0,192	28,01	1,419	1,263	50	**0,863**	**1,4**	6,480	376,36	28,64	**0,97**	**5,9E-05**
5	200	8,993	0,259	25,68	1,218	2,328	100	**0,831**	**1,5**	8,490	309,76	26,84	**0,93**	**4,0E-03**
6	400	11,925	0,344	22,75	0,964	2,932	200	**0,571**	**2,4**	11,510	213,16	24,21	**1,10**	**1,3E-03**
7	800	14,237	0,411	20,43	0,765	2,312	400	**0,254**	**6,0**	13,750	324,00	21,59	**0,58**	**1,7E-03**
	C_c	=	0,841											

Figure 4. Consolidation test in investigation point 497+20D at a depth of 6.35 m

interpolating the obtained consolidation test results, the constrained deformation modulus of the soil sample is determined to be 1.6 MPa.

Comparing the test results with the CPT and DMT interpretations, it can be concluded that in the specific range the DMT test has determined the exact modulus of soil constrained deformation E_{oed} = 1.6 MPa. Interpretations of the CPT test up to a depth of 6.3 m showed the values of the soil constrained deformation modulus E_{oed} = 3.0 MPa, but then a 40 cm thick layer with E_{oed} = 25.9 MPa was identified. Judging by this comparison, there is a possibility that the CPT interpretations of the test show slightly better soil constrained deformation properties than they actually have. However, given that different coefficients, partial factors are used in geotechnical calculations (soil strength reducing and others), we can safely use the specified constrained deformation properties, by carefully analysing not only the CPT survey data but also other available information. We can conclude that the main advantage of the DMT test is that it determines the soil properties for each 20 cm thick layer, so a larger stratum with an average parameter value is not formed. Comparing the results of the DMT and the consolidation test, it can be stated that the study provides an accurate estimate of the modulus of soil constrained deformation. Using these data, the sedimentation of the existing bedrock can be accurately estimated.

4.2. The interpretations of the results obtained in the study point (498+40D)

The interpretations of the results obtained in the second study point (498+40D) are summarised and plotted to make the comparison of soil parameters easy to understand (see Figure 5). As described in the previous study point, various correlations and formulas have been developed for expressing CPT and DMT data in physical-mechanical parameters.

Comparing the obtained results, it can be seen that the research of the static probe (CPT) shows higher strength values in all the considered positions. Comparing the results of CPT and DMT, CPT shows on average 8% higher value of friction angle and 200% higher value of constrained deformation modulus in loose sand, 9% higher value of friction angle and 90% higher value of constrained deformation modulus in dense sand, 230% higher undrained shear strength and 185% higher value of constrained deformation modulus in low baring capacity soils (peat, organic layers).

As described in previous study point soil deformation and slope stability are most significantly affected by material bond, constrained deformation modulus and friction angle. The biggest differences in the obtained results are observed in the strength properties of the soil constrained deformation modulus and undrained shear strength; therefore, these parameters will be analysed in more detail in this investigation point.

