The use of CPTu and DMT for the characterisation of soft red gypsum tailings

M. Maček
University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia,
matej.macek@fgg.uni-lj.si

J. Smolar[1], A. Petkovšek[2]
University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia,
jasna.smolar@fgg.uni-lj.si[1], ana.petkovsek@fgg.uni-lj.si [2]

ABSTRACT: Soft tailings deposited in ponds represent a specific group of soil-like materials, which need to be reliably characterised when soil covers are constructed on them before the end closure. Intact sampling is often difficult and thus piezocone penetration test (CPTu) and flat dilatometer test (DMT) are often used for mechanical characterisation of sludge. In tailings, the mineralogical composition, particle's shape and density may be significantly different from those in natural soils and may influence the CPTu and DMT measurements and consequently to the evaluation of engineering properties. This paper presents results of CPTu, DMT and field vane test (FVT) performed inside the pond where a red gypsum sludge has been deposited for 18 years. Programme of complementary laboratory testing were realised too. CPTu and DMT measurements were evaluated using procedures developed for soils and obtained mechanical properties were compared with those measured in the laboratory. Analysis show the advantages and limitations of some field tests for the characterisation of soft tailings.

Keywords: CPTu; DMT; tailings; tailings characterisation

1. Introduction

The conventional rehabilitation and postoperational closure of soft tailings involve the placement of a stable cover on the tailings surface. Soft tailings may have limited bearing capacity, which makes placement of the cover difficult and in many cases the additional dewatering and improvement have to be done before [1,2].

For the proper design and construction of covers, reliable geotechnical parameters of soft tailings are of vital importance. Determination of geotechnical parameters by in situ and laboratory tests represents a challenge due to (i) soft nature and specific mineral composition of deposited material, (ii) limitations of sampling methods, (iii) limitations of conventional (standard) in situ and laboratory geotechnical equipment and investigation methods and (iv) procedures for evaluation of tests results using (semi)empirical correlations, which were developed for natural soils.

Considering the difficulties in obtaining intact samples, direct-pushed in-situ test methods, such as piezocone penetration test (CPTu) and flat dilatometer test (DMT), present one of the most useful tools for the mechanical characterisation of soft tailings in their undisturbed state [3-6]. Mineral composition, particle shape and pore water chemistry of tailings, may differ significantly from natural soils and may influence CPTu and DMT measurements and interpretation of results based on (semi)empirical relationships developed for conventional soils.

This paper presents results of CPTu, DMT and field vane test (FVT) and laboratory tests performed on the sludge. CPTu and DMT measurements were evaluated using procedures developed for soils. Obtained material properties were compared with those measured in the laboratory. It was found that by the use of CPTu and DMT it was not possible to reliably predict the engineering properties in the first 5 m of the sludge. Furthermore, the constrained moduli estimated by CPTu or DMT is to high based on laboratory data and observed settlements.

2. Location and materials

Tests were conducted on a red gypsum sludge, deposited behind the 50 m high embankment dam with the volume of the reservoir of approximately 7 200 000 m^3. Red gypsum appeared as a waste during the neutralisation of waste sulphuric acid in the production of Titanium dioxide. The sludge was deposited hydraulically in the period of 1991 up to 2008 by using wet filling. During the deposition, the sludge was permanently covered by at least 1 m of water to prevent dusting. The position of the outflow pipe was periodically changed inside the reservoir to prevent the formation of local mud cones. For the design of solidification and end closure, the field tests were performed on six investigation points (TJ) (Fig. 1) in 2013, 5 years after the end of wet deposition. The CPTu, DMT and FVT tests were carried out at all points from a floating raft anchored deep into the sludge. CPTu dissipation tests were performed at various depths to obtain hydraulic conductivity of the sludge as well as to determine the excess pore pressures due to the effect of older deposits in previous years.

At points TJ-1 and TJ-4, geotechnical drilling and sampling for laboratory investigations were performed.

