Challenges in the Interpretation of the DMT in Tailings

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ABSTRACT: Evaluation of tailings constitutive parameters by in situ tests is still a major challenge in geotechnical and geo-environmental engineering. The present paper attempts to address this topic using the DMT in order to identify approaches intended to the assessment of soil parameters in a consistent and complementary way to laboratory results. Proper account to rate effects on penetration and dissipation pore pressures is made by using a research dilatometer with a porous element at the center of the blade. Drainage effects are considered an essential step in the characterization and design of tailings storage facilities, since a characteristic feature of these deposits is their spatial variability, producing tailings in the so called intermediate permeability range. In addition, some comments are made in respect to our ability in assessing soil properties and static liquefaction

1 INTRODUCTION

The DMT was introduced and developed by Marchetti (1980), whose contribution set the standards for equipment, testing procedures and interpretation methods. The test gives two independent significant measurements (p_0 and p_1) from which soil strength, stiffness and stress history can be assessed. Interpretation methods proved to produce accurate and realistic prediction of soil properties in clay and sand but have not been systematically tested in tailings.

The research questions in connection with the DMT in tailings, mostly not yet addressed in comprehensive bases, are:

a) Would methods developed for the interpretation of DMT in sand and clay provide consistent framework for the assessment of properties in tailings?
b) Do Standard DMT testing rates in tailings (intermediate permeability soils containing sand, silt and clay) provide measurements of fully drained or fully undrained conditions?
c) Recognized as a 2 parameter test (p_o and p_1), the addition of a third independent measurement (soil stiffness in the SDMT) helps refining our ability in predicting soil behavior, particularly in the case of static and dynamic liquefaction?

To answer these questions, field tests carried out in different tailing dams are re-visited in this paper, including results from the SDMT comprising and a blade developed to record pore pressures. The aim of the paper is not to produce answers to those raised questions, but to give insights to the problem of interpreting dilatometer tests in tailings.

2 CHARACTERIZATION

The importance of comprehensive characterization of tailing dams, and the ability of in situ tests to do so, has been acknowledged in by a large number of publications. Papers in tailings generally cover the following topics:

a) Characterization of spatial variability of tailing dams and their variation in hydraulic conductivity and mechanical properties in a deposit;
b) Definition of saturated layer and the determination of equilibrium pore pressure (close attention has to be given to a precise determination of the position of the water table at the time of the investigation programme
c) Prediction of constitutive parameters from laboratory and in situ testing data.
d) Assessment of potential liquefaction.

The present paper concentrates on the last two topics, concentrating on DMT interpretation methods conceived to estimate the mechanical properties of tailings and static liquefaction potential.

3 TESTING SITE AND METHODS

A dominant effect on tailings is the variability in grain size distribution and consequently in soil permeability. Under this condition, the in situ behaviour at given loading rates changes considerably and the simplest idealized approach of broadly distinguishing between drained and undrained conditions for the interpretation of in situ tests is no longer applicable, since the response can be affected by partial consolidation.

Assessment of rate effects from in situ tests requires the pore pressure to be measured which is not a standard practice in the DMT. In fact few comprehensive set of results reporting pore pressure measurements in the dilatometer were published for tests carried out in clay and sand (Robertson et al, 1988; Lutenegger, 1988; Campanella and Robertson, 1991), and no experience is reported for intermediate permeability soils.

In order to address the issue of rate effects in dilatometer tests, a research dilatometer was constructed. It is a simple design where the dilatometer membrane is replaced by a porous element connected to a pressure transducer (Fig. 1). The device records only excess pore pressures generated during penetration and dissipation after halting the blade at a given depth. With this set up a complete set of results can only be attained by driving two probes (SDMT and pore pressure blade) side by side, about 1m apart, allowing a SDMTU profile to be obtained. Tests are reported herein for clay, sand and tailings.

a) b) c)

Fig. 1. Equipment (a) DMT blade; (b) Blade adapted for pore pressure measurements; (c) saturation of pore pressure element.

