WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2021.138518

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVII ISSUE 4 2021

pp. 559 –572

Research paper

Strengthening of the soft soil loaded with heavy construction traffic based on dilatometer tests

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Abstract: The presence of soft soil of river and organic genesis in the basement of road embankments creates problems related to their high deformability. Difficult to assess water permeability, affecting the course of the consolidation and settlement process, requires field studies, such as dilatometer tests. In engineering practice, there are many factors that can affect the basement consolidation process, but they are not simply applied to theoretical models. In many cases, only the observational method allows the selected computational approach to be applied to a specific engineering problem. For this reason, it is one of the approaches strongly emphasized by Eurocode 7. The article presents an example of the application of a temporary load from heavy construction traffic to the consolidation of soft soil under service roads with verification of the subsoil parameters using the dilatometer tests. A horizontal layer of weak soil, loaded with a vertical external load caused by temporary traffic, was assumed for the calculations. For such an arrangement, the classical solution of uniaxial Terzaghi's consolidation with the water flow in the vertical direction was applied. A computational analysis of the consolidation time and maximum settlement values was performed.

Keywords: soil improvement, static consolidation, settlements calculation, traffic load, dilatometer test DMT

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1. Introduction

With the intensive developing of the road expressway and railway projects in Poland a significant problem is the foundation design on the soft soil. One of the most important problem is the reduction of soil replacement or ground improvement in favour of its consolidation.

Deformation of the soil is strongly dependent on time, especially in soft soil. This consolidation problem in a saturated soil can also be retarded by the time that it takes for the water to flow out of the soil. In compression of a soil the porosity decreases and as a result there is less space available for the pore water. This pore water may be expelled from the soil, but in soft soil this may take a certain time, due to the law permeability. Presented analysis is restricted to one dimensional deformation, assuming that the soil does not deform in lateral direction. It is also assumed that the water can only flow in vertical direction. Similar case occurs during an oedometer test or in the field, in case of a surcharge load over a large area. Because the coefficient of consolidation c_v is the quotient of the permeability k and the compressibility m_v the consolidation process takes longer if the permeability is smaller or if the compressibility is larger. The consolidation process consists of compression of the soil retarded by the outflow of water. This problem was presented by many authors in the past e.g. [2, 4, 6, 14]. Also, several authors present advanced theoretical models of this phenomena like [7, 8] or [12] In engineering practice, there are many factors that can affect the consolidation process of the basement of structure like cycling loading [11] or any type of preloading [3]. They are not simply applied to theoretical models. The complexity of the occurrence of these processes is not possible to generalize theoretically without a series of generalizations. Practically in many cases only the observational method allows the use of a selected design approach in a specific engineering problem. For this reason, it is one of the approaches strongly emphasized by the Eurocode 7 [17].

Based on the field observation of soft soil modulus increase under temporary heavy load authors focused to the problem of practical application of this type of preloading in consolidation approach. A horizontal layer of soft soil with an initial thickness H_0, uniformly loaded with a vertical external load due to temporary traffic, was assumed for the analysis. For such case, the classical solution of uniaxial Terzaghi's consolidation [16] with the water flow in the vertical direction is possible. Finally, the paper presents an example of the consolidation analysis at the construction stage for two selected sections of service roads. Both are located on alluvial soft soil – silt and peat. In the analysis, the compressibility modulus of the subgrade of the partially constructed roads was estimated and the serviceability limit state (ULS) was calculated in the Geo5 Fine software. At the construction stage both roads were used as technological roads for heavy job-site equipment (up to 40 tons cycling loading). In the final stage, as final service roads, their proper geometry was formed, and an asphalt surface was laid. The structural section of both roads is given in Fig. 1. The ground level of temporary job-site road (operation stage) is marked in red.

