Suitability of the SDMT method to assess geotechnical parameters of post-flotation sediments.

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ABSTRACT: The paper presents a comparison of results of SDMT, CPTU and SCPTU, which were obtained while investigating post-flotation deposits. Tests were performed at the Żelazny Most mine waste dump near Lubin (Poland). In this location the dump embankments are formed from post-flotation sediments of copper ore. The article contains statistical assessment of differences between geotechnical parameters of the sediments, determined using the above mentioned methods.

1 INTRODUCTION

Post-flotation sediments, which are process wastes in the processing of copper ore, are unconventional materials used in earthen structures. This is the case in the development of one of the biggest tailing waste dumps in the world, i.e. the Żelazny Most Dump near Lubin (Poland). A precise determination of geotechnical parameters of sediments is a crucial issue for the design of the development of this dump. This problem, in the case of the Żelazny Most Dump, needs to be emphasized as at present the embankments are 45 m high, and the planned development forecasts the elevation of the dump embankments to 100 m. For this reason, the most modern in-situ tests are being used to assess parameters of shear strength and constrained moduli. The basic method to investigate properties of sediments is the cone penetration tests i.e. CPTU (Młynarek, Tschuschke, Lunne 1994; Młynarek 2000)

The necessity to evaluate constrained moduli of sediments and subsoil, especially small strain shear modulus G_0, resulted in the undertaking of testing using a Marchetti dilatometer, including its latest version – an SDMT seismic dilatometer. The suitability of the application of this device is evaluated and a comparative analysis of the results with those obtained using other methods is presented in this study.

2 THE OBJECT OF THE STUDY, A CHARACTERISTIC OF POST-FLOTATION SEDIMENTS

Calibration testing for CPTU, SCPTU and DMT was performed on the beach and embankments of the Żelazny Most Dump (Fig. 1). The current volume of accumulated waste is 350 million m^3, and the length of embankments is 14.5 km. Flotation tailings are transported to the dump using the hydrotransport method, and then are spilled onto the dump beach.

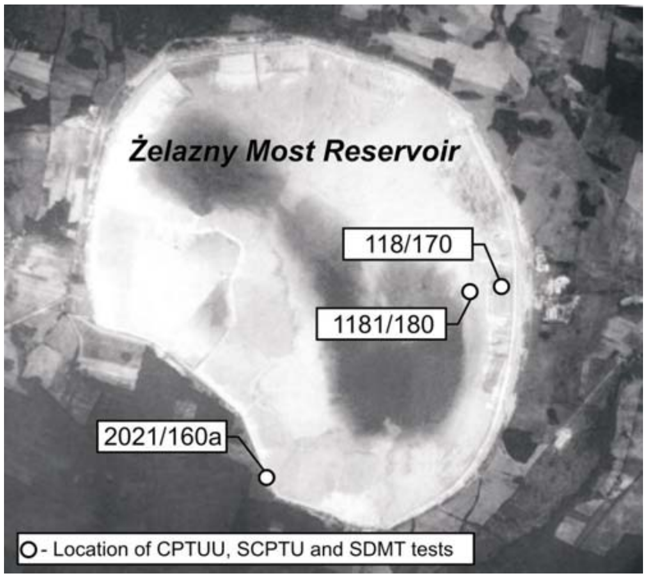

Figure 1. Location of CPTUU, SCPTU and SDMT tests

This type of waste transport and beach formation results in the segregation of sediment grains (Wierzbicki 2000). Embankments are formed from the material found on the beach in a zone approx. 70

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m wide. The concentration of the material and the method of its transport to the dump results in the sediments embedded in the embankments exhibiting numerous laminations and considerable anisotropy of the structure (Młynarek 2000). The grain size distribution of sediments classifies them as silty and fine sands. Some sediments exhibit the grain-size distribution of silts and silty clays. This group of sediments is found at the distance ranging from 60 to 300 m from the top of the embankment (Wierzbicki 2000) and generally is not used for the construction of the embankments. Calibration tests were performed at the so-called investigation points, where apart from SCPTU and SDMT also CPTU was conducted along with vane tests, and MOSTAP cores were collected for the purpose of laboratory testing. Calibrations of SCPTU were performed through an analysis of significance of differences between measured values of cone resistance q_c, friction of the frictional sleeve f_s and excess pore pressure, measured in this test and the values recorded in the standard CPTU. The comparison was performed at various levels of geostatic stress σ_{vo}. This analysis showed that mean values of parameters from CPTU – q_c, f_s, u_2, u_1 did not differ statistically from identical parameters obtained from SCPTU. On the basis of this assessment it was assumed that parameters from SCPTU may be used to calibrate parameters from SDMT, and as a result may constitute the basis for an unambiguous assessment of the suitability of a seismic dilatometer to investigate mechanical properties of sediments, embedded in the dump.