3.1 Clay

Comprehensive site investigation carried out in clay at the Tubarão experimental testing site in Brazil comprises SDMT, CPTU, vane, shear wave velocity and SPT performed to identify soil type and stratigraphy (e.g. Mantaras et al, 2014, Odebrecht & Schnaid, 2015). A typical dilatometer profile, including pore pressure measurements is presented in Fig. 2, revealing essentially a 15 m thick, very soft, essentially normally consolidated clay. In the Tubarão profile, the DMT pore pressure acting on the membrane during and immediately after penetration are high and comparable (slightly lower) to those measured behind the cone tip in the CPTU.

3.2 Sand

Site characterization of the Araquari Testing Site located in Southern Brazil began in 2014 supported by the ISSMGE. Conceived primarily to study the behaviour of pile foundations, the work started by comprehensive site investigation comprising SPT, CPTU, SDMT as well as laboratory testing.

The soil conditions at Araquari consist of about 12m of fine dense sand underlain by 12m of fine sand-silty soils and clean dense sand to about 30m.

The equilibrium pore pressure is at about 1m below ground level. Penetration of the SDMTU indicates that penetration pore pressures were approximate hydrostatic in the top layers and some excess pore is generated in the sand-silty layer below 12m. In clean sand the p_0 and p_1 readings recorded just after penetration correspond to a fully drained test and are therefore controlled by the soil effective stresses. Similar findings are reported by Campanella & Robertson (1991) at the upper part of McDonald´s Farm.

Below 16m, pore pressures are generated during penetration which is a common features in silty sands. These pore pressures are dissipated shortly after halting the DMT, p_0 and p_1 readings are drained and the p_2 closing pressure corresponds to hydrostatic.

3.3 Gold Tailing

SDMTU tests were carried out at the *Fazenda Brasileira* disposal plant from Bahia State, northeast Brazil. The site is being a subject of research for the past 10 years at Federal University of Rio Grande do Sul as reported by Bedin et al (2012), Schnaid et al (2013) and others.

A typical DMT profile including index parameters and penetration pore pressure measurements is presented in Fig. 4. The soil profile identified by DMT data ranges from clay to silt and excess pore pressures are high (same order of magnitude as those measured by CPTU).

