Dilatometer and seismic dilatometer tests in different depositional environments

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ABSTRACT: Seismic dilatometer has been established as a common investigation tool for site characterization. Results obtained at two test sites using a seismic dilatometer, equipped to record both P- and S- waves (SPDMT), are presented in the paper. At Belgrade Waterfront test site soil is young, NC, "well-behaved" which makes DMT measurements (A, B) and DMT standard interpretation procedure accurate in predicting geotechnical parameters. At Kuzmin test site results of dilatometer test are more difficult to interpret since partial drainage conditions emerge during test performance. A procedure that compensate for errors that are introduced by the partial drainage conditions is applied to restore undrained A and B values from the dissipation curve. These undrained values are used in standard DMT interpretation procedure to yield geotechnical parameters. DMT parameters derived from consideration and without consideration of partial drainage effects are compared. Results of both P- and S- wave velocity measurements and interpretation are presented.

Keywords: dilatometer; body waves; partial drainage; silt

1. Introduction

In the past eight years DMT and SDMT is increasingly used both for practical and research purposes in Serbia. DMT measurements and DMT based correlations used for geotechnical parameter derivation are found to be very useful for designing railway and road infrastructure, industrial facilities and for characterization of thick deposits of disposed overburden in open pit-mines. In the mentioned time span of 8 years 2.2 km of soil has been tested by the dilatometer which corresponds to approximately 11000 tests performed at every 0.2 m. Various soil types, such as collapsing loess, highly-overconsolidated marls, normally-consolidated clays, loose to dense quartz sands, etc. have been investigated and some of the results are reported in [1-3]. Recently, a new SPDMT has been used at two sites, one located in Belgrade and other in the village of Kuzmin, for geo-characterization of thick deposits of clayey and silty soil.

Recent challenge in the interpretation of the DMT test is related to the partial drainage effect [4-6] and its influence on the measured pressures A (p_0) and B (p_1). Partial consolidation of soil around the blade is particularly significant in silts where calculated DMT parameters can have low values in respect to the reference value obtained in undrained test. For practical purposes a short "A and deflate" dissipation test [7] can be performed to determine if significant drop in penetration pore pressure impacts the interpretation of the test results. Further interpretation of a short dissipation test using the method developed in [5] allows quantification of partial drainage effects and its influence on derived parameters.

The paper is divided in two main parts. The first part discusses results obtained by short dissipation tests, while the second part gives insight into the body wave velocity measurements and its interpretation in saturated soil.

2. Description of test sites

2.1. Belgrade Waterfront test site

Belgrade Waterfront (BW) is one of the most significant construction sites in Republic of Serbia. It is located in the Belgrade center district next to the Sava River. Historical name for this part of Belgrade is "Venetian lagoon" since in the past it was frequently flooded and people living there had to use boats and rafts for they daily transport. The construction site is divided into 32 plots occupying both left and right river banks. Comprehensive field investigation campaign, including drilling, Menard pressuremeter tests, Bi-directional static load tests, cone penetration (CPT) and dilatometer tests, have started in 2015 and are still in progress. Seismic dilatometer, CPT's and drillings are used for site characterization of plot 12.

Soil profile consists of 5 to 7 m of soft, organic *clayey fill* underlay by Stillwater/floodplain facies which can be divided in two distinct layer, top layer of LOC soft *clay*, 6 meters thick, and bottom layer composed of very soft *silty clay* interbedded with fine sand. The thickness of this sub-layer is 7 meters. Underneath the floodplain facies, riverbed sediments, 2 meters thick, composed of *sand* and *gravel* are found underlain by overconsolidated *marly clay* and marl. Non-penetrable soft rock layer (hereby named *carbonate-marly complex*) is formed as a sequence of interchanging sandstone, marl, claystone and limestone layers, and it is found at 27 meters depth. At the time of field investigations water level was at 6 meters below ground surface.

Soil profile with index properties (w-water content, w_L-liquid limit, w_P-plastic limit, IP-plasticity index and CF-clay fraction) and corrected cone resistance q_t at BW site are shown in Fig. 1. From Fig. 1 it can be observed that water content in *silty clay* layer (from 12 to 18 meters) is slightly superior to liquid limit, which is a typical behavior of sensitive clays, however its