Because of lack of soil replacements carried out on the analysed sections 1 and 2, finally there was a problem to use them in the operation stage without any additional improvement of the basement. For this purpose, additional in-situ tests and verification calculations were performed to verify the originally adopted soil parameters for the design and predicted settlements of the roads. As verification tests, a total of 13 dilatometer tests (DMT – Marchetti Dilatometer

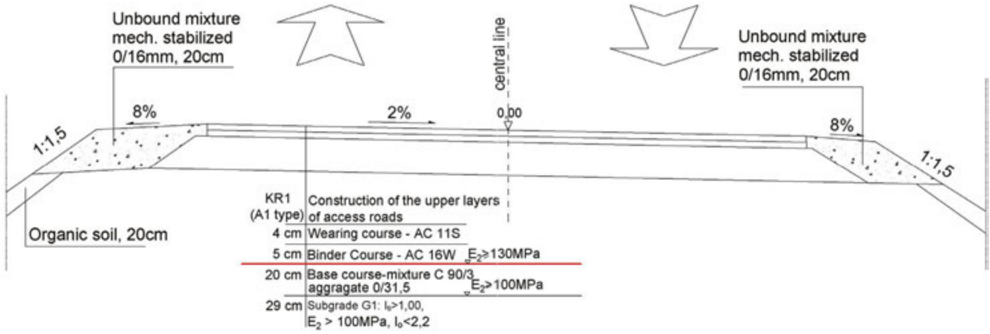

Fig. 1. Typical design section of the analyzed roads

Test [18]) were done for two selected sections and parallelly for greenfield area nearby. The location of the DMT test and both service roads is presented in Fig. 2. The analysis covered the following road sections:

- Section 1 approx. 500 m – 7 DMT tests for service road and 2 tests in the greenfield area;
- Section 2 approx. 250 m – 3 DMT tests for service road and 1 test in the greenfield area.

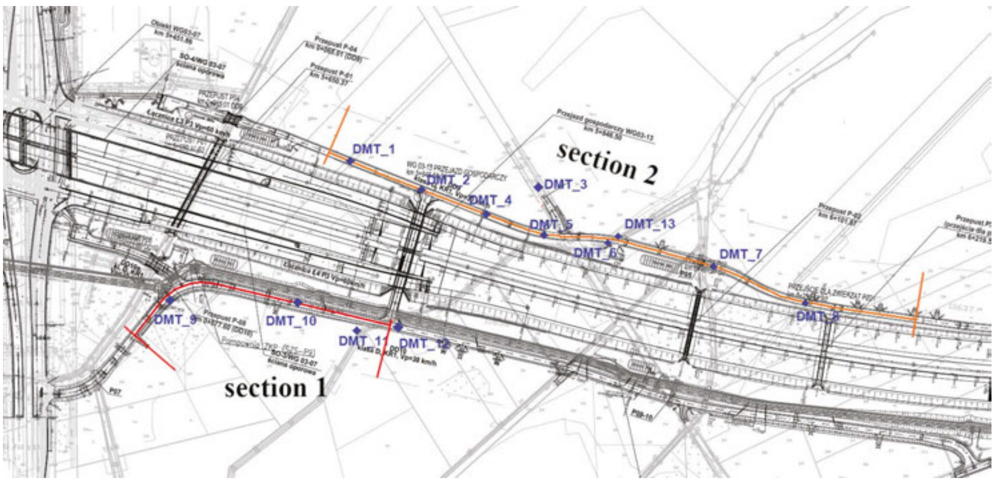

Fig. 2. The field tests DMT location map

The aim of this study was to understand the variability (increase in time) value of the deformation modulus of soft soil under the influence of heavy traffic job-site load in a period of about 24 months of construction. Because of thin layer of binder and asphalt should be added in the last stage (red line in the Fig. 1) and only local traffic was provided by this road it was reasonable to use all the compacted base and consolidated subgrade without any additional replacements and improvements of soft soil of 2 m thickness below. The widespread use of DMT research in various geological conditions requires the verification or adaptation of existing formulas to determine the geotechnical parameters of local soil in Poland [1, 5, 15].

2. Geotechnical conditions

Analysed area is located in the river valley, on the alluvial deposits [9]. The ground elevation is approx. 5 m above river level. In the basement there are river deposits, formed as sand of various granulations (fine and medium) and soft alluvial and organic deposits (organic silt, gyttja and peat). Fig. 3 shows general scheme of the soil layers in the area. The groundwater table is located relatively close to the ground surface. In general, there are the difficult soil and water conditions and the layers of cohesive and organic soil require strengthening. Typical geotechnical cross-section is presented in Fig. 3. Geotechnical parameters of each layer are described in Table 1.