Due to the similarity of results obtained at different investigation points, only results for the location TJ-4 are presented in this paper.

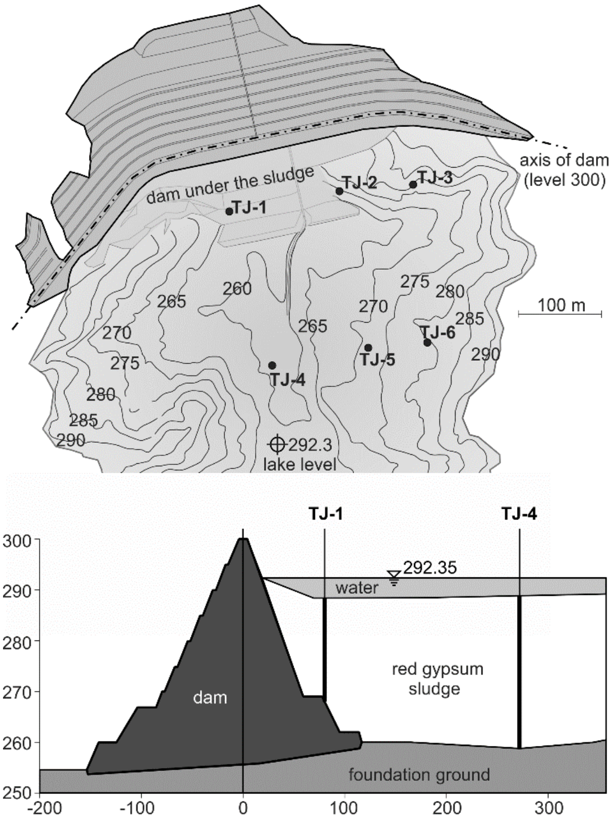

Figure 1. Position of the investigation points TJ inside the reservoir area (top) and cross-section (bottom). The iso-lines on the plan view show the altitude of the natural ground before filling [7].

3. Methods

The characterisation of the sludge was made based on field investigations and laboratory testing. The laboratory tests were used to verify the validity of the field tests results and to supplement them with additional material parameters.

The retrieved samples deformed during transportation and were not intact, therefore all the laboratory tests were performed on either disturbed or reconstituted specimens. It is believed that due to soft nature of the sludge measured material characteristics are still representative for the sludge.

The list of performed field and laboratory tests is given in Table 1.

Table 1. Field and laboratory tests used for the characterisation of the sludge.

Performed test	Standard
Field test	
CPTu	EN ISO 22476-1 [8]
DMT	EN ISO 22476-11 [9]
FVT	prEN ISO 22476-9 [10]
Laboratory test	
determination of water content	CEN ISO/TS 17892-1 [11]
determination of density	CEN ISO/TS 17892-2 [12]
determination of particle density	CEN ISO/TS 17892-3 [13]
determination of particle size distribution	CEN ISO/TS 17892-4 [14]
oedometer test	CEN ISO/TS 17892-5 [15]
direct shear test	CEN ISO/TS 17892-10 [16]

4. Evaluation of CPTu and DMT

4.1. CPTu

The CPTu tests were carried out according to EN ISO 22476-1 [8]. Cone resistance q_c, sleeve friction f_s, and pore pressure u_2 were recorded in 2 cm intervals. The equipment meets the requirements of application class 2.

The following empirical equations were used to obtain engineering properties:

- Undrained shear strength c_u of fine grained soils [17]:

$$c_u = \frac{q_t - \sigma_v}{N_{kt}} \tag{1}$$

where q_t is corrected cone resistance, σ_v is initial vertical stress and N_{kt} is empirical constant typically between 10 and 18.

- Friction angle φ' of coarse grained soils [18]:

$$\tan\varphi' = \frac{1}{2.68}\left(\log\left(\frac{q_c}{\sigma_v - u}\right) + 0.29\right) \tag{2}$$

where u is the initial pore pressure.