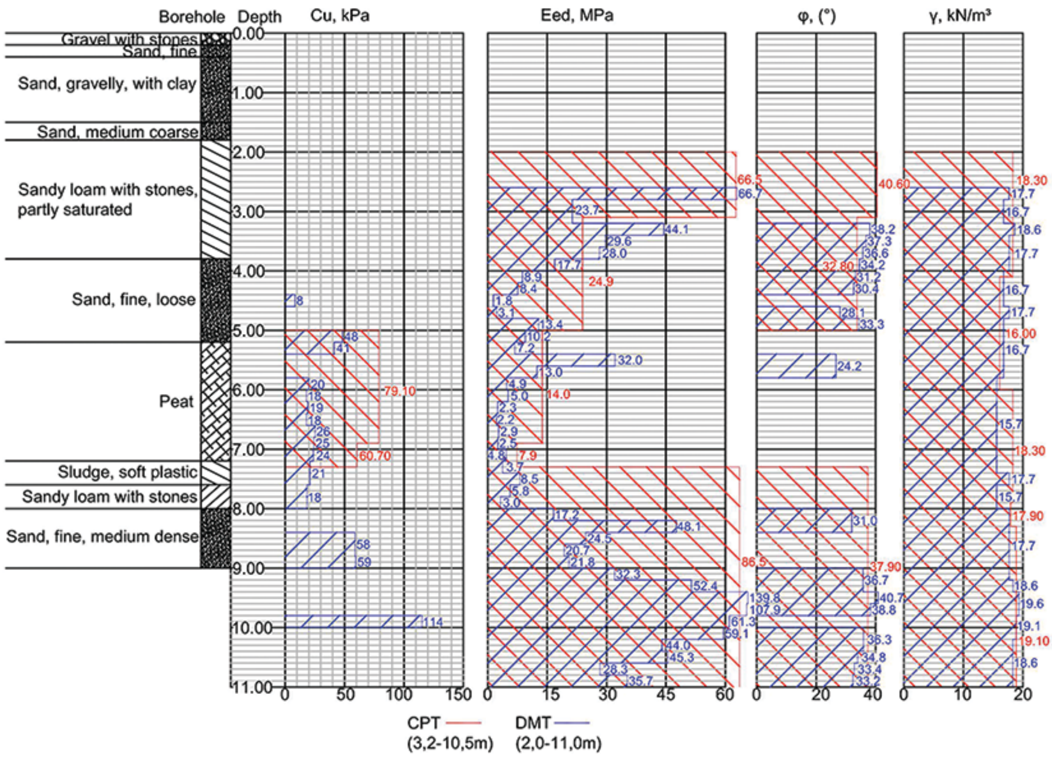

Figure 5. Results obtained in the study point 498+40D

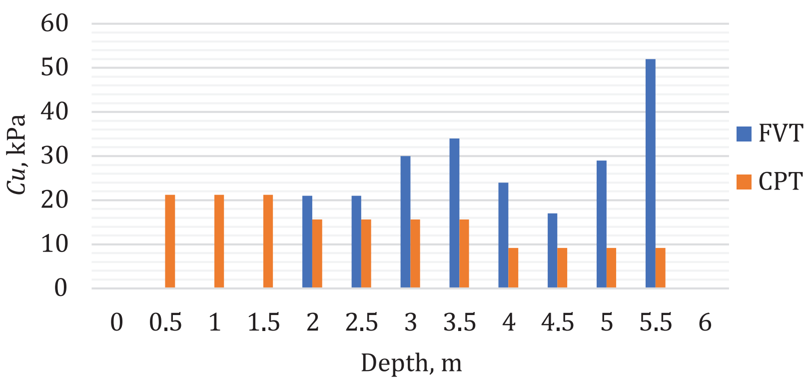

Figure 6. Soil undrained shear strength in investigation point 498+40B

Undrained shear strength values obtained with CPT are averagely by 230% higher than values obtained with DMT. Although only DMT and CPT studies were duplicated at this point, CPT and Field Vane (FVT) tests were duplicated at the base of road slope 12 m sideway (similar as in the previous investigation point). Therefore, it is possible to compare the results at point 498+40B and determine whether the CPT study shows higher/lower undrained shear strength (see Figure 6).

Obtained FVT and CPT test results are summarised in Figure 6. As can be seen from the results obtained, the FVT test shows a higher strength of soil undrained shear strength than the CPT study. Therefore, it can be concluded that the interpreted results of CPT and DMT at study point 498+40D show a lower strength of the soil bond than it is actually. The correlation of DMT test data provides a greater margin of strength, which, when developing design solutions, would force the engineer to develop more complex and expensive design solutions, but at the same time it would increase the reliability of the construction.

The results of the CPT study showed an average of 100% higher modulus of soil constrained deformation than DMT. In this investigation point (498+40D), 6 soil samples were taken at a depth interval from 6.00 m to 7.45 m to perform a consolidation test in the laboratory. From the results of the consolidation test performed in the laboratory (see Table 3) it is possible to determine the value of the soil constrained deformation modulus. Thus, it is possible to compare the values obtained with DMT and CPT research data.

Comparing the consolidation test results with the CPT and DMT interpretations, it can be concluded that DMT test has determined a very precise modulus of soil constrained deformation E_{oed}. Differences in results are very minimal, so it can be concluded that the DMT test provides very accurate data on soil deformation, consolidation (constrained deformation modulus). Interpretations of the CPT test show greater values than the consolidation test. Judging by this comparison, there is a possibility that the CPT interpretations of the

Table 3. Consolidation test results in investigation point 498+40D

Depth, m	Density, Mg/m^3	E_{oed}, MPa	CPT E_{oed}, MPa	DMT E_{oed}, MPa
6.00	1.00	2.00	14.00	4.80
6.25	1.00	2.40	14.00	2.30
6.70	0.98	2.10	14.00	2.20
6.95	1.07	3.30	7.90	2.90
7.20	1.13	2.60	7.90	3.70
7.45	1.09	5.50	7.90	3.70

test show better soil constrained deformation properties than they are actually. Considering that different coefficients and partial factors are used in geotechnical calculations (soil strength reducing and others), we can use the specified deformation properties from CPT test, by carefully analysing not only the probing data but also other available information and, if necessary, manually reducing deformation modulus for geotechnical calculations.