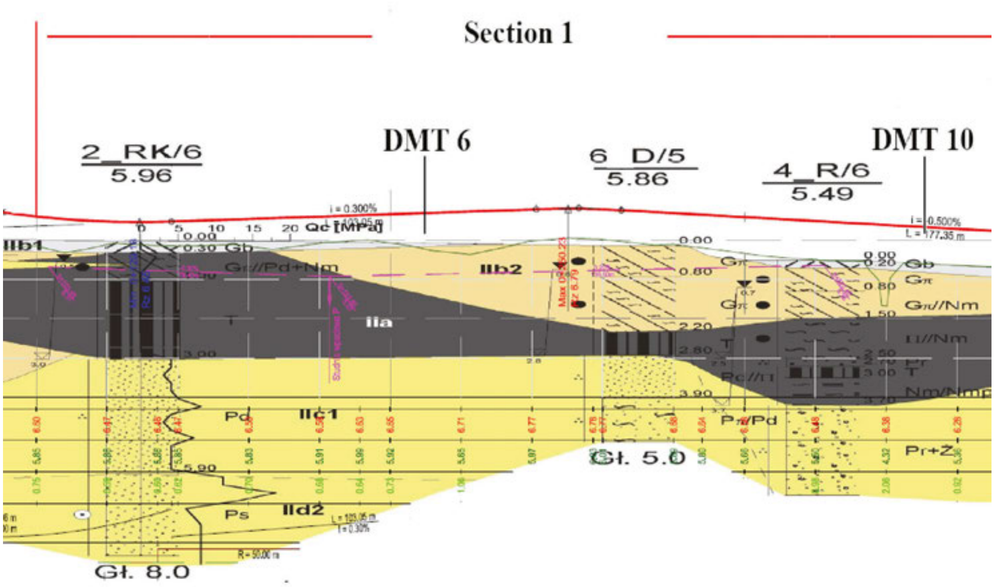

Fig. 3. Geotechnical cross-section of the section 1 area [9]

On the section 1 of the service road at depth up to approx. 3.4 m b.g.l. there are alluvial soft soil – silt deposits (DMT 10). This layer IIb2 is in the soft-plastic and plastic state and passes to the peat layer IIa. Below of this complex, there is a continuous layer of sandy sediments of various granulation in a loose (IIc1) and medium dense (IId2) state. The groundwater level stabilizes at a depth of 0.5–2.1 m b.g.l.

In the location of second analyzed section 2 up to a depth of approx. 4.5 m below the ground level (DMT 6), there are alluvial deposits in the soft-plastic and plastic state (IIb2). As in the case above, there are also organic soils of the IIa layer. Below there is a complex of sandy sediments of layer IIc1 and IId2. The groundwater level stabilizes at a depth of 0.5–1.7 m b.g.l. Locally, in both sections the water table is under pressure.

Table 1. Geotechnical parameters of subsoil

Soil layer and type	Physical parameters				Strenght parameters				Defformation parameters		
					Drained tests		Undrined tests				
	Density index/ (Liquidity index)	Specific density	Bulk density	Coefficient of permeability	Friction angle	Cohesion	Friction angle	Shear strength	Poisson ratio	Deformation modulus	Oedometric modulus
	$I_D/(I_L)$ [–]	ρ_s [t/m^3]	ρ [t/m^3]	k [m/s]	φ' [°]	c' [kPa]	φ_u [°]	τ_f [kPa]	v [–]	E [MPa]	E_{oed} [MPa]
IIa Or (Peat, Soft clay)	(0.70–0.85)	2.50	1.00–1.60	10^{-8}–10^{-5}	–	–	0	20–60 25*	–	2	2–16 4*
IIb2 sasiCl, clSi, Si, clSa	(0.30–0.45)	2.65–2.68	1.90	10^{-8}–10^{-5}	27	2	0	50-180	0.32	7	8–12
IIc1 FSa, siSa	0.20–0.35	2.65	1.85	10^{-5}–10^{-4}	28	0	28–29 28*	0	0.30	18	20–40 23*
IId2 MSa, CSa	0.35–0.45	2.65	2.00	10^{-4}–10^{-3}	33	0	36–39 37*	0	0.25	30	40–180 44*