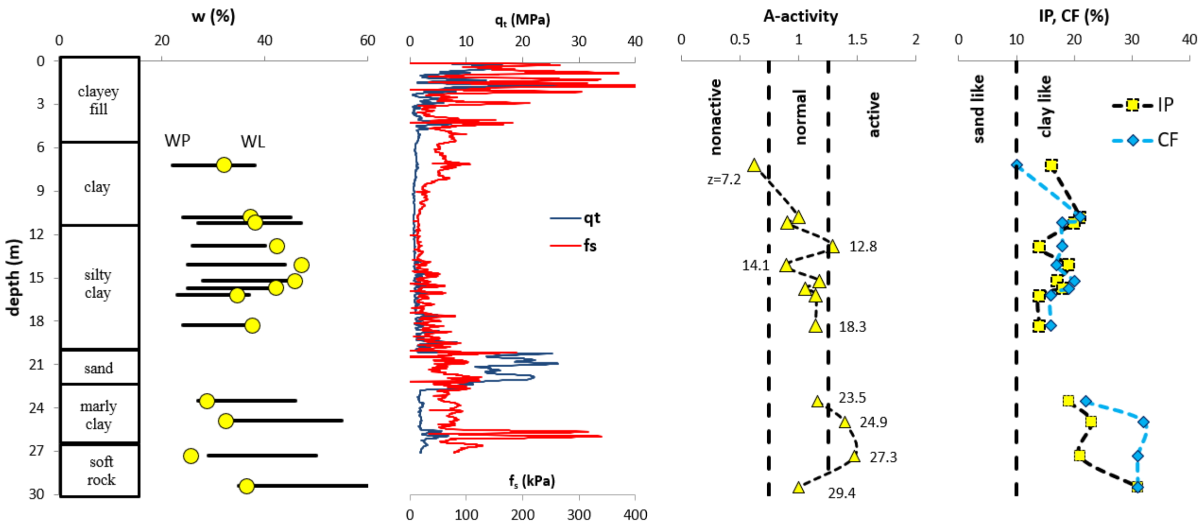

Figure 1. Typical soil profile with index properties at Plot 12 of Belgrade Waterfront test site

sensitivity estimated from CPT based correlations (Robertson, 2016) is on average 3-5, but it can be as high as 8 at some depths. In marly clays and marls water content is close to the plastic limit which is a typical feature of highly overconsolidated clays.

2.2. Kuzmin test site

The main purpose of in situ testing at Kuzmin test site is the optimization of the foundation design for the overpass at highway E-75. The preliminary research stage included eleven boreholes and seven mechanical CPT's. In the subsequent phase one additional SPDMT was performed to supplement previously obtained test results. Particular interest was to obtain reliable estimation of undrain shear strength (s_u) as a basic parameter for pile bearing capacity estimation. Other parameters, such as V_s and M_{DMT}, obtained from SPDMT have been used for seismic response analysis and pile group settlement prediction.

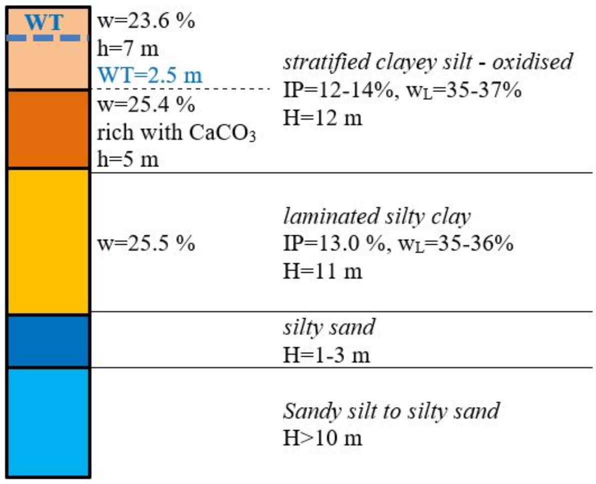

Figure 2. Soil profile at Kuzmin test site

Soil profile consists of four distinct layers formed in fluvio-lacustrine environment. First layer consists of predominantly *clayey silt* with cross and inclined stratification up to depth of approximately 12 m. It can be divided into two sublayers where bottom part, from the seventh meter and below, is rich with precipitated calcium-carbonate and have 2-3 % lower natural water content in respect to the upper part of the layer. The upper 12 meters are found to be oxidized. Underneath is *laminated silty clay*, 11 meters thick, in which lamination is a consequence of cyclic changes in deposition of clay and silt fraction. The third layer, one meter thick, is composed of *silty sand* which has varying thickness throughout the test site. The deepest layer, encountered at approximately 27 meters from the ground surface, is composed of *sandy silt* interbedded with silty sand. Soil profile with basic properties of layers is given in Fig. 2. Water level is found at 2.5 meters below ground surface.

3. Seismic dilatometer test (SPDMT)

The seismic dilatometer (SPDMT) is the combination of the traditional mechanical flat dilatometer (DMT) with a SPDMT seismic module placed above the DMT blade (Fig. 3).

