Application of SCPTU and SDMT in the Assessment of Settlement of Tailings Deposits Loaded by Trial Embankment

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ABSTRACT: The paper presents results of an analysis of settlements of a trial embankment founded on deposited mine tailings within the disposal site for post-flotation tailings OUOW Żelazny Most, ranking second in the world in terms of its size. A grid of control benchmarks was installed on the embankment constructed in the natural scale in order to register settlements and displacement of the embankment. In the area of the benchmarks installation reference tests were conducted by SCPTU and SDMT and tailings samples were collected for analyses of grain size distribution, physical properties and deformation parameters of tailings. Distributions of constrained moduli estimated based on the interpretation procedures of SCPTU and SDMT were compared with analogous moduli from oedometer tests, while settlements determined based on these moduli were compared with the actual settlements of the trial embankment.

1 INTRODUCTION

Excavation and processing of copper ore is connected with the production of considerable amounts of mining wastes. These wastes need to be managed or safely disposed in specifically constructed facilities. The facilities are considered as hydroengineering objects, within which wastes and water originating from technological processes are accumulated. The tailings are hydraulically transported to the site and discharged from the dams surrounding the facility area. Due to segregation process the coarsest tailings sediment close to the discharge points, exhibiting advantageous mechanical parameters, whereas the finer material is transported by water to the inner pond causing that amount of fine particles increases with an increasing distance from the discharge site where the fine tailings form the weak subsoil. In the case of a change in deposition technology the knowledge on the response of weak tailings to additional load becomes particularly important. In such a situation it is crucial to obtain a spatial distribution of reliable deformation parameters of tailings depending on the place of their deposition. In view of the specific character of the medium, its heterogeneity, anisotropy and variable drainage conditions the determination of deformation parameters of tailings requires appropriate research methods and verification of test results using back analysis.

2 THE TEST SITE

This study was conducted at OUOW Żelazny Most (the mining wastes neutralization facility Żelazny Most), one of the largest hydroengineering facilities in the world (Fig. 1). The importance of this object may be manifested in the fact that within the 37 years of its operation over 560 million m^3 tailings have been deposited. The object of 1400 ha in area is surrounded by dams being raised as the disposal site is filling. At present dams at their highest cross-section exceed 60 m. Dams are raised using the upstream method. The tailings are discharged by spigotting pipes onto the beaches causing that the coarsest tailings sediment close to the dams and can be re-used to its raise. Finest tailings flow down towards the pond and where they sediment in water.

Fig. 1. The general view OUOW Żelazny Most.

The pond capacity ranges from 5 to 7 million m^3. Deposited tailings constitute a heterogeneous material with strongly exhibited anisotropic properties. With an increasing distance from the discharge site the amount of fine particles in tailings increases, both globally and in terms of the formation of a greater number of silty laminations in the profile. In order to identify spatial variation of physico–mechanical properties of tailings a trial embankment was constructed perpendicular to the dam, partly founded on the beach, partly entering the pond (Fig. 2). In the construction of the trial embankment, of the total length of 1100 m, over 150 thousand m^3 of coarse tailings were used. The trial embankment was constructed by front-formation method and the embankment material subjected to compaction. The trial embankment formed on the deposited post-flotation tailings was a testing platform, from which in–situ tests were conducted.

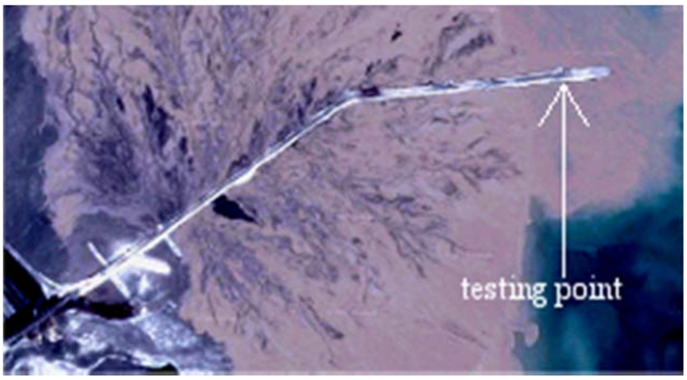

Fig 2. The location of trial embankment within OUOW Żelazny Most.

Fig. 3. Trial embankment during formation.