* – average value

3. Marchetti dilatometer test

One of the basic approaches of settlement analysis based on the oedometer modulus E_{oed} of the subsoil. Accuracy of this calculations depends on the precision of the estimation of this parameter in the most precise way. One of this option are in-situ tests. Because of this several dilatometer test DMT (Fig. 2) were performed in order to determine the strength and deformation properties of the soil in-situ. The value of compressibility modulus in dilatometer test is obtained by applying to dilatometer modulus E_D the correction factor R_M [10]:

$$E_{oed} = R_M \cdot E_D \tag{3.1}$$

where:

$R_M = 0.12 + 1.8 \log K_D$ for organic soil (gyttja and organic silt);
$R_M = 0.5 + 2 \log K_D$ for non-cohesive soil $I_D < 3$;
$R_M = R_{M,0} + (2.5 - R_{M,0}) \log K_D$ for $0.6 < I_D < 3$;
$R_M = 0.14 + 2.36 \log K_D$ for $I_D < 0.6$.

To extract dilatometer modulus E_D it's necessary to measure values of pressure p_0 and p_1 which are used to determine dilatometer modulus at the depth of the measurements. The test starts by inserting the dilatometer a flat steel blade into the ground. By use of a control unit with a pressure regulator, a gauge and audio signals, the operator determines, in about 1 min, the p_0 – pressure required to just begin to move the membrane and the p_1 – pressure required to move its centre 1.1 mm into the soil. The blade is then advanced into the ground of one depth increment, typically 20 cm, using common field equipment with constant value of velocity 0.02 m/s [18].

$$E_D = 34.7(p_1 p_0) \tag{3.2}$$

where: p_1 – pressure required to move the centre of membrane 1.1 mm into the soil, p_0 – calibrated "lift-off" pressure required to initiate movement of the membrane against the soil.

Dilatometer modulus characterizes the relationship between the stress acting on the membrane and its one-millimetre displacement and reflects the stiffness of the soil. In clay and silt, the measured soil stiffness corresponds to the conditions without drainage, and in sands, the obtained stiffness measure should be related to the conditions of full drainage. The measured values of pressure p_0 and p_1 as well as the calculated values of the effective vertical stress σ'_{vo} and the hydrostatic pore pressure u_0 were used to determine rest parameters for modulus extraction [11]:

$$K_D = \frac{p_0 u_0}{\sigma'_{v0}} \tag{3.3}$$

$$I_D = \frac{p_1 p_0}{p_0 - u_0} \tag{3.4}$$

where: K_D – horizontal stress index, I_D – material index.

The Marchetti's classification based on the I_D material index where the value of the material index $I_D < 0.10$ points to peat or soft clay. However, it should be pointed out that the diagram was developed based mainly on the mineral soil tests. In the literature we can find the diagram which shows the relationship between the material index I_D and the dilatometer modulus E_D [11]. Soils are classified as organic/soft soil one where the material index $I_D < 0.6$ and the dilatometer modulus $E_D < 1.2$ MPa. In the Table 2 there are presented all the soil types classified by the Marchetti's material index. In the Fig. 4 there are presented interpreted values of several parameters from one of the test DMT 5. The main target of the tests was to compare the outcomes of deformation modulus from tests on the greenfield (without overload from heavy traffic) and with those one made on the service road after several weeks of job-site heavy equipment load. The example outcomes of this comparison are presented in the Fig. 5 for road of Section 1 and in Fig. 6 for road of Section 2 and in details at Table 3. In the presented graphs

Table 2. Soil classification based on material index I_D

Soil Type		Material Index I_D (–)
Organic soil and cohesive soil	Peat/Soft clay	< 0.10
	Clay	0.10–0.35
	Silty clay	0.35–0.60
	Clayey silt	0.60–0.90
	Silt	0.90–1.20
	Sandy silt	1.20–1.80
	Silty sand	1.80–3.30
Non-cohesive soil	Sand	> 3.30