- Friction angle $\varphi'$of fine grained soils [19]:

$$\varphi' = 29.5° \cdot B_q^{0.121}(0.256 + 0.366\, B_q + \log Q_t) \tag{3}$$

where B_q is pore pressure ratio $(u_2 - u)/(q_t - \sigma_v)$ and Q_t is normalised cone resistance $(q_t - \sigma_v)/(\sigma_v - u)$.

- Constrained modulus M [20]:

$$M = \begin{cases} (q_t - \sigma_v) \cdot \min(Q_t, 14) & I_c \geq 2.2 \\ 0.0188(q_t - \sigma_v) \cdot 10^{0.55 I_c + 1.68} & I_c < 2.2 \end{cases} \tag{4}$$

where I_c is soil behaviour type index and F_r is normalised friction ratio $f_s/(q_t - \sigma_v) \cdot 100\%$.

$$\mathrm{I_c} = ((3.47 - \log \mathrm{Q_t})^2 + (\log \mathrm{F_r} + 1.22)^2)^{0.5} \tag{5}$$

- Overconsolidation ratio OCR [21]:

$$OCR = 0.24\, \mathrm{Q_t}^{1.25} \tag{6}$$

CPTu measurements were evaluated using unit weights estimated from CPTu (uncorr.) and unit weights measured in laboratory (corr.). The laboratory unit weights were in average 5-7% lower than the ones predicted from CPTu results. This difference is relatively low but results in about 20% difference in calculated effective stresses.

4.2. DMT

The DMT tests were carried out according to EN ISO 22476-11 [9] using the Marchetti flat dilatometer [22]. A standard 0.2 mm thick steel membrane and standard pressure gauge with accuracy of 10 kPa or 0.5% were used.

A dilatometer blade was pushed into the soil with a penetration rate of 2 cm/s, and stopped every 20 cm to conduct the tests. Once at the testing depth, a circular steel membrane was expanded horizontally into the sludge by increasing gas pressure. Two pressures were measured: pressure$A$, which is required just to begin moving the membrane against the sludge has to be achieved within 20 s from the start of the test, and pressure B, which is required to expand the center of the membrane by 1.1 mm into the sludge, within 20 s from the measurement of pressure A. Upon correction of the recorded pressures A and B for the membrane stiffness and pressure gauge zero offset, material index I_D, horizontal stress index K_D, and dilatometer modulus E_D were calculated. These DMT intermediate parameters were used to determine engineering properties as follows:

- Undrained shear strength c_u of fine grained soils [22]:

$$c_u = 0.22 \cdot (\sigma_v - u) \cdot (0.5K_D)^{1.25} \tag{7}$$

- Safe estimate of friction angle φ' of sands [23]:

$$\varphi' = 28° + 14.6° \log K_D - 2.1°(\log K_D)^2 \tag{8}$$

- Constrained modulus M [22]:

$$M = R_M \cdot E_D \tag{9}$$

where R_M is calculated as:

$$R_M = \begin{cases} 0.14 + 2.36 \log K_D & \text{if } I_D \leq 0.6 \\ R_{M,0} + \left(2.5 - R_{M,0}\right) \log K_D & \text{if } 0.6 < I_D < 3 \\ 0.5 + 2 \log K_D & \text{if } I_D \geq 3 \\ 0.32 + 2.18 \log K_D & \text{if } K_D > 10 \\ \geq \ 0.85 & \end{cases} \tag{10}$$

where $R_{M,0} = 0.14 + 0.15(I_D - 0.6)$.

- Overconsolidation ratio OCR [22]:

$$OCR = (0.5\, K_D)^{1.56} \tag{11}$$

As in the case of CPTu, the DMT unit weights were higher than laboratory measurements. Again, the DMT measurements were interpreted using a unit weight estimates from DMT (uncorr.) and unit weights from laboratory (corr.).

4.3. FVT

FVT were performed according to prEN ISO 22476-9 [10] using Geonor H-10 equipment. A 65 × 130 mm field vane was pushed to the desired depth, and then rotated at a rate of 1 °/sec. After the peak torque had been measured, the vane was quickly rotated 25 times to remould the sludge. The torque was measured again to determine the remoulded shear strength.