3 SCOPE OF THE STUDY

For the purpose of multifaceted assessment of properties of deposited tailings and taking into consideration their variation depending on local silting conditions, cross-section profiles were established perpendicular to the longitudinal axis of the trial embankment, with the in-situ testing points at every 100 m. Within each testing point located in the embankment axis SCPTU and SDMT penetration tests were performed throughout the entire thickness of deposited tailings, supplemented with the sampling of deposit cores using the Mostap soil sampler. All in situ tests were being carried out within two weeks field campaign starting from SCPTU, sampling and finishing with SDMT. Deposit cores of 1 m in length and a diameter of 65 mm were collected from the profile at every second metre of profile depth increment. Deposit samples from the cores were selected for laboratory analyses of grain size distribution, physical properties and deposit deformation parameters. Constrained moduli of tailings were determined based on the oedometer test. In order to verify the actual embankment settlement at each testing cross-section profile benchmarks were placed on each side of the embankment at a distance of 20 m and 45 m from the embankment axis. Benchmarks installed outside the embankment were to provide an assessment of displacements of beach surface in the area of the embankment. Additionally, in order to identify strength conditions of tailings which were not affected by the construction of the trial embankment some supplementary in situ tests (CPTU) at the locations 50 m distant from the embankment axis in pond area have been carried out.

4 EXPERIMENTAL MATERIAL

This paper presents the results of tests, which were performed along the embankment axis at a distance of 1000 m from the axis of the southern dam at OUOW Żelazny Most. The results of penetration tests, confirmed by the analysis of laboratory tests of deposit cores collected from the testing points allowed to identify 4 characteristic deposit zones along the profile of the testing point:

- zone 1, formed to a depth of 9.5 m, which is composed by tailings varying in grain size, used in the construction of the trial embankment, in the form of the displaced embankment,
- zone 2, isolated at a depth from 9.5 m to 15.5 m, constructed from fine tailings deposited in that site, to which fragments of the embankment were displaced in the form of layers,
- zone 3, identified from a depth of 15.5 m to 25.5 m, composed solely of fine tailings,
- zone 4, deposited along the profile at a depth from 25.5 m to 44 m, under which natural subsoil was identified, composed of alternating embedded layers of silty and sandy deposits.

The results of laboratory analyses document that zone 1 is built of deposits with a grain size composition representative for silty sands (Fig. 4). A part of the embankment formed above the water level in the pond is characterised as dense one, while sandy tailings lying in the deeper part of this zone are in a loose state. A slight excess pore water pressure was recorded in this zone (Fig. 5). Zone 2 is composed of fine tailings sedimenting within the pond, which in terms of grain size distribution correspond to silts and silty clays, towards which layers of silty sands were displaced from the trial embankment. The presence of such displaced layers (e.g. at a depth of 13.8 – 14.8 m) is very well documented by the results of SCPTU and SDMT (Figs. 5, 6). This zone is characterised by high excess pore water pressure, locally reduced in the sites of sandy interbeddings. Zone 3 is the most homogeneous zone, composed solely from the silty fine tailings. Deposits in this zone in terms of their grain size distribution are silty clays and silts. Recorded high excess pore water pressures and the results of dissipation of this pressure (Fig. 7) indicate that deposits in this zone may be classified as underconsolidated deposits (Tanaka & Sakagami 1989). Deposits constituting the profile of zone 4 form strongly layered sediments of varied grain size composition in the form of alternating sandy and silty interbeddings. These interbeddings are particularly visible in the form of zig-zag effects on all CPTU penetration characteristics (Fig. 5). These effects also result in different drainage and deposit

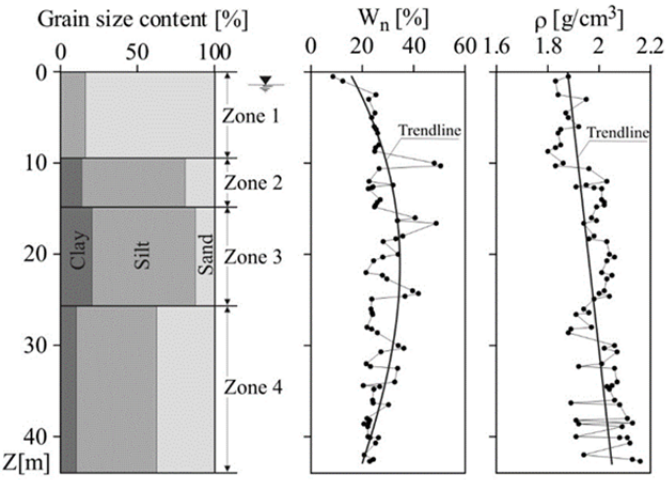

Fig. 4. Profile of grain size distribution and tailings properties.