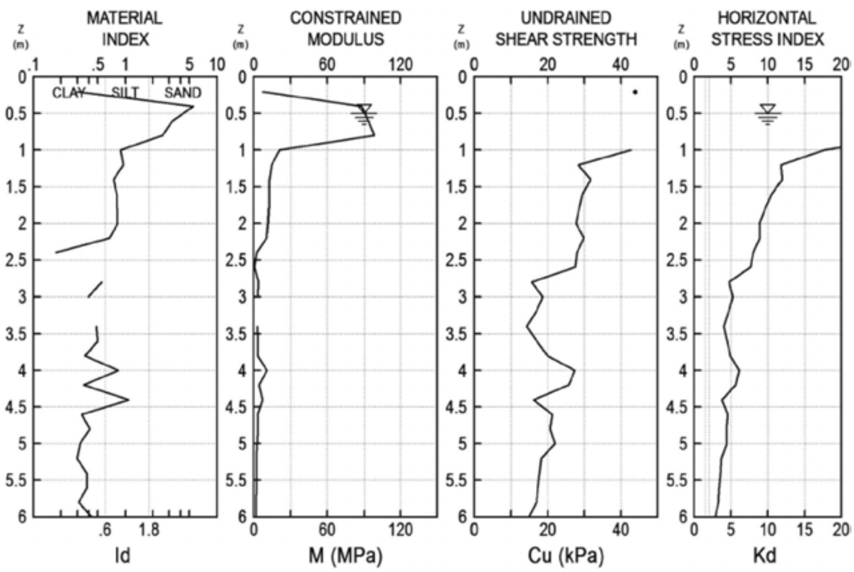

Fig. 4. DMT5 dilatometer test results [9]

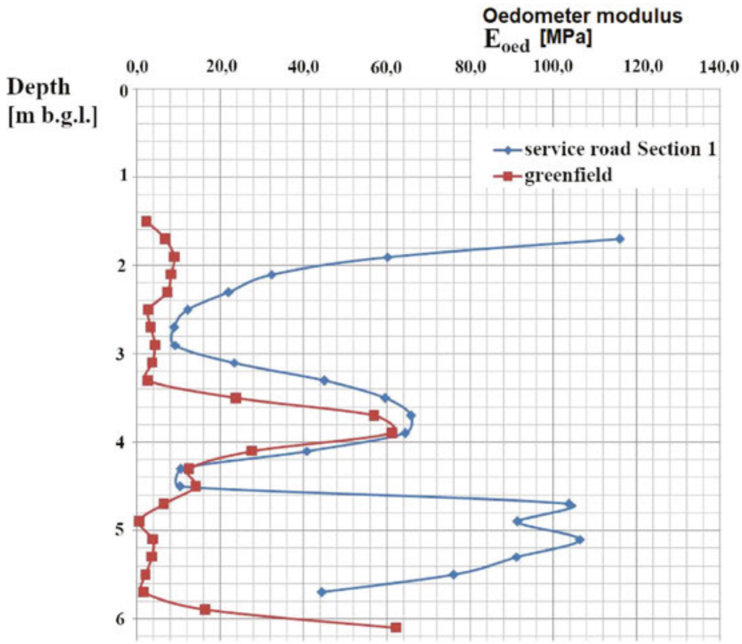

Fig. 5. Compressibility modulus from the DMT tests in the basement of section 1 and in the greenfield

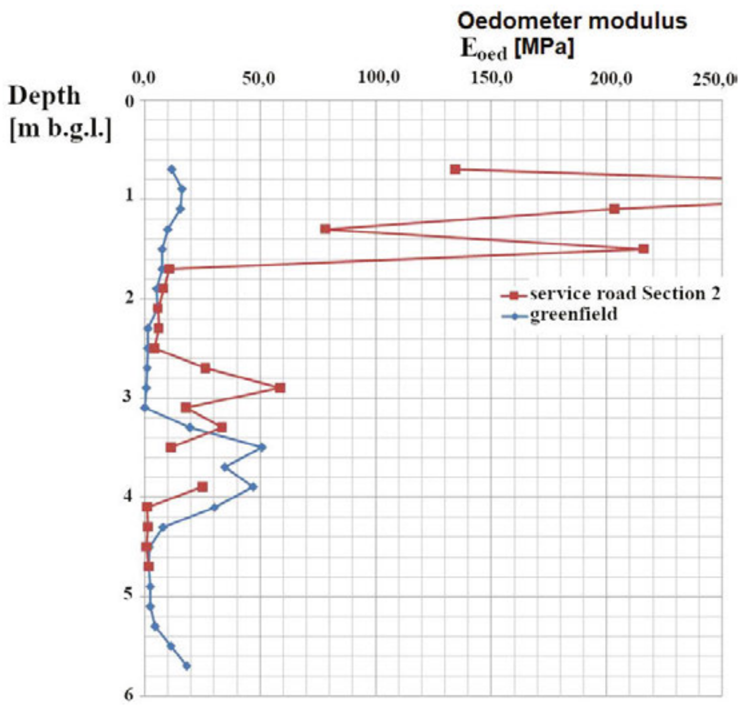

Fig. 6. Compressibility modules from the DMT tests in the substrate of section 2 and greenfield

it is well visible the increase of modulus value between virgin stage and after several weeks of site traffic operation strengthening over time generally from 2 to 3 times (the greenfield modulus of Section 1 was approx. $E_{\mathrm{oed}} = 1.1$ MPa and for Section 2 $E_{\mathrm{oed}} = 3.3$ MPa).