3 CHARACTERISTIC CURVES OF SCPTU AND SDMT IN POST-FLOTATION SEDIMENTS

Figure 2 presents characteristic curves of SCPTU and SDMT in one of three investigation points. It may be observed that q_c from SCPTU and P_0, P_1 from SDMT react in a similar way to changes in soil properties, in particular to the sediment macrostructure. Similar trends are also observed (Fig.3) in the D_r (SCPTU) and K_d (SDMT) profiles. Changes in macrostructure, as has been indicated previously, are the effect of numerous and very thin interbeddings in sandy sediments with cohesive soils. The effect is very well documented also by the recorded pore pressures u_1 and u_2.

High consistency is also found for the trend in the recorded seismic wave along with depth (Fig. 2).

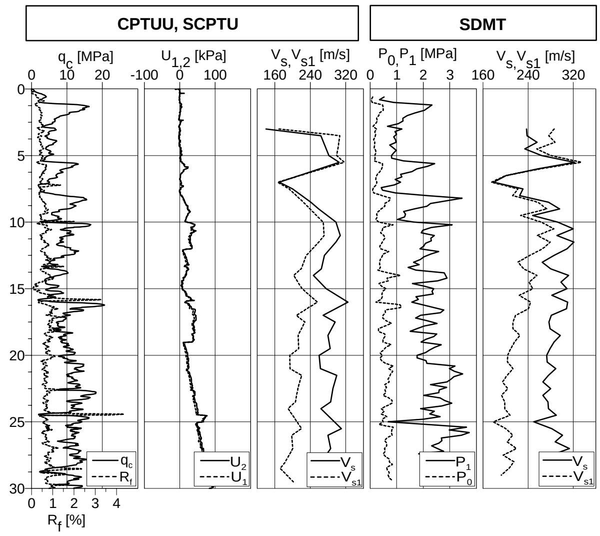

Figure 2. CPTUU, SCPTU and SDMT characteristics at investigation point No. 118/170

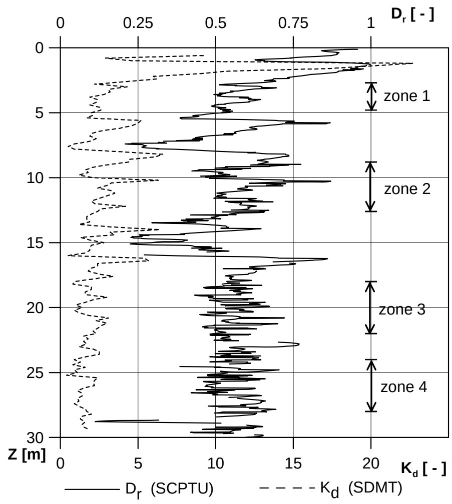

Figure 3. Changes of D_r and K_d with depth

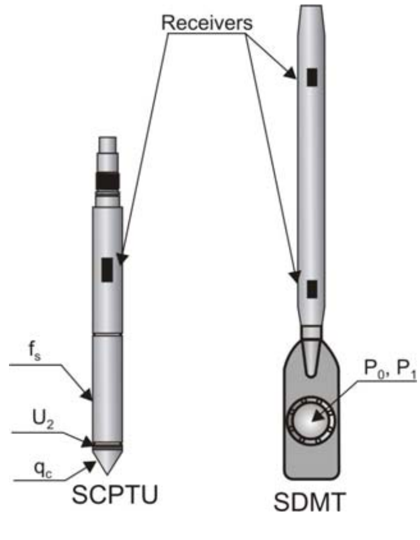

Figure 4. SCPTU cone and SDMT blade

The seismic cone by Ap van den Berg (Holland) used in this study was equipped with one geophone, whereas the seismic dilatometer – with two geophones (Fig. 4). A comprehensive assessment of

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the consistency or inconsistency of SCPTU and SDMT may be obtained through a statistical analysis of differences between the geotechnical parameters of sediments estimated with the application of both tests. Such an analysis is presented below.

4 METHODOLOGY OF ASSESSMENT OF COMPATIBILITY OF ESTIMATION FOR GEOTECHNICAL PARAMETERS OF SEDIMENTS USING SCPTU AND SDMT

Four geotechnical parameters of sediments were selected for the analysis, i.e. relative density D_r, effective friction angle ϕ', constrained modulus corresponding to oedometer modulus M and shear modulus G_0. The selection of parameters was based on the inclusion in the analysis of a differing effect of geostatic stresses on measured parameters in both tests. (Jamiolkowski, 2002).