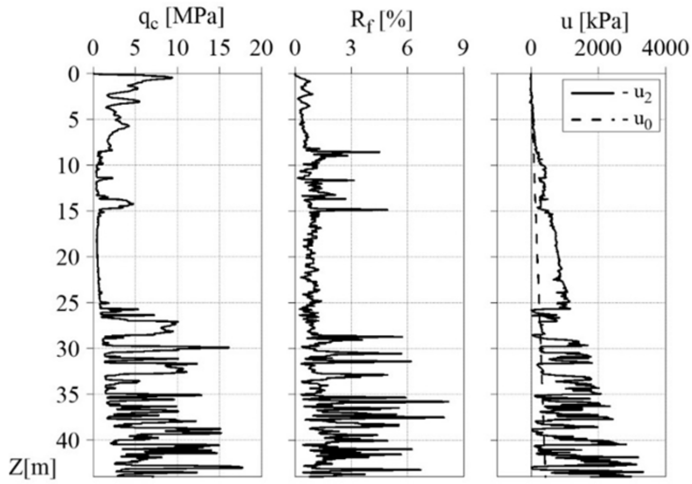

Fig. 5. CPTU profiling in mine tailings loaded with trial embankment.

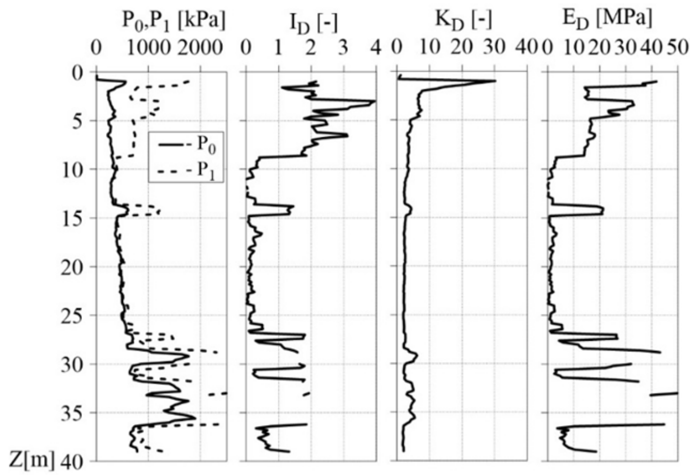

Fig. 6. DMT profiling in mine tailings loaded with trial embankment.

consolidation conditions than those in the zones lying above. Characteristics of the deposits in each particular zones are well illustrated by the location of areas identifying deposits composing these zones in the CPTU and DMT classification systems (Figs. 8, 9).

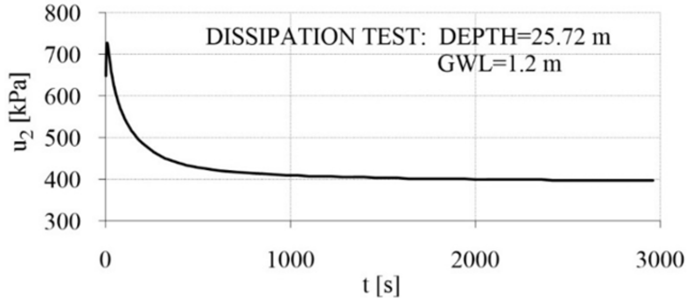

Fig. 7. Dissipation curve in tailings loaded with trial embankment.