Table 3. Final soft layer parameters for calculation

DMT number	Section number	Depth of soft soil layer [m b.g.l.]	Oedometer modulus based on DMT test in road axis [MPa]
DMT 1	1	2.2–3.4	5.4
DMT 5	1	0.8–2.0 2.0–7.0	12.2 2.5
DMT 6	1	1.2–3.4 5.0–6.0	6.0 1.2
DMT 7	1	2.0–4.2	1.9
DMT 8	1	1.2–2.4	4.3
DMT 9	2	1.0–2.4	6.4
DMT 10	2	1.6–2.2 3.4–3.8	9.2 10.3
DMT 12	2	1.8–2.2 4.0–4.2 4.4–4.8	4.1 12.6 0.8

While check of the soft soil modulus was done, the permeability of the consolidated material was measured. This test of dissipation of pore water pressure was conducted for organic soil and alluvial clay to estimate the time of consolidation. One of the exemplary results of the typical dissipation test graph on the testing area is shown at Fig. 7. The test was performed at depth 3 m with the material index 0.39 and T_{flex} value 0.77 min. To estimate the horizontal coefficient of consolidation c_h the dissipation tests were conducted. This method consists in stopping the blade at a given depth, then taking a sequence of readings A. In practice the method is based on the rate of decay of the total contact horizontal stress σ_h [16]. The c_h coefficient was obtained as:

$$c_h = \frac{7\ \mathrm{cm}^2}{T_{\mathrm{flex}}} \tag{3.5}$$

where: T_{flex} – the time associated with the contraflexure point in the A-log t curve.

In order to estimate the consolidation time of the soft soil and thus the time to complete settlements, the in-situ filtration coefficient was determined in selected DMT tests as presented in Table 4 with the location of each test at Fig. 2. The depth of tests varies from 1.8 to 4.6 m so whole thickness of the soft soil layer was checked. The range of permeability of the consolidated layer is between 1×10^{-7} up to 7×10^{-9} m/s but average value is 4.6×10^{-8} m/s.

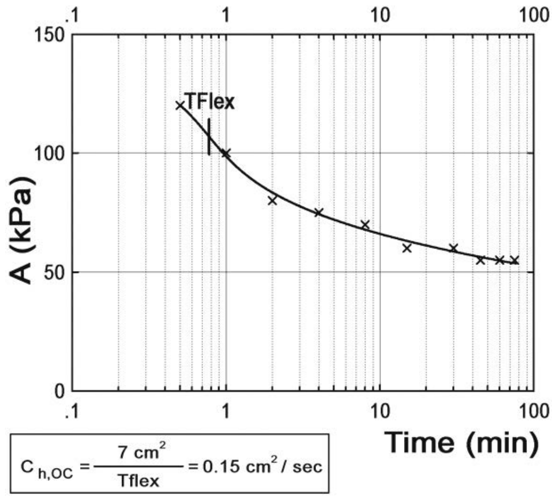

Fig. 7. DMT5 dissipation test at depth of 3 m [9]

Table 4. Coefficient of permeability results by DMT tests [9]

Test number	Depth [m bgl]	Permeability coefficient k [m/s]
DMT 3	3.2	7.0×10^{-9}
DMT 5	3.2	5.4×10^{-8}
DMT 6	3.4	3.3×10^{-8}
DMT 7	3.0	1.0×10^{-7}
DMT 10	3.8	2.2×10^{-8}
DMT 11	1.8	2.7×10^{-8}
DMT 11	3.6	9.0×10^{-8}
DMT 12	4.6	1.1×10^{-7}
DMT 13	4.4	4.9×10^{-8}