5. Results

5.1. Identification of the tailings

The tailings consist of mineral gypsum ($CaSO_4x2H_2O$) (app. 80% of dry mass) and amorphous iron oxides (app. 15% of dry mass). Other minor mineral constituents are titanium dioxide (TiO_2), lime ($Ca(OH)_2$), quartz (SiO_2) and magnesium oxide (MgO) [7]. The gypsum particles are needle like, elongated, covered by iron oxides with the average particle density (ρ_s) of 2.36 t/m^3.

According to Unified Soil Classification System (USCS) the sediment belongs to the group of silt to elastic silt (ML\MH) [24]. The grain size distribution (Fig. 2) confirms previous classification and shows that the sediment becomes finer with depth.

The field identification of tailings based on CPTu and DMT is presented in Fig. 3. Both tests show similar material behaviour group as laboratory tests, but no changes with depth are observed. From the top of the sludge to the depth of about 5 m scatter of results is large, indicating the unreliable results of CPTu and DMT measurements at shallow depths (small effective stresses in very soft tailings). The sensitivity of conventional CPTu and DMT was found to be too low to measure reliable data in the sludge with very low resistance to penetration/deformation. The sensitivity is also problematic for any evaluation of CPTu and DMT derived material properties.

It is interesting to note that material belongs to the same material behaviour group regardless of using different unit weights for evaluation of CPTu or DMT.

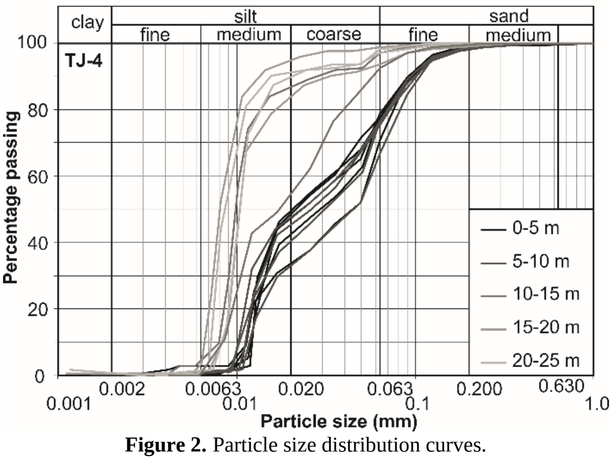

Figure 2. Particle size distribution curves.

5.2. Undrained shear strength

Due to the very soft nature of the sludge, it was not possible to prepare specimens for unconfined compression strength tests or for triaxial compression tests. Therefore, only data from field tests could be compared.

The DMT calculation of undrained shear strength is directly related to effective stresses which are influenced by unit weight prediction. The effective stresses calculated using CPTu or DMT unit weights (uncorr.) are about 20% higher than those calculated from unit weights measured in the laboratory (corr.). As a consequence, 20% higher undrained shear strength should be expected when using unit weights from DMT. Contrary to expectation, using the DMT predicted unit weights results in lower undrained shear strength. This seems to be a result of different K_D, which is also effective stress dependent.

CPTu calculated undrained shear strength using, N_{kt} = 13, is not significantly influenced by the estimation of vertical stress in the ground. The undrained shear strengths calculated from the CPTu are higher than those calculated from the DMT results. This could be a result of equation (7), which was derived for clayey soils and might under-predict undrained shear strength in silts. The difference between undrained shear strength from DMT and CPTu tests in the sludge is 40%. The FVT gives results closer to CPTu.