The following procedure algorithm was adopted for statistical assessment of compatibility of estimated geotechnical parameters of sediments. First, homogeneous sediment zones were determined in the embankments using the filtration method, in terms of relative density D_r (Fig. 3), and next in the established zones mean values were calculated for the effective friction angle - ϕ', as well as mean values of constrained moduli M and G_0. Values of relative density were determined from the formula, which was established on the basis of extensive documentation material from sediment testing, (Młynarek, Tschuschke, Lunne 1994):

$$D_r = a \cdot \sigma_{v0}^{b} \cdot \ln(q_c) + c \cdot \ln(\sigma_{v0}) + d \qquad (1)$$

where:

a,b,c,d – constants depended on tailings type

This extensive documentation material made it also possible to adopt formulas to determine constrained modulus from CPTU.

$$M = m(q_c - \sigma_{v0}) \qquad (2)$$

where:

m - constant depended on type of tailings (Młynarek, Tschuschke, Lunne 1994)

The shear modulus G_0 is obtained from V_s by SCPTU with the usual elasticity formula:

$$G_0 = \rho \cdot V_s^2 \qquad (3)$$

where:

ρ – mass density

V_s – shear wave velocity

while the effective friction angle was obtained with the formula:

$$\phi' = 17{,}6 + 11 \cdot \log(q_{c1}) \qquad (4)$$

where:

q_{c1} – normalized cone resistance

$$q_{c1} = \left[\frac{q_c}{p_a}\right] \cdot \left[\frac{p_a}{\sigma'_{v0}}\right]^{0,5} \qquad (5)$$

For the purpose of assessment of the analyzed geotechnical parameters of sediments using DMT the relationships were adopted after Marchetti (2001).

A detailed analysis of significance of differences in the assessment of geotechnical parameters of sediments using both methods may be preceded by several interesting observations, namely similar trend was found for all the investigation points. Consistent trend in changes of both parameters (D_r and K_d) shows that coefficient K_d may be used to assess changes in relative density of sediments in embankments.

It results from a comparison of constrained modulus profiles (Fig. 5) that values of moduli obtained from SDMT are higher than those from CPTU. This difference is much higher in the range of small values of σ_{v0} (at shallow depths) and high values of relative density, and the difference between moduli decreases along the depth. Differences in values of constrained moduli are well justified since sediments are characterized by their anisotropic macrostructure, connected with the above mentioned laminations. It results from studies by Muromachi (1981) that the mechanism of the formation of plastic areas under the cone differs from that in the volume of soil facing the Dilatometer membrane (Marchetti 1999).

Moreover, it clearly results from studies by Silva, Bolton (2004) that in case of stratified sands cone resistance and area of destruction zones are affected by laminations found at the distance of 3 cone diameters from the cone base. These elements probably result in different rigidity of sediments in the vertical and horizontal planes and differing values of constrained moduli determined in SDMT and SCPTU. The same factors determined differences in forecasted changes of effective friction angle of sediments along with depth (Fig. 6). Higher assessed values were obtained from CPTU for friction angle ϕ' than it was the case in SDMT, with the trend to increase the difference between friction angles along with an increase of σ_{v0}.

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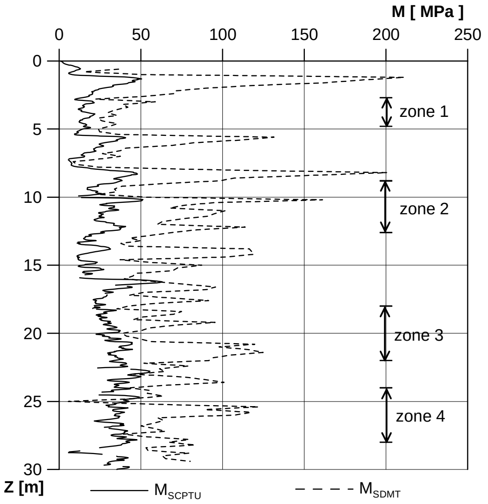