Figure 3. Seismic dilatometer equipped with additional sensors for P-wave measurements (SPDMT)

The new system equiped with two additional receivers for Vp measurements is an upgrade of the seismic dilatometer (SDMT) introduced by [8]. The SPDMT module is a probe outfitted with two uniaxial (vertical) geophones, spaced 0.604 m, for measuring the P-wave velocity V_P, along with two uniaxial (horizontal) geophones, spaced 0.500 m, for measuring the S-wave velocity V_S. Geophones have appropriate frequency and sensitivity characteristics to determine the seismic wave train arrival according to [9]. The seismic signal, acquired by the geophones, is amplified and digitized at depth. The recording system consists of one channel for each geophone, having identical phase characteristics and adjustable gain control. Usual sampling intervals of 50 μs and 200 μs are used respectively for P- and S-waves.Two different seismic sources have been used to genarate a seismic wave train at the ground surface: an impulsive source, such as 10 kg hammer hitting circular steel plate is used as P-wave generator; S-waves are generated using 10 kg sledge hammer hitting horizontally a steel rectangular base pressed vertically against the soil by penetrometer foot and oriented with its long axis parallel to the axis of the receivers, in order to offer the highest sensitivity to the generated shear wave.

Derivation of geotechnical parameters from the DMT measurements is a stepwise process and its based on applying an appropriate correlations to three intermediate DMT parameters: material index (I_D), horizontal stress index (K_D) and dilatometer modulus (E_D). For more details regarding ussual DMT procedure used for geotechnical parameter derivation the reader is refered to [10]. Experience has shown that in most clays and sands current DMT correlations produce reasonably accurate and realistic predictions of most geotechnical parameters. However in soils where partial drainage conditions prevail during testing application of standard DMT interpretation methods can produce erroneous results. This will be addresed later in the paper.

4. SPDMT results

For the BW test site all available parameters, offered by seismic dilatometer, have been measured in a single sounding. Those parameters are: penetration force measured at the ground surface (P) during every penetration interval, standard DMT pressures p_0 and p_1 measured at every 0.2 meters, closing pressure p_2 measured at every meter, shear wave velocity (V_s) measured on each 0.5 meters, compression wave velocity (V_p) measured on each meter. At 8.5 m and 23.5 m short A-dissipation test has been performed to evaluate drainage conditions in layers of particular interest to foundation design. Results of basic measurements taken during SPDMT sounding are shown in Fig. 4. Comparisson of force measured for advancing a cone with the total force measured at ground surface (Fig. 4) required to advance SPDMT and rods indicate that rod friction significantly influences force measured at ground surface. This is especially pronounced in clay and silty clay layers. However, considering local variations of total force with depth different layers are clearly discerned. Water level determined from consideration of p_2 profile vs depth is found at 6 meters from the ground surface and it approximately corresponds to a borehole water level.

For the Kuzmin test site all parameters mentioned above have been measured except P and p_2. Short A dissipation test has been performed at 12.8 m, 16.2 m and 20.2 m. Results of basic SPDMT measurements for the Kuzmin test site are shown in Fig. 5.

At both sites P-wave velocities were measured from a 10 m depth.

4.1. Drainage conditions

Standard DMT test procedure prescribes time taken for DMT test to be about 60 s after reaching the test depth. First reading (A) is taken within about 15 s and the second reading (B) after an additional 15 s after first reading. Optionaly third (C) reading is taken after B, generally in about 30 s. In both clean sand and clay there is no significant drop in pore pressure around the blade in about 60 s needed to take all three measurements. However, in partially consolidating soil pore pressure drop can be significant and the B reading or both A and B readings, can be different in comparison to their drain or undrain equivalents. New evidence [4] suggests that in NC clay and silt penetration pore pressure decay and repeated A readings variation with time reduce at approximately the same rate. This similarity allows to judge if pore pressure drop influence A and B by monitoring the variation in A reading over time. A method developed in [5] allows to compensate for errors that are introduced by the partial drainage conditions that take place around the DMT blade. This method introduces corrections for both A and B readings for either complete or incomplete dissipation curve. The complete dissipation curve being the one where pore pressures in time have reached stable value, ie repeated A readings have reached constant value. In [5] the applicability of the proposed method is checked in the Tubarão Clay Experimental Testing site where time needed for stable values of A to be reached is more than 10000 s, while A-readings at t=15 s are 244 kPa and 216 kPa at depths of 8 m and 9 m, respectively.

Results of a short dissipation tests for Kuzmin test site are shown in Fig. 6. Material index for the preceding (I_{DU}) and subsequent (I_{DL}) test depth is indicated in the figure for comparison purposes. At each depth, five repeated A readings were taken at successive time intervals of approximately t=15, 30, 60, 120 and 240 s. After completion of pore pressure dissipation, at the minimum A-reading, the membrane is rapidly inflated to measure the B-pressure at 1.1-mm displacement (indicated in Fig. 6 as B_f). Pressures were recorded using SDMT Elab software with automatic data aquisition system. *A* readings at t=15 s ranged from 656 kPa to 1113 kPa. At 13.0 m depth OCR, calculated according to [11] is 3.2 and it decreases to 1.5 at 20 m depth indicating that soil is medium to ligtly overconsolidated. This may indicate that variation in A reading can be influenced not only by a decrease in pore pressures around the blade but also by an increase in horizontal effective stress [12]. Further analysis assumes that the dissipation test and differential pressure (B-A) are influenced only by excess pore pressures and that effective stress remains unchanged. This may be supported by the fact that A decreases monotonicaly before reaching stable value, decay curve is S-shaped in *p-log(t)* and the soil is predominantly saturated low plastic silt. Undrained value of *A* (*t=0*) was found by fitting series of data points by Weibull distribution [5] using Eq (1):

$$A_t = M + (N - M) \cdot \exp(-T \cdot t^Y) \quad (1)$$

Where A_t is *A*-reading at specified time *t*, *M* and *N* are constants based on data distribution, *T* and *Y* are material constants. Eq. (1) is valid for the following boundary conditions:

for t=0: N=A_{max} (undrained value)

for t=∞: M=A_{min} (last measured value)