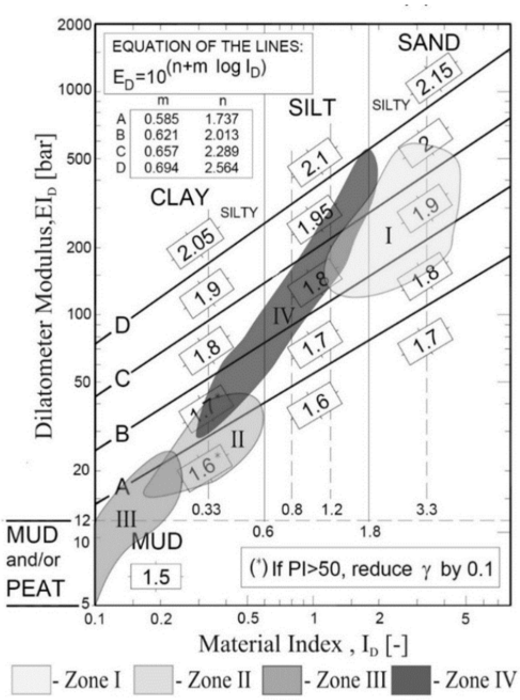

Fig. 8. Location of analyzed groups of tailings in the soil behavior chart by Robertson.

5 ANALYSIS OF TESTING RESULTS

The primary objective of this paper was to predict settlements of the trial embankment founded on subsoil formed from tailings, based on the results of in–situ penetration tests. SCPTU and SDMT were reference tests, while they were verified by laboratory analyses of samples of deposits and actual survey data of embankment settlements. Formally in order to assess the expected settlements of the trial embankment it is necessary to have information on changes in the state of stress of the loaded subsoil and the deformation characteristics of the material composing this subsoil, typically expressed in the respective deformation modulus.

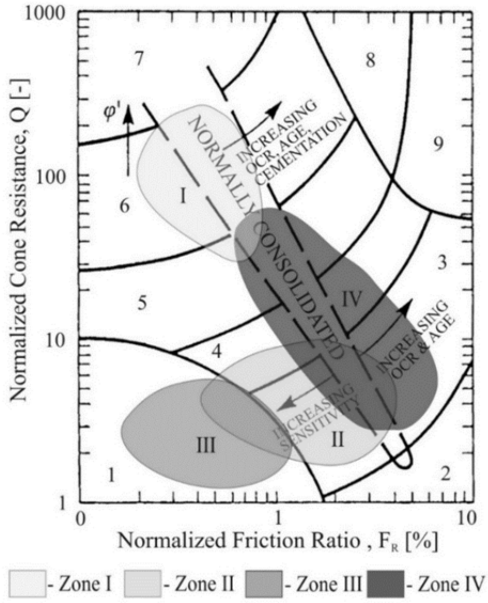

Fig. 9. Location of analyzed groups of tailings in the soil classification chart by Marchetti & Crapps.

Based on the elastic theory, in order to calculate total settlements of each layer of the loaded subsoil the relationship expressed in Eq. (1) can be used:

$$S = H\left(\frac{\Delta\sigma'_z - \nu'\left(\Delta\sigma'_x + \Delta\sigma'_y\right)}{E'}\right) \tag{1}$$

where: H = layer thickness, ν' = Poisson's ratio for drained conditions, $\Delta\sigma'_z$, $\Delta\sigma'_x$ and $\Delta\sigma'_y$ = changes in effective stress in the vertical (z) and horizontal (x and y) directions, E' = soil's elastic modulus.

The range of total consolidation settlement of fine–grained tailings may be estimated using the constrained modulus predicted from SCPTU or SDMT recorded data using Eq. (2):

$$S = \sum H_i \frac{\Delta\sigma_i}{M} \tag{2}$$

where: H_i = the thickness of the tailings layer i, $\Delta\sigma_i$ = the induced stress in the middle of layer i, M = the average constrained modulus for the stress range from σ'_{v0i} to $\sigma'_{v0i} + \Delta\sigma_i$.

For CPTU tests the constrained modulus was correlated with the corrected cone resistance presented by severed authors (Abu-Farsakh & Y. 2013, Drevininkas et al. 2013, Long & Carrol 2014, Mayne 2007). For fine–grained soils the correlated constrained modulus with cone resistance and vertical stress Eq. (3) is as follows.

$$M_{CPTU} = \alpha_1\left(q_t - \sigma_{v0}\right) \tag{3}$$

where: q_t = the corrected cone resistance, α_1 = the empirical coefficient.