Figure 5. Changes of M_{SDMT} and M_{SCPTU} with depth

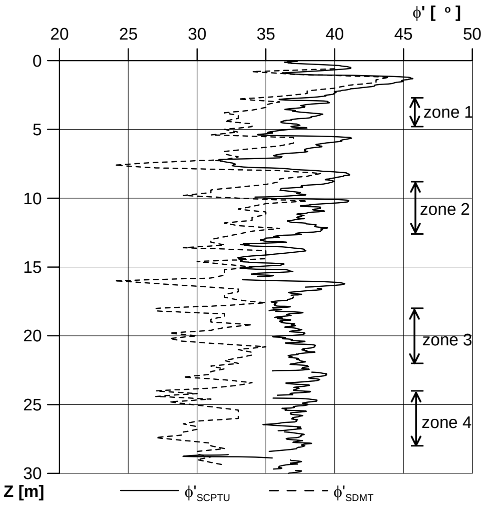

Figure 6. Changes of ϕ' with depth

5 STATISTICAL ASSESSMENT OF SIGNIFICANCE OF DIFFERENCES BETWEEN GEOTECHNICAL PARAMETERS OF SEDIMENTS FROM SCPTU AND SDMT

Statistical assessment of differences in forecasted constrained moduli and internal friction angles ϕ' of sediments was performed for rather "uniform" depth zones. In this way, it was attempted to additionally assess the effect of geostatic stress σ_{v0} on the investigated differences between mean values of M and ϕ' obtained from both tests. The analysis was carried out using the results obtained at investigation point (118/170), while in the other investigation points the results were very similar. It may be observed from Table 1 that mean values of moduli and friction angles from SDMT and SCPTU tests are statistically different at the significance level of α=0.05 in all ranges of σ_{v0} (Fig. 7), whereas comparison of significance of the variance differences proves these values to be non-significant.

The latter conclusion shows that the assessment of variation in parameters M and ϕ' measured using both methods in each range of σ_{v0} is very similar. However, confidence intervals differ in size (Fig. 7). This results from differences in sample size from SDMT and SCPTU tests.

Table 1. Results of statistical analysis of significance of differences between M and ϕ' from SDMT and SCPTU

		Mean value (ϕ', M)		p-value*
		SDMT	SCPTU	
zone 1	M_{SDMT} vs. M_{SCPTU}	35,74	15,66	0,000
	ϕ'_{SDMT} vs. ϕ'_{SCPTU}	33,92	37,60	0,000
zone 2	M_{SDMT} vs. M_{SCPTU}	73,81	29,08	0,000
	ϕ'_{SDMT} vs. ϕ'_{SCPTU}	33,58	38,03	0,000
zone 3	M_{SDMT} vs. M_{SCPTU}	72,62	32,11	0,000
	ϕ'_{SDMT} vs. ϕ'_{SCPTU}	31,33	37,05	0,000
zone 4	M_{SDMT} vs. M_{SCPTU}	66,67	36,62	0,000
	ϕ'_{SDMT} vs. ϕ'_{SCPTU}	29,95	37,20	0,000

* statistical significance

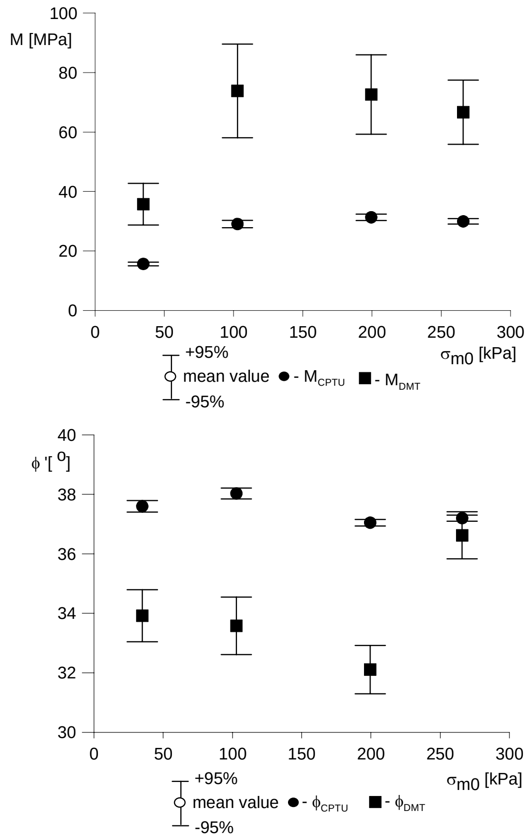

Figure 7. Statistical evaluation of mean values of M modulus and ϕ' from SCPTU i SDMT tests on different levels of σ_{v0}

The result of the analysis of significance of differences in the constrained moduli established using both methods is of paramount importance. The conclusion is consistent with previously given comment on the effect of anisotropy on deformability of sediments in horizontal and vertical direction. On the other hand, a dependence may easily be developed, which on the basis of constrained modulus from SDMT makes it possible to determine compression modulus of sediments

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based on CPTU test. Fig. 8 suggests that this dependence is statistically highly significant. The regression coefficient changed in individual investigation points from 0.79 to 0.90, while in the global analysis (Fig. 8) this coefficient was 0.76. It needs to be stressed that the coefficient defining the M_{DMT}/q_c ratio was on average 8.1, while proposed by Marchetti (1999) for NC sands should fall within the range from 5 to 10.