4.3. 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 geotechnical engineer's task is to explore the subsurface conditions at a project site, determine the capacity of the soil to carry the load without collapsing or experiencing intolerable movement and to recommend appropriate foundation alternatives. The task might also expand to provide recommendations in other related areas such as groundwater and earthwork. 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 instance, clay reacts quite differently from sand. Peat and loose fill lying below a proposed structure are not suitable for supporting the structure. The poor material must be removed or stabilized or the foundations must be supported in firm material lying below the layer(s) of poor material. In order to find out the most rational and at the same time the most economically advantageous long-term solution, geotechnical calculations must be performed.

Slope stability and construction settlement were calculated using the soil parameters obtained by the CPT and DMT methods, and the difference between the calculation results was compared. For both calculations, we used specially developed calculation software, which allowed precisely defining all input parameters, as well as taking into account partial factors. The slope stability calculation program includes several developed calculation methods – Bishop simplified; Corps of Engineers #1 and Corps of Engineers #2 (also known as the Army Corp Modified Swedish Procedure); Janbu simplified and Janbu corrected (Janbu generalized method, satisfying both moment and force equilibrium); Lowe-Karafiath (essentially the same as the Corps of Engineers method, except that it uses another variation on the assumed interslice force function); Spencer (requires a computer program capable of cyclic algorithms). Therefore, it is easy to compare the parameters and take them into account when choosing the final solution.

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. It is one of several methods of slices developed to assess the stability of slopes. The main assumption of slope

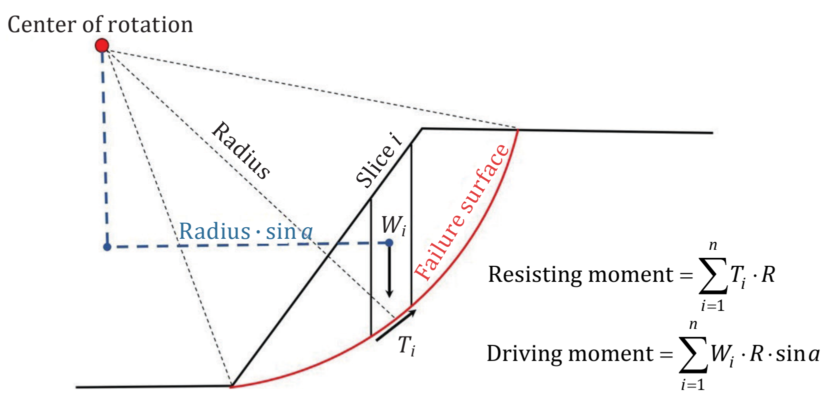

Figure 7. The Bishop Method of Slices

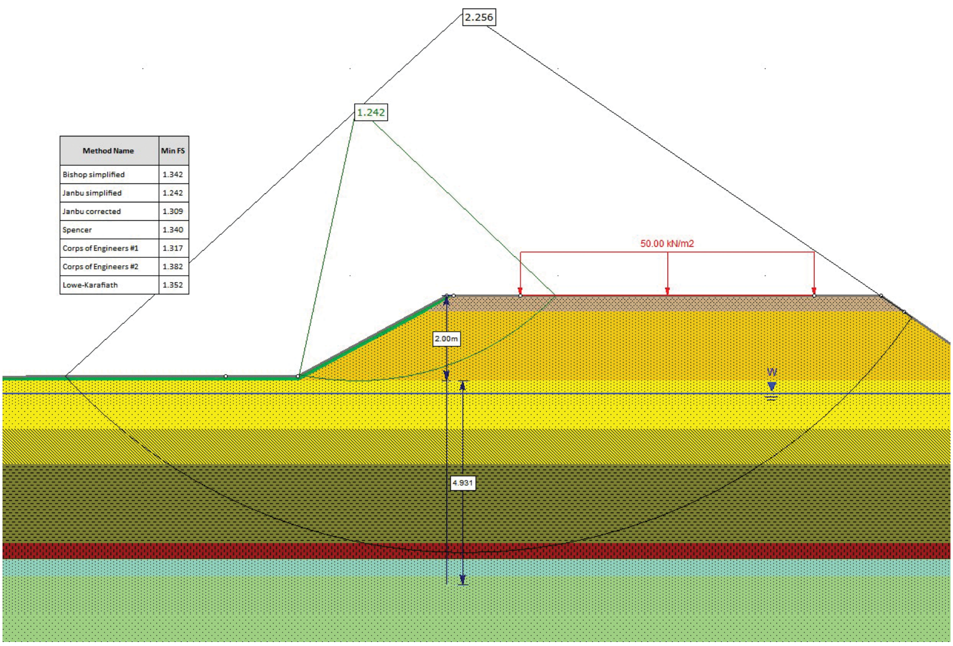

Figure 8. Slope stability calculation results using CPT soil parameter interpretations at investigation point 497+20D