A_{max} is found using Excel Solver by trial and error adjusting equation parameters *T* and *Y* to minimize the sum of the squared errors between measured and predicted A-readings. This produces best fit curve to data points for assumed A_{max}. In the next step A_{max} is changed and squared error calculated again. These steps are repeated until A_{max} that gives minimum sum of the squared errors is found. Undrained B value (B_{max}) is found by addopting a simplified approach, ie Eq. (12) from [5] using the stress exponent n=0.5. In order to approximately restore standard B_{30} pressure (measured in standard DMT 15 s after A reading) corresponding to t=30 s drop in pore pressure, ie difference in A readings at t=30 and t final, should be taken into account. Hence, B_{30} is found as a sum of B_f and pressure drop from t=30 s to t final. Results of the analysis are shown in Table 1

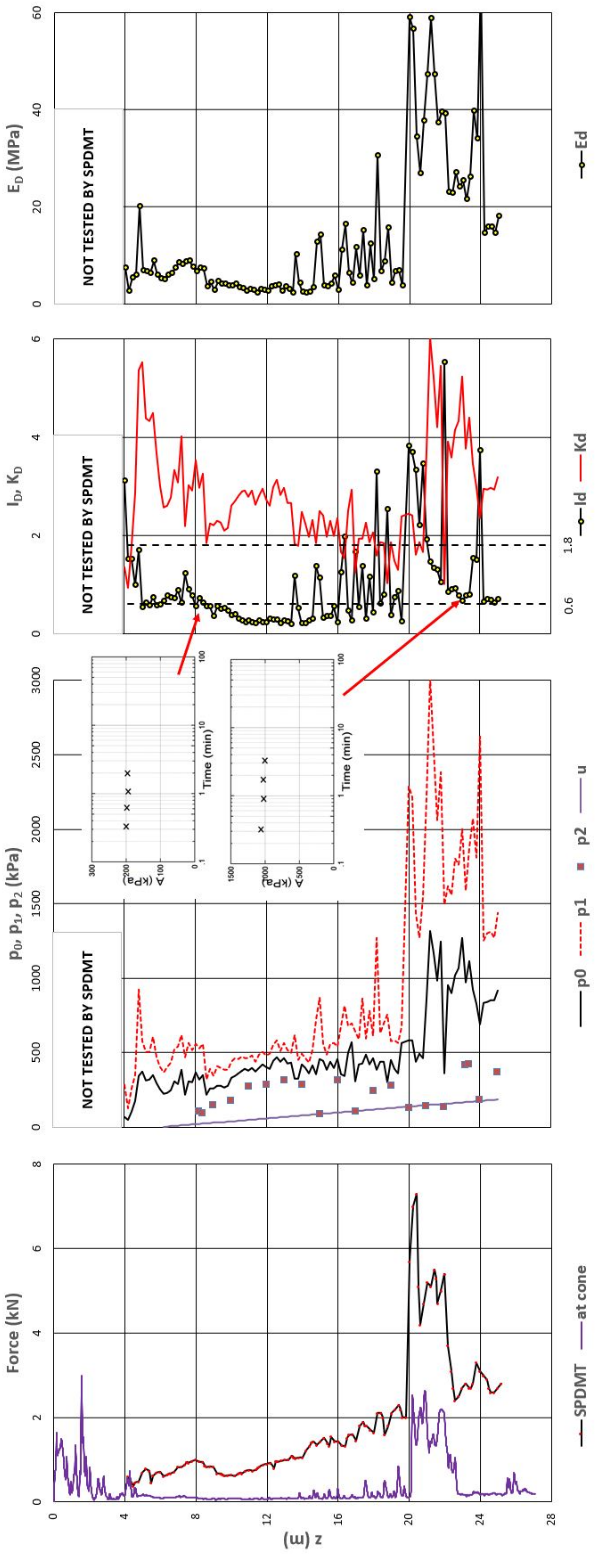

Figure 4. DMT results at BW test site