4. Calculation methodology

In the first step, on the basis of the field tests time of the consolidation was checked. Then consolidation settlements were extracted. The calculations based on consolidation analysis determined according to Terzaghi's theory and in-situ data:

– the thickness of the soft soil layer from DMT tests in the axis of the analyzed sections;
– permeability coefficient – the average value was applied;
– soft soil compressibility modulus – based on comparative tests carried out in the green-field area.

$$U_v = \left(1 + \frac{1}{2 \cdot T_v^3}\right)^{-\frac{1}{6}} \tag{4.1}$$

$$T_v = \frac{C_v \cdot t}{H^2} \tag{4.2}$$

where: U_v – degree of vertical consolidation, T_v – time factor, C_v – coefficient of consolidation, H – thickness of the consolidated layer, t – time of consolidation.

It was assumed in the analysis that at the construction stage, the movement of heavy equipment on technological roads is equal to the equivalent uniformly distributed load from vehicle traffic $q = 25$ kN/m^2. In the target phase of operation, due to the traffic category of service roads, the loads will not be greater. The results of the calculations – the forecast consolidation time of the soft soil based on the original value of soil parameters measured in the greenfield are presented in Table 5. Calculated time of consolidation settlements for the Section 1 takes about 7 months. For the Section 2 where stiffness of soft layer is higher settlements will take place much faster within about 1 week.

Table 5. Calculated consolidation time for roads in section 1 and 2

DMT number	Section number	Thickness of consolidated layer [m]	Time of consolidation (up to 90% Ur) [weeks]
DMT 5	1	6.8	~27
DMT 6	1	3.2	~6
DMT 7	1	2.2	~3
DMT 10	2	1.2	~1
DMT 12	2	1.0	~1

The settlements analysis was calculated on the basis of oedometer modulus according to the following formula:

$$s_i = \sum \frac{\sigma_{z,i} \cdot h_i}{E_{oed,i}}, \tag{4.3}$$

where: σ_{zi} – additional vertical stresss in the center of the soft layer, h_i – thickness of the soft layer, $E_{oed,i}$ – oedometer modulus of soft layer.

The calculations done in Geo5 software considers the following construction stages:

– initial stage;
– excavation, incomplete replacement of the soil and a temporary job-site road installation;
– load from heavy equipment along the technological road (temporary stage – 24 months);
– adding an asphalt layer of the final service road;
– local traffic on the service road (final stage).

For the calculations, the weight of the exchange material was assumed as $\gamma = 20$ kN/m^3 and the weight of the soft soil as $\gamma = 17$ kN/m^3. Compressibility modulus was extracted individually from each DMT test and summarized in Table 3.

The results of analysis with the maximum calculated settlements in the last construction stage are presented in Fig. 8. Analysis was done by Geo5 software in each DMT section presented in Fig. 2. In Table 6, there are summarized settlements in each analyzed section at final construction stage, based on individual DMT test profiles. Calculated settlements do not exceed $s < 4$ cm which is lower than the permissible value $s_{max} = 10$ cm.