stability is that the resisting forces are greater than the driving forces (see Figure 7). Formulas and calculation procedure are described in the Bishop Method of Slices (2023).

For the calculation of slope stability, the same constructive solution has been adopted for all calculations. It was assumed that the place where the probing was started on the existing foundation (at a depth of about 2 m) was the existing ground surface and a 2 m high road embankment was built on it. In addition to the backfill load, a distributed transport load of 50 kN/m^2 was applied. The road embankment was built with a slope of 1:2 and additionally assessed that the slope structure was reinforced with grass. The calculations used partial factors of Eurocode 7 – design approach 1, combination 2. The results of the first calculation using the CPT interpretation at investigation point 497+20D are shown in the graph (see Figure 8).

As can be seen from the results obtained, the stability of the slope is ensured because F_{safety} is greater than 1 in all methods. Within the road P32 site, the biggest problems were with soil deformations, so the results obtained were not surprising, as during the geotechnical survey it was determined that the upper soil layers were sandy and had relatively good properties, but low bearing capacity started at a depth of about 3.5 m.

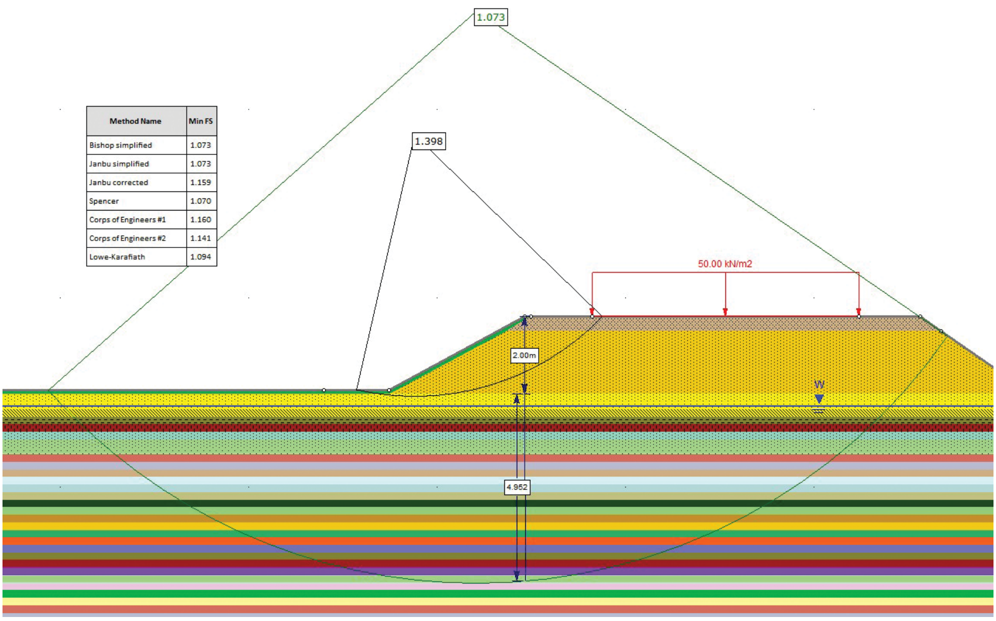

Figure 9. Slope stability calculation results using DMT soil parameter interpretations at investigation point 497+20D

Comparing the CPT and the DMT interpretations, it was found that the CPT method at investigation point 497+20D showed 180% higher undrained shear strength. Given that undrained shear strength is one of the most important properties of bound soils, such a difference in soil parameters can significantly reduce slope strength. The calculation of slope strength using DMT parameters is shown in Figure 9.