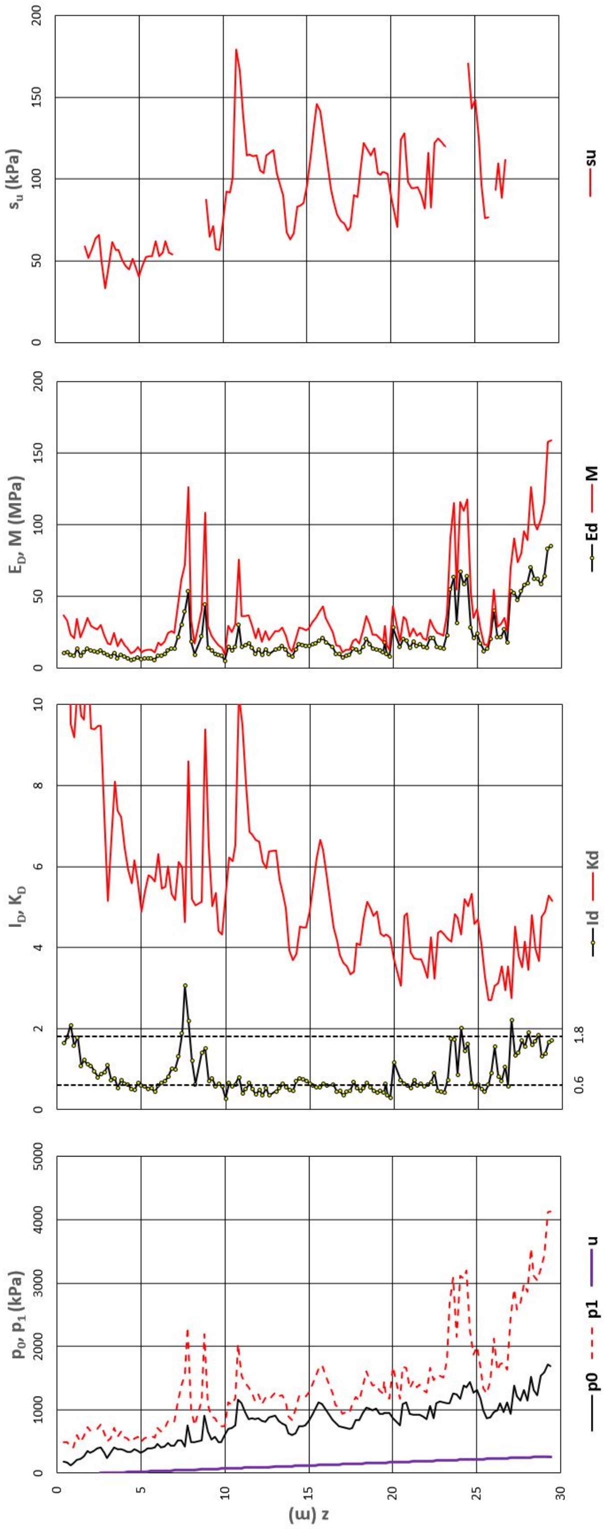

Figure 5. DMT results at Kuzmin test site

and Table 2. Results indicate that s_u is the most influenced parameter by drainage conditions. When partial drainage occur around the blade standard DMT interpretation procedure will produce significantly lower s_u values compared to s_u estimated from the same correlations but using undrained *A* and *B* readings which are not influenced by partial consolidation. This finding is not new and it is supported by previous research [5, 6].

Vertical drained constrained modulus (M), estimated from DMT, is less influenced by partial drainage conditions which is attributed to its dependency on both pressure difference and lift off pressure. It should be mentioned that M is ussually target parameter for most practicioners.

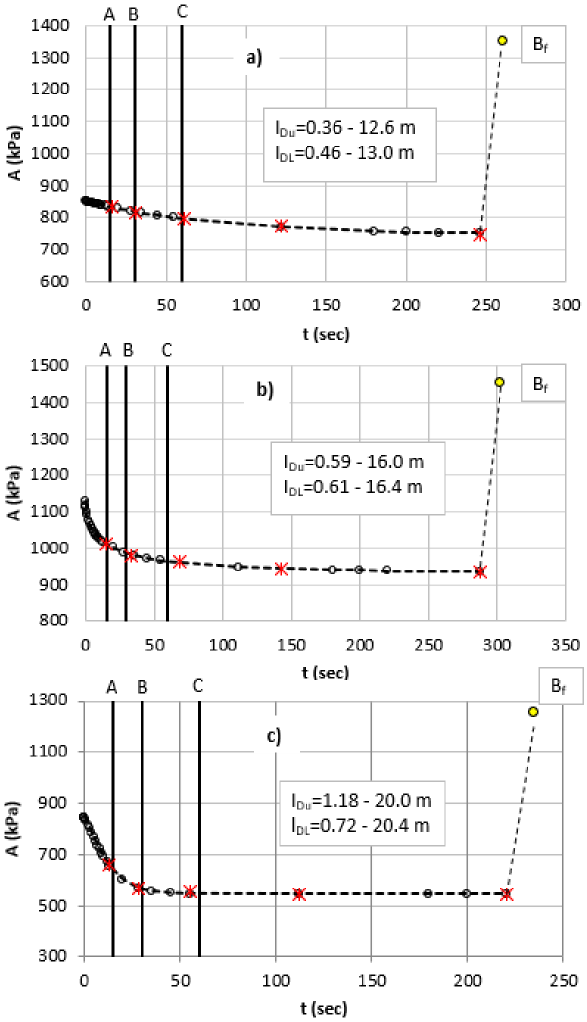

Figure 6. Timed sequence of A readings at Kuzmin test site at depths: a) z=12.8 m, b) z=16.2 m and c) z=20.2 m