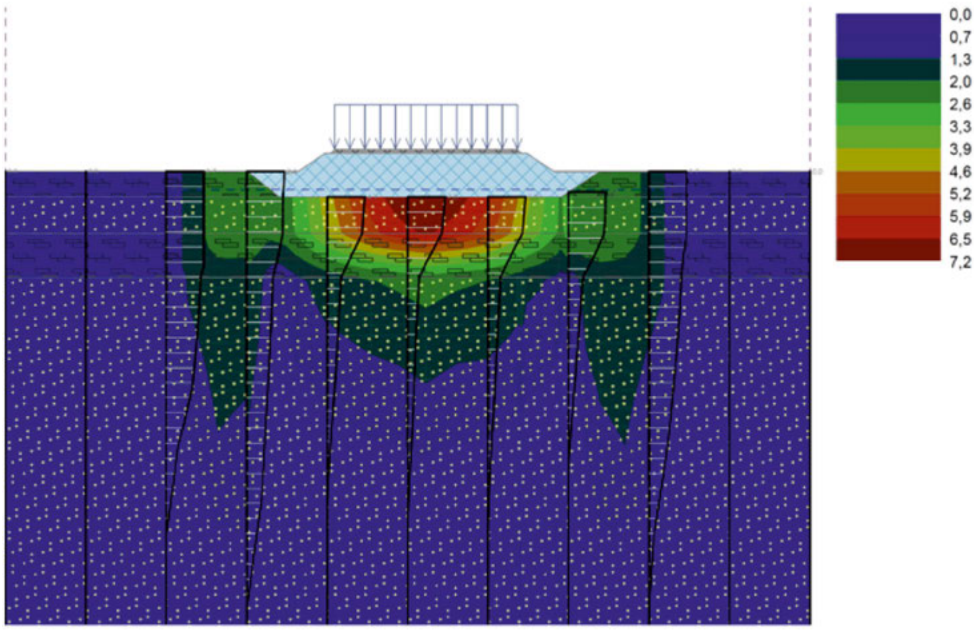

Fig. 8. Settlements analysis in section 1 – DMT1

Table 6. Outcomes of the final consolidation settlements

DMT number	Section number	Settlements for the service road final operation stage [mm]
DMT 1	1	7.2
DMT 5	1	34.7
DMT 6	1	22.4
DMT 7	1	22.8
DMT 8	1	8.0
DMT 9	2	6.6
DMT 10	2	3.8
DMT 12	2	12.1

5. Conclusions

In the dilatometer in-situ tests it is clearly visible increase of the value of compressibility modulus of soft soil – from 2 to 3 times. This is from comparison compressibility modulus in the axis of the service roads and greenfield. The increase is due to long term temporary load of heavy equipment traffic on technological roads in comparison to the same soil profile in the nearby greenfield area. These differences are visible up to a depth of approximately 3 m below the surface. Those outcomes indicate a zone of stress increase from the embankment and job-site traffic along it. Good quality in-situ tests should be done to get knowledge about real basement geotechnical model for calculations.

On the basis of analysis, in some cases it is reasonable to take into account the fact of possible soft soil consolidation process under temporary traffic load in the construction stage. However, it should be remembered that load from heavy equipment traffic is variable and cause slower consolidation effect. In such cases, the authors propose to use a correction factor and make twice final consolidation time in relation to the presented calculation approach.

In the presented case of two service road sections, calculated time of consolidation with correction factor gives a total period of approximately 14 months. In comparison to the final construction period of 24 months, it can be safely assumed that the consolidation settlements have been stabilized and completed.

Presented example confirms the possibility of use soft subsoil for temporary service roads even without typical embankment overload. Actually, service road in both sections is under operation for more than 6 month and the additional settlements (both with creep effect) are in the acceptable range.

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Wzmocnienie gruntów organicznych obciążonych ciężkim ruchem budowlanym w świetle badań dylatometrycznych

Słowa kluczowe: wzmocnienie podłoża, konsolidacja statyczne, obliczanie osiadań, obciążenie ruchem, badania dylatometryczne DMT

Streszczenie:

Występowanie gruntów słabonośnych genezy rzecznej i organicznej w podłożu nasypów drogowych stwarza problemy związane z ich dużą odkształcalnością. Trudna do oceny wodoprzepuszczalność, mająca wpływ na przebieg procesu konsolidacji i osiadania, wymaga przeprowadzenia badań terenowych, których przykładem są badania dylatometryczne. W praktyce inżynierskiej występuje wiele czynników, które mogą wpływać na proces konsolidacji podłoża, ale nie są one w prosty sposób aplikowane do modeli teoretycznych. W wielu przypadkach jedynie metoda obserwacyjna, pozwala na zastosowanie wybranego podejścia obliczeniowego w konkretnym zagadnieniu inżynierskim. Z tego tez powodu jest to jedno z podejść mocno akcentowanych przez Eurokod 7 [17]. W artykule przedstawiono przykład aplikacji tymczasowego obciążenia od ciężkiego ruchu budowlanego do konsolidacji podłoża słabonośnego pod drogami serwisowymi z weryfikacją parametrów podłoża metodą dylatometryczną. Do obliczeń przyjęto poziomą warstwę gruntu słabego obciążoną równomiernie pionowym obciążeniem zewnętrznym od ruchu tymczasowego. Dla takiego układu możliwe jest klasyczne rozwiązanie jednoosiowej konsolidacji Terzaghiego z przepływem wody w kierunku pionowym. Przeprowadzono analizę obliczeniową czasu konsolidacji i maksymalnych wartości osiadań.

2021-06-07, Revised: 2021-09-05