After the calculation, the slip surface with the lowest safety factor was determined and plotted. Comparing the two calculations, it can be seen that the difference between the safety factors is minimal. The result difference is 16% (DMT – F_{safety} = 1.070; CPT – F_{safety} = 1.242). However, a comparison of the slip surfaces shows that for the CPT study, it is located directly on the roadside, while there is a risk of the entire carriageway structure slipping for the DMT study. For a more accurate comparison of the results, Figure 9 and Figure 10 illustrate the slip surface, which roughly coincides with the calculation of slip surface by other methods. The result difference of slip surfaces located on the roadside is 12% (DMT – F_{safety} = 1.398; CPT – F_{safety} = 1.242). Judging by the calculation results, it can be seen that DMT research determined better soil parameters in the upper layers of the geology. The result difference of slip surfaces of the entire carriageway structure is 110% (DMT – F_{safety} = 1.070; CPT – F_{safety} = 2.256). Judging by the calculation results, it can be seen that DMT research determined worse soil parameters in the weak

Table 4. Safety factors for slope stability

Calculation based on properties of	Slip surface location	Factor of safety						
		Bishop simplified	Corps of Engineers #1	Corps of Engineers #2	Janbu simplified	Janbu corrected	Lowe-Karafiath	Spencer
CPT 497+20D	Directly on the roadside	1.342	1.317	1.382	1.242	1.309	1.352	1.340
DMT 497+20D		1.504	1.471	1.572	1.398	1.473	1.528	1.494
CPT 497+20D	Under entire carriageway structure	2.374	2.409	2.624	2.256	2.436	2.329	2.372
DMT 497+20D		1.073	1.160	1.141	1.073	1.159	1.094	1.070
CPT 498+40D	Directly on the roadside	1.342	1.317	1.385	1.225	1.303	1.352	1.34
DMT 498+40D		1.511	1.478	1.581	1.404	1.479	1.536	1.500
CPT 498+40D	Under entire carriageway structure	2.517	2.482	2.535	2.136	2.325	2.345	2.509
DMT 498+40D		1.336	1.414	1.407	1.247	1.354	1.356	1.353

soil layers. Given that it is almost impossible for the entire carriageway to slip, Figure 13 illustrates the existing base problem and the slip surface is formed directly through the low-bearing soils, which are highly fluid.

As in the first investigation point, the slip surface at point 498+40D for the CPT survey is located on the roadside, but for DMT survey there is a risk of the entire carriageway structure slipping. The safety factors for slope stability are summarised in Table 4. As can be seen from the obtained results, the minimum safety values for DMT and CPT are equal and differ from 1.8% to 16%.

Both DMT calculations further confirm that the existing soil layers are highly compressible. Judging by the results of the calculations, it can be concluded that by defining the soil parameters for each 20 cm thick layer, the existing properties of the soil layers can be represented more accurately. The soil layers are non-homogeneous, so the properties can vary greatly within the same soil type.

4.4. Construction settlement calculations using interpreted values

Settlement occurs from soil consolidation due to a reduction in voids or spaces between soil particles due to applied loads or changes in moisture content. The loss of moisture in soils causes consolidation. As the moisture takes up volume in the soil, and when the moisture is expelled, the soil loses volume and consolidates. In the opposite circumstance, when there is a buildup of moisture in the soils, smaller clays and silts, which were previously used to fill the voids between larger soil types and provide additional structural support, will drain downwards in the ground when the moisture eventually subsides. This will cause the supporting soil to lose its load-bearing capabilities. If the water content increases in clayey, organic soils, there is a possibility of observing the phenomenon of swelling.

The main problem in the section of the P32 road was the deformation of the soil, because under the embankment weak load-bearing capacity soil layers were found in the variable thickness and depth. Within the framework of the research, the calculation of the structure settlement was performed using the soil parameters obtained in the interpretations of CPT and DMT tests. For settlement calculations, we used specially developed calculation software, which allowed precisely defining all input parameters, as well as taking into account partial factors. For analytical slope stability calculation, consolidation and settlement formulas were developed. Brief description of analytical calculations is given in a geotechnical design manual (SCDOT, 2019).

For the calculation of construction settlement, the same constructive solution was adopted for all calculations. It was assumed that the place where the probing was started on the existing foundation (at a depth of about 2 m) was the existing ground surface and a 2 m high road embankment was built on it. In addition to the backfill load, a distributed transport load of 50 kN/m^2 was applied. The road embankment was built with a slope of 1:2. The calculations used partial factors of Eurocode 7 – design approach 1, combination 2. The results of the first calculation using the CPT interpretation at investigation point 497+20D are shown in Figure 10, and the calculation using the DMT interpretation at point 497+20D is shown in Figure 11.

According to the obtained results of the calculations, the greatest deformation occurs in the layers of peat, sludge and flowing loam, because the constrained deformation modulus of these layers has the lowest values. The settlement of the structure is determined to be 3.98 cm. Given that the calculation model defines that the peat layer starts from a depth of 2 m, the amount of deformation is not too large; however, it must be acknowledged that this is a simplified calculation that uses only a few interpreted soil parameters – density and E_{oed} (constrained deformation modulus).