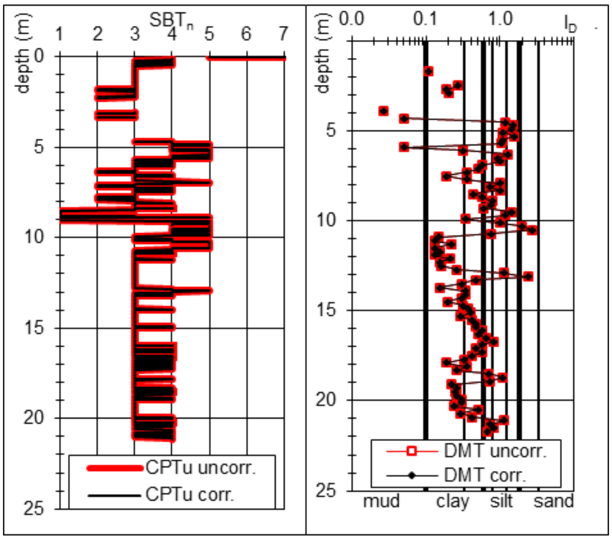

Figure 3. Identification based on CPTu and DMT. CPTu SBTn 1 sensitive soil, 2 organic soils – clay; 3 silty clay to clay; 4 clayey silt to silty clay; 5 silty sand to sandy silt; 6 clean sand to silty sand; 7 gravelly sand to dense sand; DMT I_D <0.1 mud, 0.1-0.33 Clay, 0.33-0.6 silty clay, 0.6-0.8 clayey silt, 0.8-1.2 silt, 1.2-1.8 sandy silt, 1.8-3.3 silty sand, 3.3-10 sand.

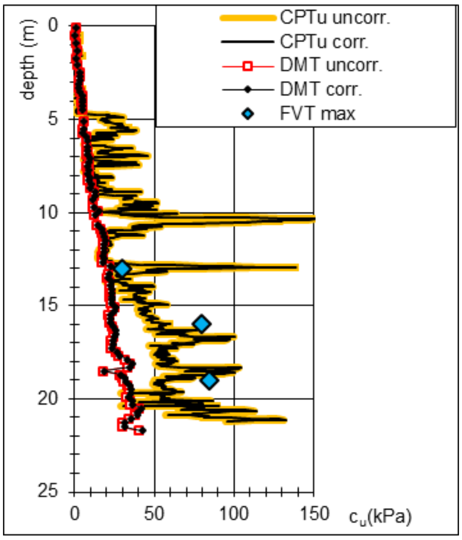

Figure 4. Undrained shear strength based on CPTu, DMT and FVT.

5.3. Drained shear strength

Fig. 5 shows friction angles (φ') calculated from the CPTu and DMT using unit weights obtained from CPTu or DMT (uncorr.) or measured in the laboratory (corr.). The influence of the unit weight used in the CPTu or DMT evaluation could be observed in the calculations of friction angles. A difference of around 1° was observed due to different unit weights used in friction angle calculation and is smaller than spatial variation of it.

CPTu and DMT calculated friction angles are generally close to laboratory direct shear tests results. Laboratory test at the depth of 8.5 m was performed on sand like red gypsum sludge and thus gives higher values of friction angle than silt type sludge. The CPTu friction angles at the depths greater than 10 m calculated using Eq. (3) for fine grained soils are much higher than expected for fine grained soils. As no laboratory measurements were performed at depth greater than 10 m it is unclear if this is a real value of friction angle or Eq. (3) is resulting in friction angles that are higher than in reality.

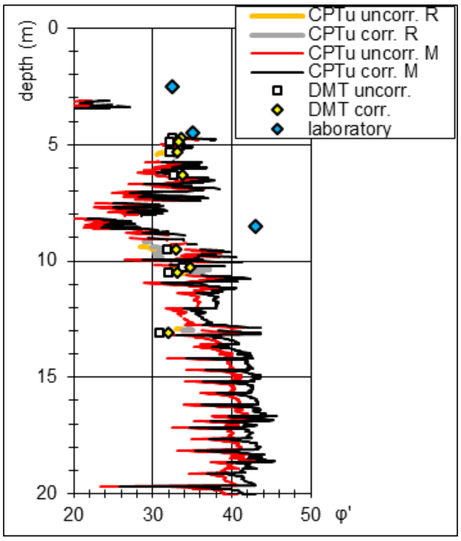

Figure 5. Drained shear strength based on CPTu, DMT and laboratory measurements. R – calculated using eq. (2) for coarse grained and M – calculated using eq. (3) for fine grained soils.