Depending on the type of soil, drainage conditions and the history of loading the values proposed in the literature for coefficient α_1 change within the range from 2.75 to 8.25 (Abu-Farsakh & Y. 2013, Drevininkas et al. 2013, Long & Carrol 2014, Mayne 2007). Based on a series of calibration tests conducted under varying deposition conditions of post-flotation tailings, which were referred to oedometer tests, the following values of coefficient α_1 were recommended (Tschuschke 2006):

- for silty tailings freely sedimenting within the pond $\alpha_1 = 18.4$,
- for silty tailings accumulated onto the beach in the form of separated silty and sandy layers $\alpha_1 = 4.2$,
- for sandy deposits sedimenting on the beach while their natural macrostructure is maintained $\alpha_1 = 3.1$,
- for sandy deposits embedded into the dams, the natural structure of which has been damaged $\alpha_1 = 3.6$.

In the case of the analysed profile for zone 1 the assumed value of coefficient $\alpha_1 = 3.6$, for zone 4 depending on the grain size composition $\alpha_1 = 4.2$ or 3.1, while for zones 2 and 3 the intermediate value of coefficient is $\alpha_1 = 11.3$, resulting from the partial consolidation deposits loaded by the trial embankment. The adoption of the intermediate value of coefficient α_1 in zones 2 and 3 is justified by the results of oedometer tests of deposit samples collected from a similar depth, before and after the construction of the trial embankment (Fig. 10). At this depth an increase in cone resistance was also observed – from about 0.3 MPa before the embankment construction to about 0.7 MPa for tests carried out from the surface of the constructed embankment performed within this study. The distribution of constrained modulus in the analysed tailings profile, estimated based on cone resistance values, is presented in Fig. 11.

For SDMT tests, constrained modulus Eq. (4) is a function of dilatometer modulus, Eq. (5) and correction factor, which in turn occurs in the function of two other DMT parameters, i.e. the material index Eq. (6) and the horizontal stress index Eq. (7).

$$M_{DMT} = R_M E_D \tag{4}$$

$$E_D = 34{,}7(p_1 - p_0) \tag{5}$$

$$I_D = \frac{p_1 - p_0}{p_0 - u_0} \tag{6}$$

$$K_D = \frac{p_0 - u_0}{\sigma'_{v0}} \tag{7}$$

where, M_{DMT} = the constrained modulus, R_M = the correction factor, E_D = the dilatometer modulus, I_D = the material index, K_D = the horizontal stress index, p_0 and p_1 = corrected first and second readings, u_0 = in–situ pore water pressure, σ'_{v0} = in–situ vertical effective stress.

The value of the correction factor is not constant and it is determined from the original procedure given by Marchetti (Monaco et al. 1999):

$$\text{if } I_D \le 0{,}6 \qquad R_M = 0{,}14 + 2{,}36 \log K_D \tag{8}$$

$$\text{if } I_D \ge 3 \qquad R_M = 0{,}5 + 2 \log K_D \tag{9}$$

$$\text{if } 0{,}6 < I_D < 3 \quad R_M = R_{M0} = (2{,}5 - R_{M0}) \log K_D \tag{10}$$

$$\text{where} \qquad R_{M0} = 0{,}14 + 0{,}15(I_D - 0{,}6) \tag{11}$$

$$\text{if } K_D > 10 \qquad R_M = 0{,}32 + 2{,}18 \log K_D \tag{12}$$

$$\text{if } R_M < 0{,}85 \quad R_M = 0{,}85 \tag{13}$$

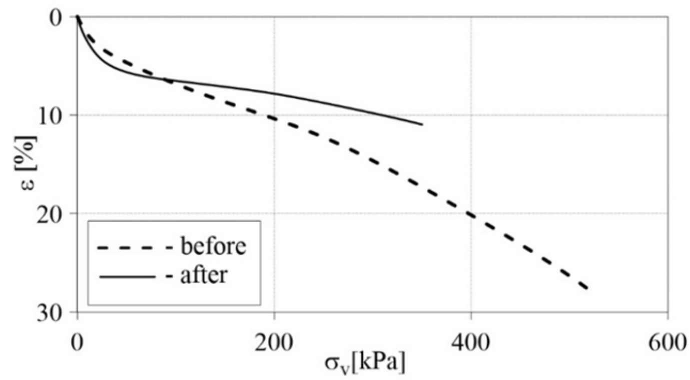

Fig. 10. Oedometer test results for tailings samples collected from a similar depth before and after the construction of trial embankment.