According to the obtained results of the calculations, the greatest deformation occurs in the layers of peat, sludge and flowing loam,

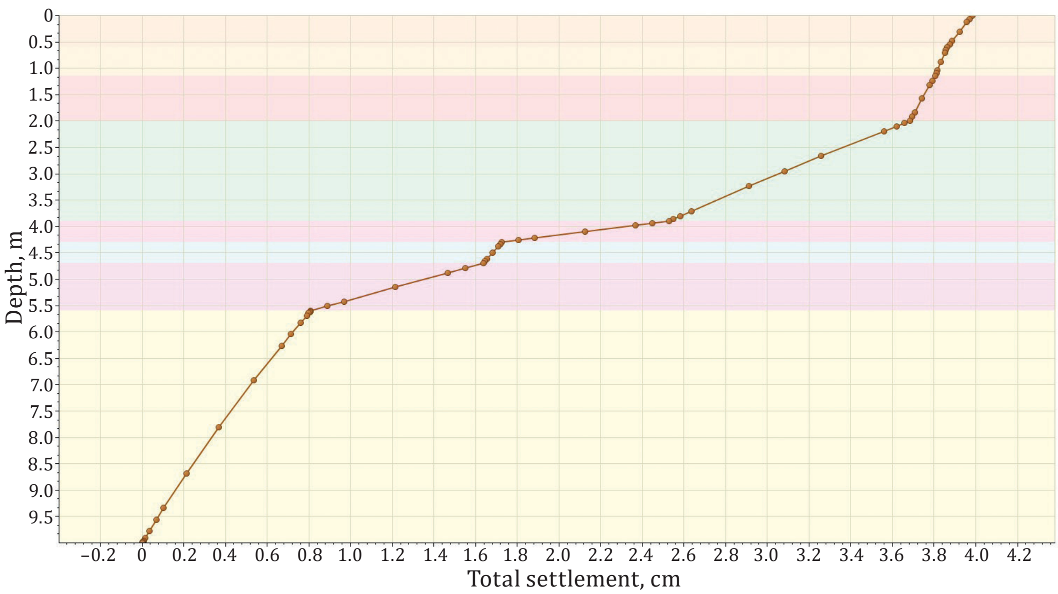

Figure 10. Construction settlement results using CPT soil parameter interpretations at investigation point 497+20D

because the constrained deformation modulus of these layers has the lowest values. The settlement of the structure is determined to be 12.00 cm. 11 cm of the total deformation of the structure occurs in the range from 2.4 m to 5.4 m. Comparing the results of the CPT and DMT calculations, it can be seen that in both calculations the largest deformations occur in the same soil layers. The settlement volume determined by the CPT study is 3.98 cm, but with the DMT study it is 12 cm. The difference between the results obtained is 8.02 cm or approximately 3 times. Given that we have previously determined