5.4. Constrained modulus

Fig. 6 shows the compression curve of the sludge in which each loading/unloading stage followed after 24 hours. Fig. 7 shows the consolidation curves of the same specimen for the loading stages of 0-4.5 kPa and 12.5-25 kPa. At the loading stage 0-4.5 kPa the consolidation curve consists from primary and secondary consolidation and shows behaviour expected for very soft soils. At loading stage 12.5-25 kPa there is no clear division between primary and secondary consolidation. Due to large creep deformations in previous loading stages, the sludge appears to be overconsolidated.

The constrained moduli (M) calculated from CPTu and DMT measurements are presented in Fig. 8. Some influence of unit weight to the result could be observed again.

CPTu calculated constrained moduli were up to 2 times higher than DMT estimated constrained moduli, which was also observed by Maček et al. [25] for natural soft soils. In the case of the sludge, the constrained moduli calculated from CPTu or DMT tests were higher than the ones measured in laboratory.

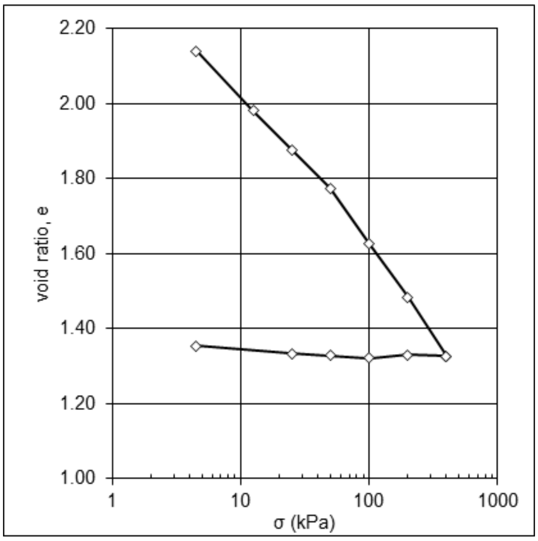

Figure 6. Compression curve of TJ-4 4.5 m.

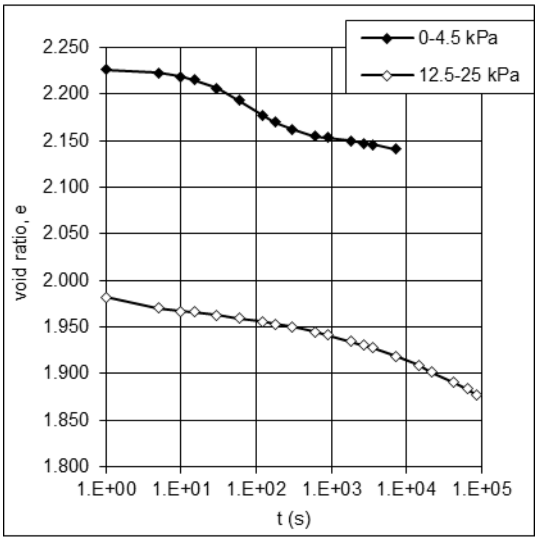

Figure 7. Consolidation curves of TJ-4, 4.5 m depth for loading stages 0-4.5 kPa and 12.5-25 kPa.