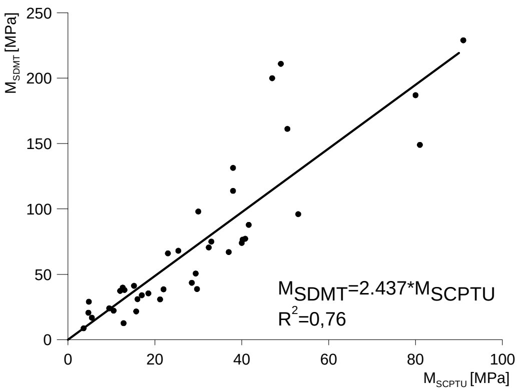

Figure 8. Relationship between the modulus M from SDMT and SCPTU tests

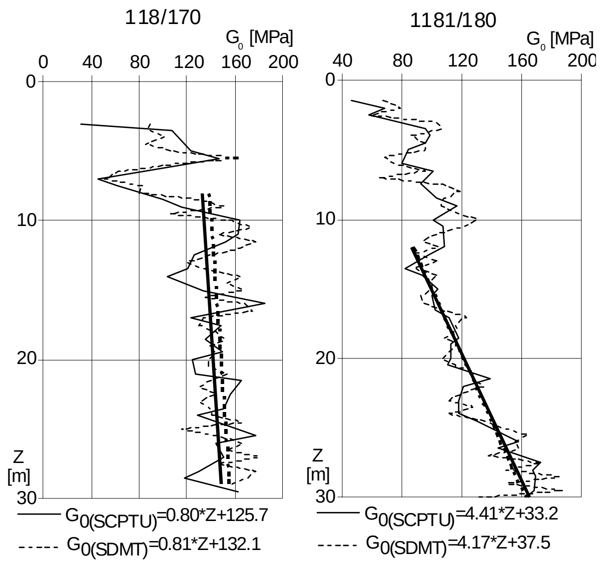

Figure 9. Changes of $G_{0(SCPTU)}$ and $G_{0(SDMT)}$ with depth

The main aim of the investigations was to analyze the suitability of SDMT to assess the G_0 modulus, while - as it has been said previously - the reference point for this analysis was SCPTU. The most unambiguous assessment of differences in the forecasted shear modulus G_0 found using both methods may be obtained by analyzing zones of sediments in subsoil with a uniform parameter D_r. In this way the effect of this factor on this dependence is eliminated, while the effect of the trend of changes in shear modulus G_0 along with a change of σ_{v0} is taken into consideration. Figure 9 shows two extreme case of the effect of the trend in the investigated points. To assess differences in the forecasted modulus G_0 with the use of both methods, the significance of differences between coefficients of regression line was investigated. The conducted analysis (Table 2) showed that the coefficients of regression line in each node do not differ statistically at $\alpha = 0.05$. This conclusion makes it possible to formulate an unambiguous opinion that the assessment of values of modulus G_0 using both methods and its variation along with changes in the state of geostatic stress in subsoil is very similar.

Table 2. Results of statistical analysis for relationship G_0 versus depth

Inv. point	F	p	k(0,05)
118/170	0,040	0,841	3,991
1181/180	0,161	0,689	4,007
2021/160a	0,187	0,669	4,183

k-critical value on significance level α=0,05

6. CONCLUSIONS

On the basis of the conducted investigations a general opinion may be formulated that the seismic dilatometer may be considered a very useful device for the assessment of values of constrained moduli in sediments. An especially crucial conclusion is the finding that the identification of the trend in changes of moduli and effective friction angle along with changes in geostatic stress in the dump embankments using SCPTU, CPTU and SDMT is almost identical. The shown effect of laminations (anisotropy) on the forecasted values of moduli and the effective friction angle of sediments emphasizes the advisability of the application of both tests at the dump. This principle ought to be also applied in geotechnical situations of soils with exposed macrostructure and - connected with it - anisotropy. As shown in Fig. 9, there is practically coincidence between G_0 from SCPTU and G_0 from SDMT tests.

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