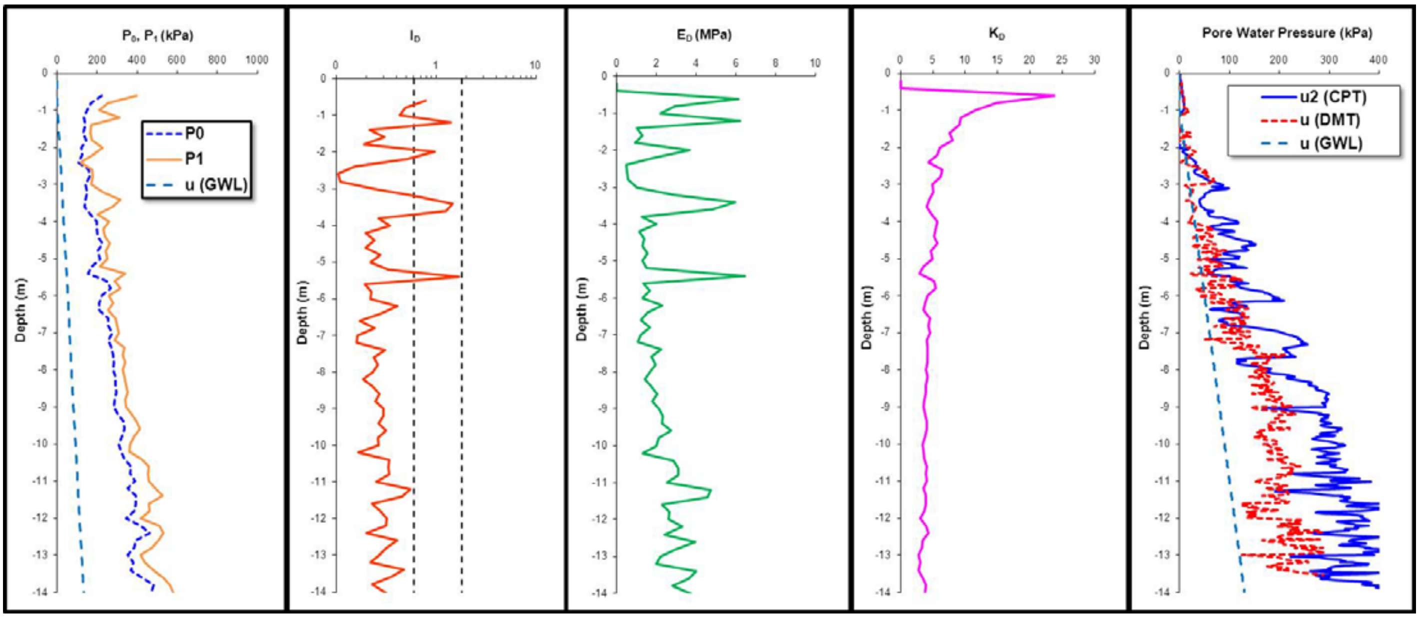

Fig. 2. Typical soil profile at the Tubarão experimental testing site

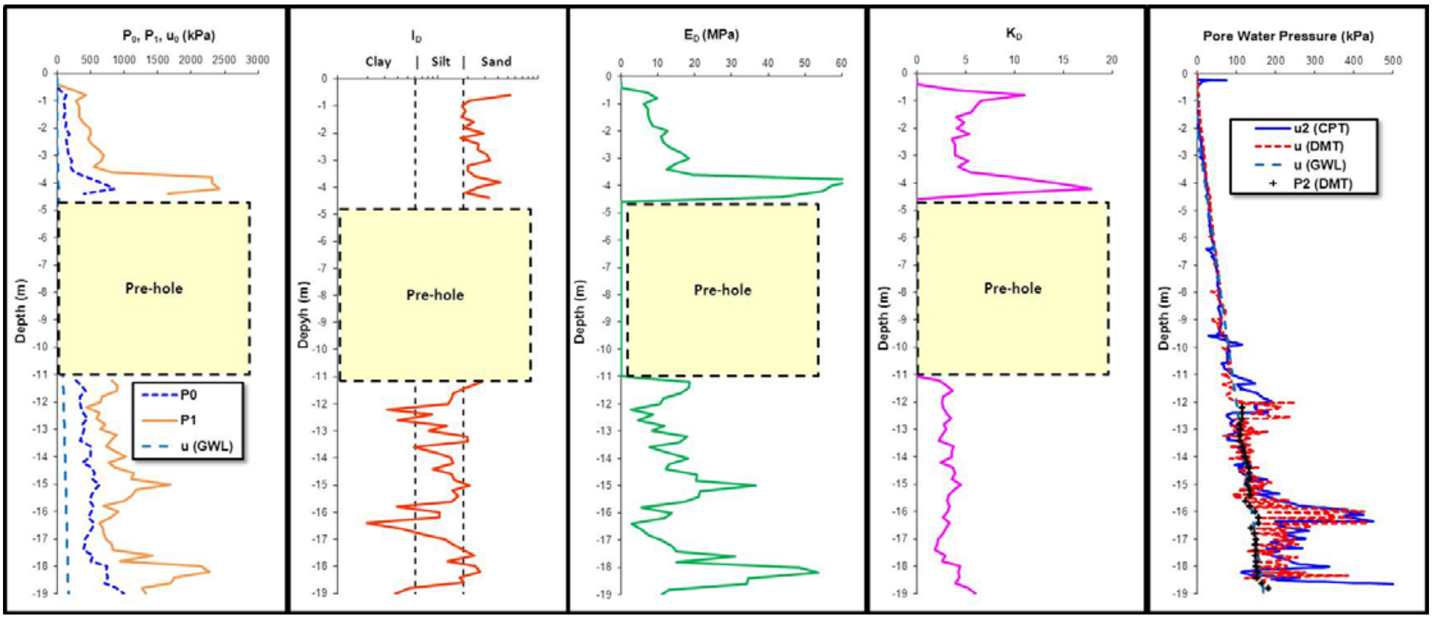

Fig. 3. Typical profile at the Araquari experimental test site.