Table 1. Comparison of the standard A_{15} and calculated A_{max} readings for the Kuzmin test site

depth (m)	A_{15} kPa	A_{max} kPa	A_{15}/A_{max}	s_{u15} kPa	s_{u15}/s_{umax}
12.8	834	850	0.98	104	0.97
16.2	1013	1130	0.90	124	0.85
20.2	656	845	0.78	55	0.64

Table 2. Comparison of standard DMT parameters and calculated by consideration of partial drainage

depth (m)	B_{30} kPa	B_{max} kPa	$I_{Dstandard}$	I_{Dmax}	$M_{standard}/M_{max}$
12.8	1419	1416	0.75	0.71	1.03
16.2	1501	1602	0.51	0.43	0.97
20.2	1272	1390	1.20	0.76	0.91

From the results presented in Tables 1 and 2 it seems that I_D is a good indicator of how significantly partial drainage can affect the standard DMT interpretation procedure. In all calculations presented above unit weights of each layer have been determined in the laboratory.

Recent tests performed using Medusa DMT [13] in calibration chamber have show that A-readings may be obtained in about 1-2 s from the start of the test cycle and B-readings in about 4-5 s after A without loss in accuracy. These findings are promising in respect to soils where partial consolidation may occur during testing using traditional DMT equipment and may widen the range of soils in which DMT tests are performed in fully undrained conditions.

4.2. P- and S- waves profiles and interpreted wave velocities

The test interpretation in terms of deriving V_s and V_p can rely on different approaches using the same test data. V_p is estimated using *interpolation or direct* method, which consideres intervals characterized by a constant slope on times-depths diagram, and *pseudo-interval* method which consideres time delay for the same receiver positioned at two consecutive depths. V_s is estimated using the *true-interval* method, considering the delay between two consecutive receivers at depth. The determination of the delay time is based on the cross-correlation algorithm applied to the selected portion of two seismograms.

In order to identify the P-wave train arrival time vertical seismic profile (Fig.7) has been reviewed which allows continuity in tracking the same reference point on the waveform. The P waveforms are easily identified visually in each record and reference points can be located with precision on the first peaks.

P-wave arrival times, corrected for the ray path inclination-T_c, plotted against depth are used to estimate V_p as a slope of a straight line segments fitted to the test data, Fig 8. The slope of each segment is the average wave velocity over the depth spanned by the segment. This interpolation method is convenient when subsoil layering has to be determined. The interpretation reduces inaccuracy in the travel time determinations by mediating among several arrival times over homogeneous velocity layers. The second procedure used in estimation of V_p rely on determining delay in arrival times to the same receiver when placed at two different distances from the source. Fig. 8 shows that all data points can be fitted with a single line for Kuzmin test site defined by a slope corresponding to P- wave velocity of 1656 m/s.

Interpreted S-wave velocity profiles for BW and Kuzmin test site are shown in Fig. 10. It can be inferred that V_s profiles closely correspond to the borehole log data. For the Kuzmin test site Vs increase in the layer rich with carbonate which may indicate that cementation is present. For the Kuzmin test site Vs in the top 30 m of the soil profile (V_{s30}) is 220 m/s. According to this parameter, considering recommendations of EC-8, site is classified as ground type C which is important for site specific seismic evaluation and dynamic analysis of soil-structure interaction.

For BW test site V_p interpreted using interpolation method vary from 1445 to 1568 m/s.