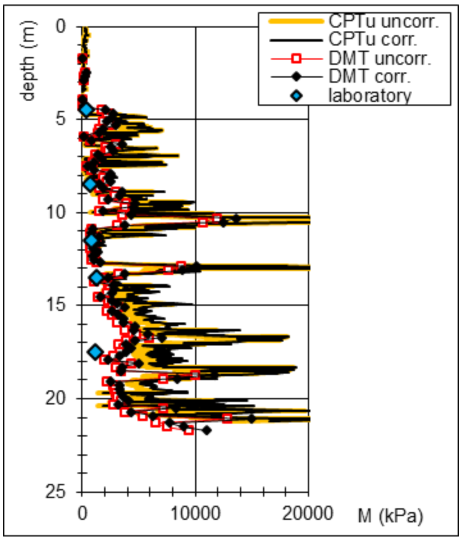

Figure 8. The constrained modulus calculated using DMT and CPTu and compared with ones from laboratory oedometer tests.

One of the reasons for differences in the constrained moduli could be high creep, which might not be included in a fast “undrained” field tests, while laboratory oedometer tests include a part of a long term creep. To illustrate: from Fig. 7 it could be seen that the void ratio changes in the first 100 s (time of primary consolidation of stage 0-4.5 kPa) is only one third of final void ratio change. The effect of creep starts to be important in prolonged exposure to higher stresses.

It also seems that constrained moduli are in general more influenced by creep than by the effect of partial drainage which could lower DMT calculated constrained moduli.

5.5. OCR

OCR for young sediments should be 1 or even less than 1, if the ground is not fully consolidated. The OCR calculated from CPTu and DMT are above 1. This indicates that there might be another influence to the overconsolidation or that the equations developed for the OCR estimation for natural soils are not reliable for the sludge (Fig. 9).

From the results it seems that there is an increase of OCR with depth and that OCR calculated from CPTu is higher than OCR calculated from DMT. The first could be result of creep, as the lower parts of the sludge are the oldest. The second could also be related to the rate of CPTu and DMT tests and the effect of creep on them or the nature of measurements. Some possible influence of creep on measurements was already discussed in connection with constrained modulus calculation.

Unit weights used in CPTu or DMT calculations influenced OCR. This is expected, as the decrease of unit weight (i.e. decrease of stresses) should increase OCR. It was found that the increase of OCR in percent is greater than reciprocal value of the decrease of effective stress in percent.

Due to disturbed nature of samples and high creep it was impossible to measure OCR in the laboratory.

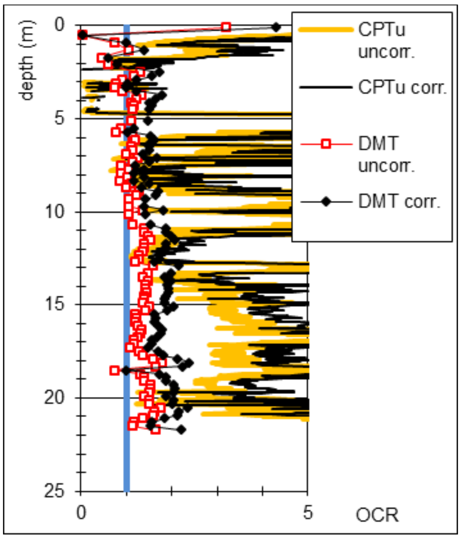

Figure 9. The OCR calculated using DMT and CPTu. Blue line represents OCR 1.

6. Conclusions

Based on field and laboratory investigations and analyses of results the following conclusions can be made:

- There are some influences of unit weight and stresses in the sludge pond on calculated engineering properties. These influences were found to be negligible compared to other spatial variations.
- The CPTu and DMT identification is in reasonably good agreement with the laboratory classification. The accuracy of field identification is too small to observe variations in grain size distribution of red gypsum sludge.
- Drained shear strength can be reasonably well predicted with CPTu and DMT.
- DMT gives lower undrained shear strength than CPTu or FVT. This could be due to Eq. 7, which was derived for clayey soils with low friction angle and might not be suitable for use in silts with higher friction angle.
- Constrained moduli calculated from CPTu and DMT are higher than measured in the laboratory. This could be the result of relatively fast field tests, which are not taking into account long term creep deformations.
- OCR calculated from CPTu and DMT is higher than 1 and indicates some source of overconsolidation, like creep or error in OCR estimation by using equations for natural soils.

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