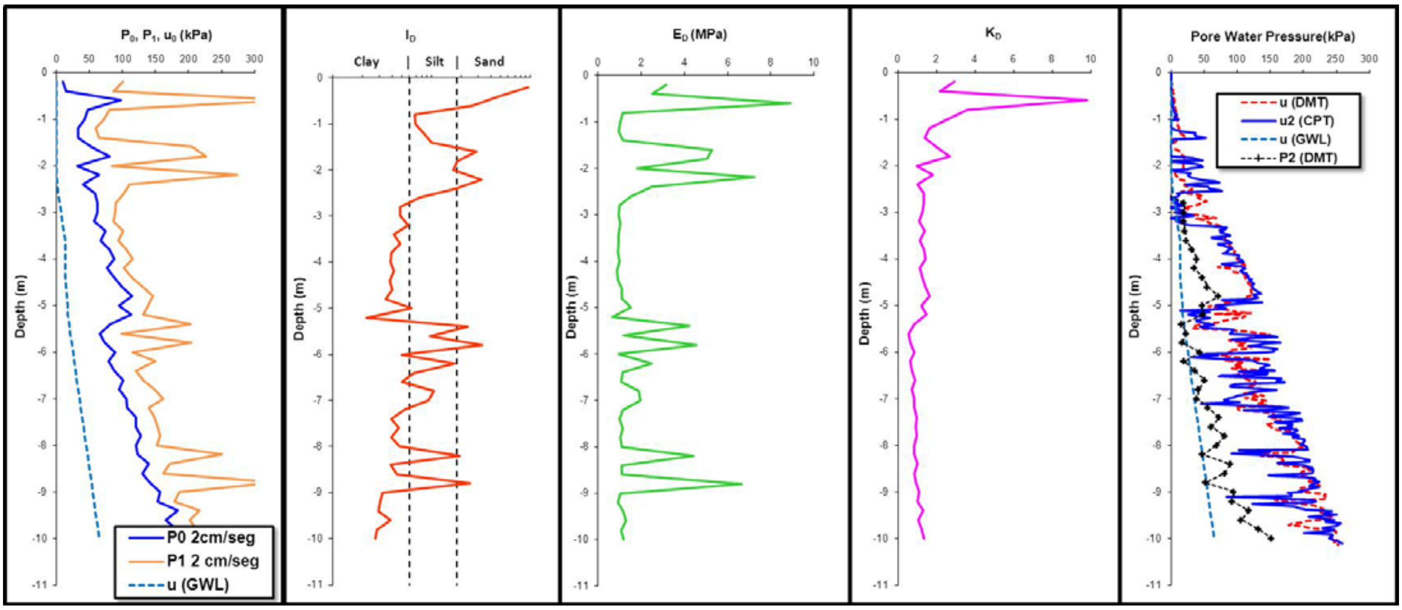

Fig. 4. Profile at the *Fazenda Brasileira* gold tailings.

4 RATE EFFECTS

Rate effects in the DMT are related to both penetration and inflation rates (unlike CPT measurements that reflect penetration rate only). To evaluate rate effects in the DMT, a series of tests were carried out in the 3 testing sites under a number of different procedures. Results were compared to piezocone tests carried out at different penetration rates. Procedures adopted in the present work are:

a) Standard tests: 20mm/s penetration rate, A reading at 15s, B reading at 30s and C reading at 60s after halting the blade;
b) Tests at faster and lower penetration rates (in respect to the 20mm/s standard practice);
c) Tests at different time intervals after halting the blade at a given depth.

Typical examples of the recorded data are shown and discussed herein to illustrate the influence of rate effects on pore pressure values. Comparisons between DMT and CPTU in soft, normally to lightly overconsolidated clay indicate large excess pore pressures generated in both DMT and CPTU penetration, CPTU yields slightly larger pore pressures during penetration and show dilatant response during dissipation, in opposition to DMT monotonic dissipation response (see Fig. 5). As recognized by Campanella & Robertson (1991) the measured total stresses p_0 and p_1 are strongly controlled by the high penetration pore pressure. During the 1min interval required for DMT measurements (without expansion of the membrane in this reported case), pore pressure exhibit marginal consolidation effects, corroborating the concept that in clay the DMT is predominantly undrained.