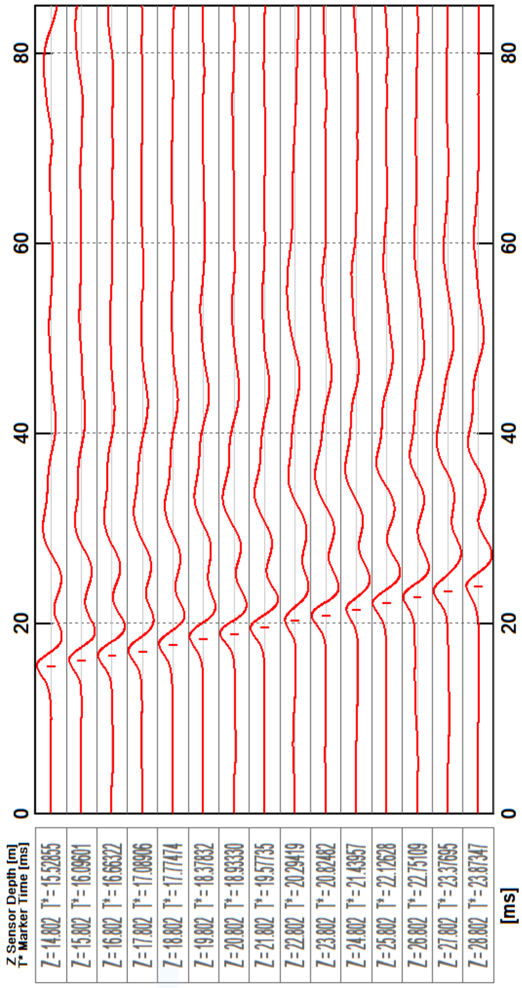

Figure 7. SPDMT recorded seismic traces of P-wave at Kuzmin test site

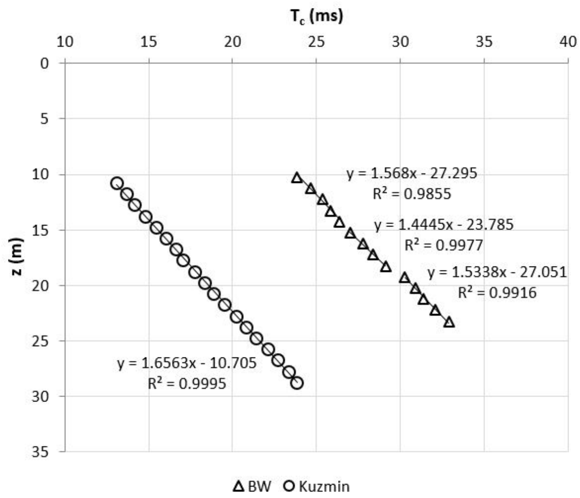

Figure 8. V_p travel time curves

Recent research suggest that soil is fully saturated when $V_p \geq 1450$ m/s [14]. According to estimated P- wave velocities soil is most likely fully saturated at both locations.

Fig. 9 shows comparisons of P-wave velocity derived from interpolation method and from pseudo interval delay time for Kuzmin test site. Results indicate that later method is very sensitive to the quality of the recorded signal and the subsequent signal processing which could influence selection of the reference point.