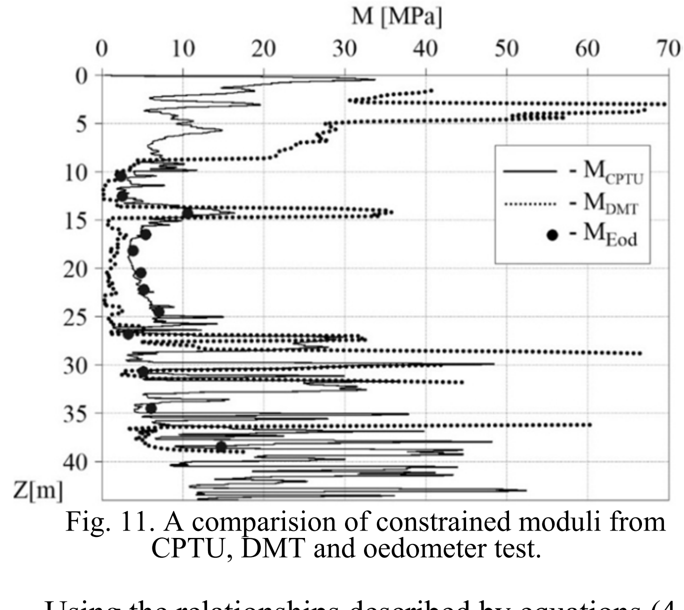

Fig. 11. A comparision of constrained moduli from CPTU, DMT and oedometer test.

Using the relationships described by equations (4-13) the distribution of the constrained modulus of tailings with depth was determined in the analysed profile (Fig. 11). A comparison of moduli established on the basis of two different tests shows that their distributions and values in each particular sediment zones differ markedly. In zone 1 values of moduli M_{DMT} exceed on average 3- to 4-fold the values of moduli M_{CPTU}, while in two successive zones, 2 and 3, it is the opposite, with values of moduli M from CPTU being on average 2–fold greater than those from DMT. Within zone 4 similar values of moduli were estimated based on CPTU and DMT in layers composed of silty deposits and much higher values of moduli determined based on DMT in comparison to CPTU in layers of sandy deposits. In order to show that the diverse assessment of distributions of constrained moduli estimated from CPTU and DMT is not caused by the natural variation of the tailings profile, a comparison was made for the distributions of another deformation characteristic, i.e. initial shear modulus Eq. (14), determined based on two independent down-hole tests, SCPTU and SDMT using the true interval method.

$$G_0 = \rho V_s^2 \tag{14}$$

where: G_0 = the small strain shear modulus, ρ = tailings mass density, V_s = shear wave velocity.

The distributions of shear moduli estimated in the profile from SCPTU and SDMT are consistent, values of moduli coincide showing no variation shown for the constrained modulus (Fig. 12). Moreover, in view of the fact that reliability of results of seismic tests was confirmed based on the results of cross-hole seismic tests (Jamiolkowski 2012) it needs to be stated that the presented differences in the assessment of constrained modulus result from the adopted methodology. A recommendation for the indication of more reliable distribution of the constrained modulus in the tailings profile may be provided by the results of reference tests for this modulus using oedometer. A comparison of constrained moduli determined in the oedometer test with comparable moduli estimated based on the results of penetration tests CPTU and DMT indicates that the latter are typically underestimated in relation to the moduli established based on laboratory analyses. Underestimation of values of moduli from CPTU is slight, while it is considerable in the case of DMT. On the other hand, it is difficult to state to what degree samples of very sensitive tailings became strengthened as a result of their collection. For more comprehensive deformation characteristic of the analysed material distributions with depth were presented in each particular zones of the profile for the value of coefficient α_2 (Mayne 2007), which defines the ratio of the constrained modulus to the initial shear modulus Eq. (15):