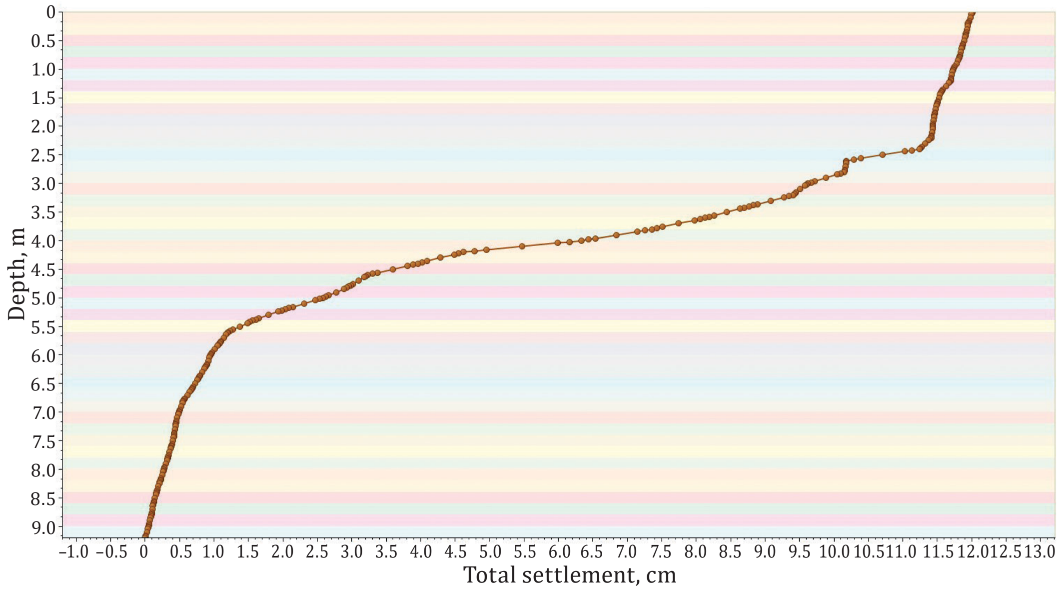

Figure 11. Construction settlement results using DMT soil parameter interpretations at investigation point 497+20D

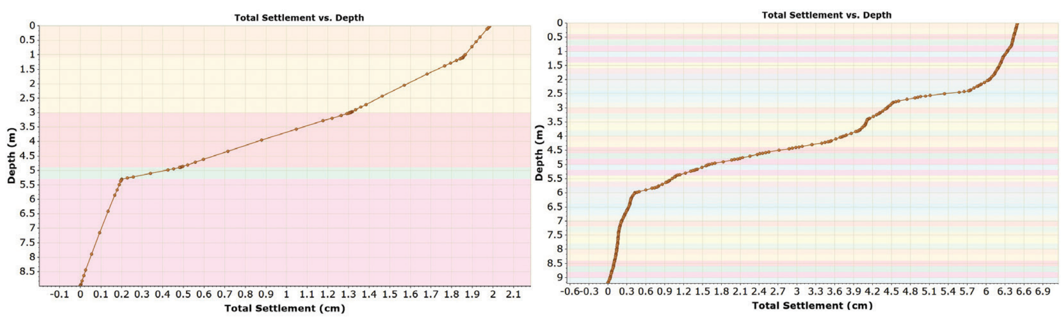

Figure 12. Construction settlement results using soil parameter interpretations at investigation point 498+40D – left side CPT; right side DMT

that the sludge deformation values for the DMT study coincided with the results of the consolidation test (at a depth of 6.35 m), it can be concluded that the calculation with the CPT test data gives a more optimistic structural settling result than that actually expected.

The compaction of the structure was also calculated at study point 498+40D. The obtained results are summarised in Figure 12.

According to the obtained results of the both calculations, the greatest deformation occurs in the layers of peat, sludge and loose sand, because the constrained deformation modulus of these layers has the lowest values. The settlement of the structure is determined to be 1.99 cm from CPT data and 6.50 cm from DMT data. 90% of the total deformation of the structure occurs in the range from 2.0 m to 5.5 m. The difference between the results obtained is 4.51 cm or approximately 3.25 times. Given that we have previously determined that deformation values for the DMT study coincided with the results of the consolidation tests (6 test samples), it can be concluded that the calculation with the CPT test data gives a more optimistic structural settling result than that actually expected.

The CPT and DMT methods are very different in terms of both the probing equipment and the research process itself. The DMT study interprets the obtained test data in 20 cm increments, so that changes in soil properties can be assessed very accurately. The CPT survey first identifies the same soil types and then the geotechnical survey engineer divides the survey data into layers of equal strength (usually layer thickness > 0.4 m) and the layer average cone resistance is interpreted. It is possible that this difference significantly affects the results obtained during the correlations. The results of the average data do not allow estimating the changes in strength within one soil type. The amount of deformation and the results of other geotechnical calculations when evaluating the minimum and maximum values of the soil could differ significantly from the results obtained using the average values of the layers. However, in-depth research should be carried out in another study to ascertain this.

4.5. Construction solutions from the safety and economic point of view

Road design is a complex, time-consuming, and very responsible process. When developing road solutions, it is necessary to take into account the data of geotechnical investigation and finding low bearing capacity soils or revealing other problems, geotechnical calculations must be performed to determine whether special solutions need to be provided in the project.