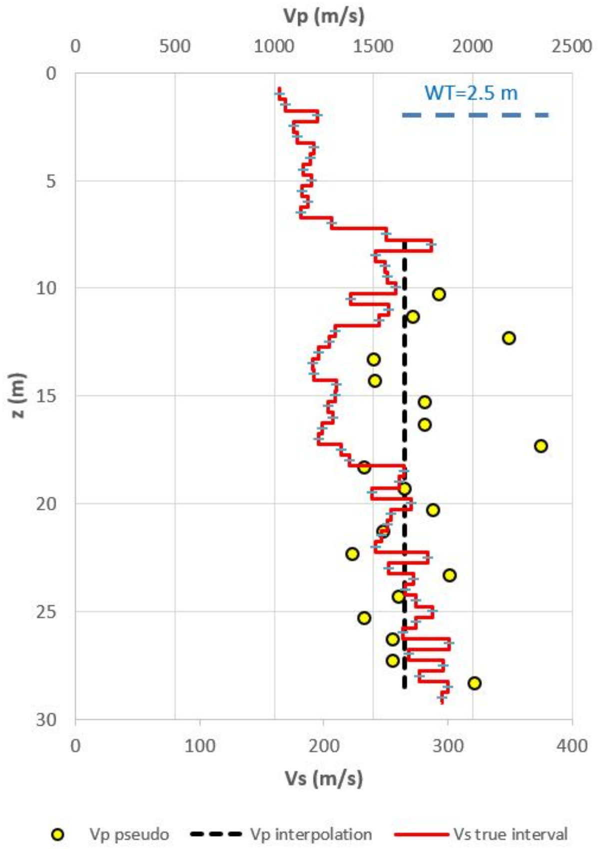

Figure 9. V_p and V_s profiles for Kuzmin test site

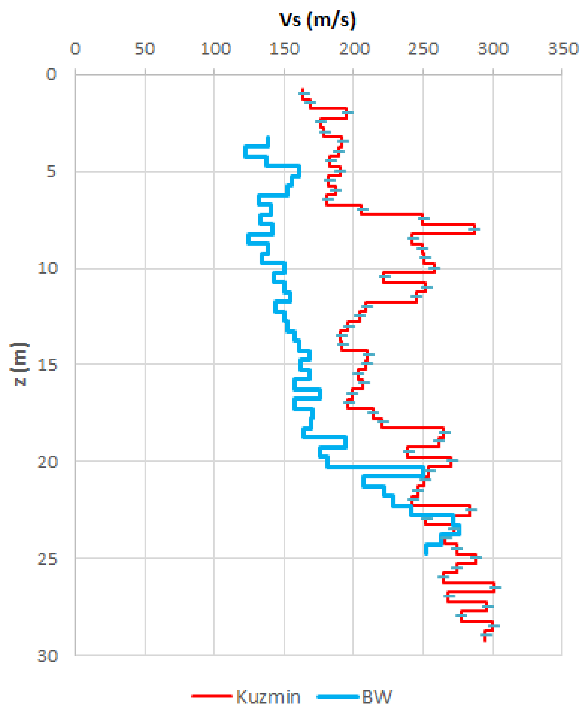

Figure 10. V_s profiles measured with SPDMT

4.3. Rigidity index profiles

The rigidity index ($I_R=G/s_u$) is an important input parameter for geotechnical applications involving bearing capacity, pile driving and porewater pressure generation. For natural clay deposits, the rigidity index ranges from less than 50 to more than 600 and it is known to decrease with increasing OCR, and for the same OCR, it increases with decreasing plasticity index [15]. The dependency of coefficient of consolidation (c_{vh}) from I_R is well documented in the literature. However, selection of appropriate s_u and shear strain modulus (G) for I_R evaluation is challenging since they are influenced by various factors such as mode of shearing, stress and strain level dependency [16]. Method described in [17] can be used to estimate I_R in soft to firm clay deposits from DMT measurements. Research presented in [18] shows that G_0 is less influenced by sample disturbance and errors in external displacement measurements than G_{50} (calculated at 50 % mobilized strength) commonly used to define I_R.

In this paper G_0 is used to deduce small strain rigidity index ($I_{R0}=G_0/s_u$) instead of G_{50} commonly used to deduce I_{R50}. Plots of small strain rigidity index versus depth for BW and Kuzmin test site are shown in Fig. 11. Rigidity index is calculated using s_{u15} determined from DMT without consideration of partial drainage. Linear interpolation between points is assumed.

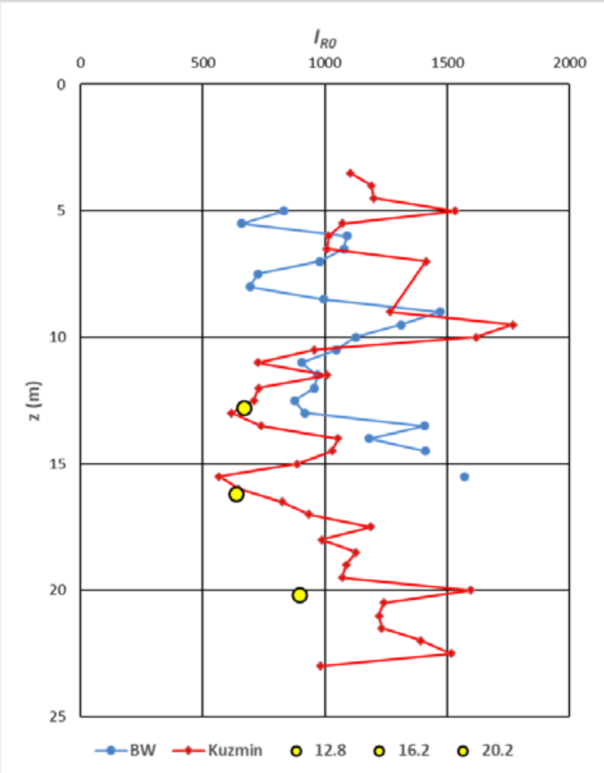

Figure 11. I_{R0} vs depth

In Fig. 11 circles represent I_{R0} corrected for partial drainage effects at depths where dissipation tests were performed. Corrected I_{R0} is calculated using s_{umax} instead of s_{u15}. Comparing results shown in Fig. 11 and results presented in Tables 1 and 2 indicate that ratio s_{u15}/s_{umax} decrease with increasing I_{R0}. Since this ratio is influenced by partial drainage effect it may be assumed that I_{R0} can be valuable parameter in assessing influence of partial drainage on estimated DMT parameters. However, additional research is needed to confirm this finding.

5. Concluding comments

This paper presents SPDMT results for two test sites. At BW test site soil is *well-behaved*, ie young, NC to LOC without significant microstructure. Standard DMT interpretation procedure gives geotechnical parameters (s_u, M and OCR) that are in agreement with the reference values measured in the laboratory.

At Kuzmin test site measurements are influenced by partial consolidation of soil around the blade which requires special procedure to be used in order to restore undrained A and B values. From the presented results and assumptions adopted in the analysis it can be concluded that partial drainage significantly influence parameters that are derived from lift-off pressure and to a lesser extent parameters that rely on both pressure difference and lift-off pressure. s_u can be underestimated by more than 50% if measured A-reading is used in the standard DMT interpretation procedure without considering partial drainage effects, while M can either be overestimated or underestimated, but not more than 10% compared to the standard value derived from the test results. Preliminar results indicate that I_{R0} can be used to assess the influence that partial drainage can have on estimated s_u. Findings presented in this paper correspond to a particular test site and additional research is required.

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