$$\alpha_2 = \frac{M}{G_0} \tag{15}$$

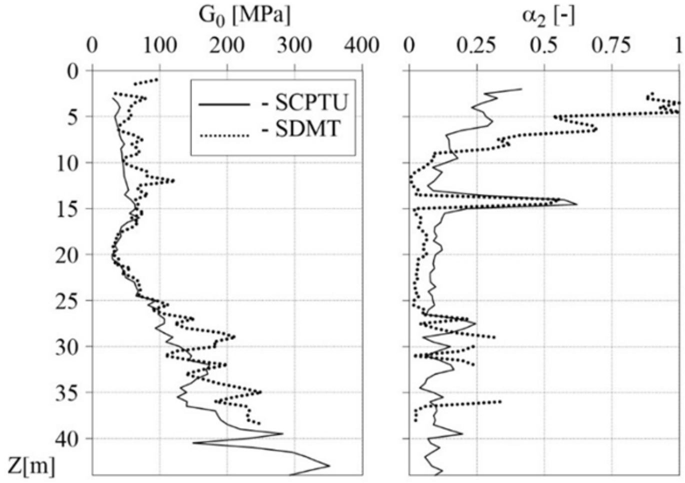

Fig. 12. Distributions of initial share modulus and coefficient α_2 estimated from SCPTU and SDMT in tailings profile.

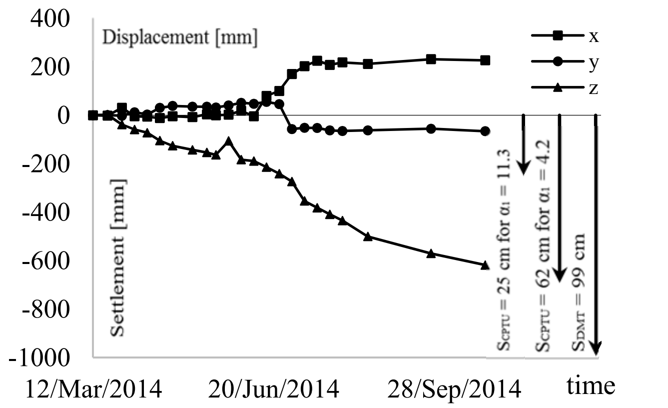

Fig. 13. A comparision of tailings settlement estimated from CPTU, DMT and control benchmark data recorded.

In the last stage of the analysis the expected settlements of the trial embankment were assessed, as determined based on constrained moduli from DMT and CPTU, which were compared with actual settlements of the embankment established by the survey measurements. However, it needs to be stressed that the greatest deformation of tailings under the embankment, including also partial displacement, was not taken into consideration, since benchmarks recording the settlement were placed on the already stabilised embankment. Settlements established from CPTU in the analysed period of tailings consolidation under the embankment amount to 25 cm and they are smaller than the actual settlement of the embankment, which is 62 cm. Settlements estimated from DMT, amounting to 99 cm, are closer to the actual settlements. In a commentary to the results of the above analysis we need to add that the assessment of settlements concerns a specific period of tailings consolidation, with the reservation that the consolidation process has not been completed, as shown by the results of dissipation tests of pore water pressure (Fig. 7) and the continuously recorded settlement of the embankment (Fig 13).

6 CONCLUSIONS

In the paper the results of SCPTU and SDMT in terms of their suitability for the prediction of settlements of a trial embankment founded on tailings under varied deposition conditions of post-flotation sediments have been analysed. The constrained moduli established on the basis of their correlation with in-situ testing parameters were verified with values of moduli determined in the oedometer test, while settlements estimated based on these moduli were compared with actual settlements of the trial embankment. It has not been conclusively stated which of the investigated penetration tests is a better tool in the assessment of deformability of loaded tailings. Results of SCPTU correlate better with the results of oedometer tests, while results of SDMT are closer to the actual settlements of the embankment.

In the light of the above it is difficult to definitely decide which of two types of tests should be preferable for the assessment of the deformation of tailings subsoil. The difference of the results obtained from the tests of concern may have the source in the following reasons:

- relatively low quality of samples taken by Mostap sampler (undisturbance condition weekly preserved),
- settlements measured may be a resultant of both subsidence as well as uplift of tailings.

Performance of similar tests after the consolidation of tailings under the trial embankment has not been yet completed, however it is believed that it should provide a final solution to this problem. Helpful should be also additional sampling of the weak tailings at the locations of penetration tests in terms of push-gel sampler which serves for taking undisturbed samples from non-cohesive or low cohesion soils (Taylor et al. 2012). Such activity is planned in the nearest future.

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