Table 5. The approximate costs of geotechnical solutions if the DMT interpretations are accurate for 1000 m long road section with road profile NP9,5

Geotechnical solutions based on DMT interpretation calculations in investigation point 497+20D	Solution of concrete columns/piles under road embankment for construction settlement		Solution of geosynthetic materials for slope stability		Soil exchange
Geotechnical solutions based on CPT interpretation calculations in investigation point 497+20D		Solution of geosynthetic materials for construction settlement		Solution of geosynthetic materials for slope stability	
Construction costs, EUR	1 401 750	495 000	202 500	165 000	1 890 000
Repair of pavement defects if the DMT's interpretations are accurate EUR	0	206 500	0	206 500	0
Road reconstruction costs if the DMT's interpretations are accurate EUR	826 000	1 239 000	826 000	1 239 000	826 000
Cost of resurfacing the pavement if the DMT's interpretations are accurate EUR	818 792	1 324 470	818 790	1 324 470	818 790
Road transport operating costs if the DMT's interpretations are accurate EUR	10 409 996	11 117 204	10 409 996	11 117 204	10 409 996
Cost of time spent by road users if the DMT's interpretations are accurate EUR	1 332 093	1 902 990	1 332 093	1 902 990	1 332 093
Total cost for a period of 50 years if the DMT's interpretations are accurate EUR	14 788 631	16 285 164	13 589 379	15 955 164	15 276 879

Table 6. The approximate costs of geotechnical solutions if the CPT interpretations are accurate for 1000 m long road section with road profile NP9,5

Geotechnical solutions based on DMT interpretation calculations in investigation point 497+20D	Solution of concrete columns/piles under road embankment for construction settlement		Solution of geosynthetic materials for slope stability		Soil exchange
Geotechnical solutions based on CPT interpretation calculations in investigation point 497+20D		Solution of geosynthetic materials for construction settlement		Solution of geosynthetic materials for slope stability	
Construction costs, EUR	1 401 750	495 000	202 500	165 000	1 890 000
Repair of pavement defects if the CPT's interpretations are accurate EUR	0	0	0	0	0
Road reconstruction costs if the CPT's interpretations are accurate EUR	826 000	826 000	826 000	826 000	826 000
Cost of resurfacing the pavement if the CPT's interpretations are accurate EUR	818 792	818 792	818 790	818 790	818 790
Road transport operating costs if the CPT's interpretations are accurate EUR	10 409 996	10 409 996	10 409 996	10 409 996	10 409 996
Cost of time spent by road users if the CPT's interpretations are accurate EUR	1 332 093	1 332 093	1 332 093	1 332 093	1 332 093
Total cost for a period of 50 years if the CPT's interpretations are accurate EUR	14 788 631	13 881 881	13 589 379	13 551 879	15 276 879

Taking into account the calculations of slope stability and construction settlement made within the framework of the study, a cost comparison for different geotechnical structure solutions was developed. In addition to the construction costs of the solutions, the potential costs of repairing structural defects were assessed. The approximate costs of geotechnical solutions if the DMT interpretations are accurate are shown in Table 5, and the approximate costs of geotechnical solutions if the CPT interpretations are accurate are shown in Table 6.

As can be seen from the estimated costs over a 50-year period in Table 5 and Table 6, the solutions developed based on DMT interpretations do not differ in terms of costs. In contrast, the cost of solutions developed based on CPT interpretations can vary by up to 2.5 million EUR. In case, if the CPT interpretations have shown that the physical and mechanical properties of the soil are higher than they are actually, there are additional costs for repairing the defects and the road must be rebuilt more frequently.

Conclusions

The main advantage of the DMT test is that it determines the soil properties for each 20 cm thick layer, so a larger stratum with an average parameter value is not formed. The soil layers are very heterogeneous, so the properties can vary greatly within the same soil type.

The main advantage of the CPT study is that the cone resistance values are obtained directly during probing and the values obtained by performing several tests at one study point should be the same. Q_c data can be checked by re-probing.

Both methods provide soil undrained shear strength values with a safety margin. The DMT study showed lower undrained shear strength values than the CPT. Constructive solutions would be more expensive, but thus safer than the CPT method.

The stability of the slopes was ensured using the soil parameters interpreted by the CPT and DMT. The CPT study showed higher values for the soil parameters, resulting in a safety factor 16% higher than for the DMT method.

DMT test has determined very precise modulus of soil constrained deformations E_{oed} compared to the consolidation test. Interpretations of the CPT test showed greater values than consolidation test. Therefore, there is a possibility that the CPT interpretations of the test show better soil deformation properties than they are actually.

The difference between CPT and DMT settlement results obtained was approximately 300%. CPT test data give a more optimistic structural settling result than that actually expected.

Average soil properties do not allow estimating the changes in strength within one soil type. The amount of deformation and the results of other geotechnical calculations could differ significantly using the average values of the layers or, on the other hand, using properties for each 20 cm thick layer. However, in-depth research should be carried out in another study to ascertain this assumption.

Geotechnical solutions developed based on DMT interpretations provide greater structural safety compared to the CPT, but also increases construction costs.

Solution total costs, developed based on CPT interpretations, can vary by up to 17% for a period of 50 years.

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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