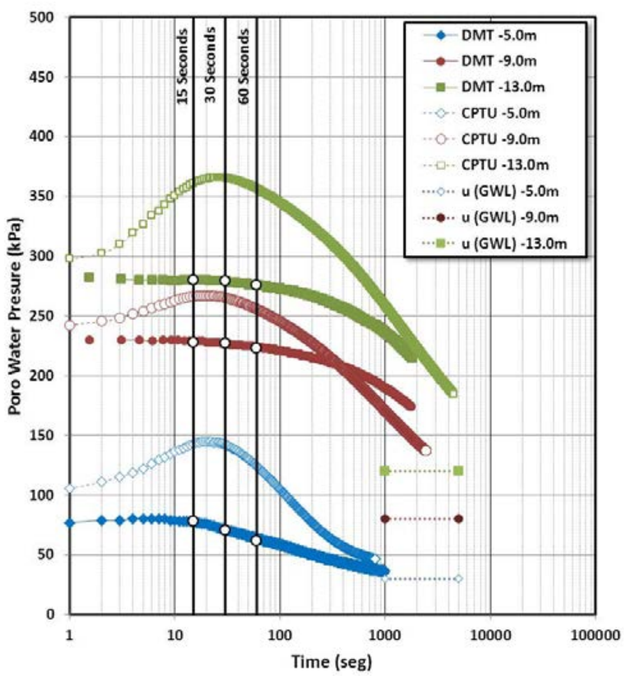

Fig. 5. Pore pressure dissipation tests in clay.

In clean sand no excess pore pressures are generated during penetration (i.e. pressures were approximately hydrostatic). In the silty sand layers of the Araquari testing site the DMT generates considerable penetration excess pore pressure that dissipates fast after halting penetration of the blade and readings at 15s, 30s and 60s correspond to drained tests, as illustrated in Fig. 6.

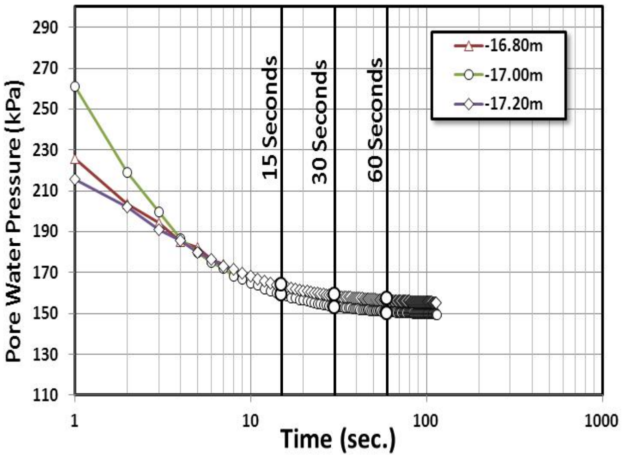

Fig. 6. Pore pressure during DMT dissipation tests in sandy clay at the Araquari testing site.

Typical DMT dissipation test results in gold silty tailings are presented in Fig. 7, in which pore pressure decay and A readings variation with time are shown to reduce at approximately the same rate. Readings at 15s, 30s and 60s are all partially drained and change continuously with time. In this set of gold tailing tests the recommendation of taking the *A*-reading in 15 sec is inadequate. An estimate of s_u would require taking the *A*-reading in 2 to 3s (infeasible) in order to insure undrained conditions given the fast rate of consolidation. An alternative would be to slow-down the test for complete pore pressure decay, but this would conflict to TC16 (2001) recommendations that states that in silts the inflation should never be slow, otherwise *B*, due to some consolidation during the expansion, will be too low, and consequently I_D, E_D, M too low as well.

Marchetti (2015) suggests to take repeated *A*-readings, for about 1min (every time deflating immediately after *A*) to verify if appreciable consolidation is taking place during the time for determining *A* and *B*. Results shown in Fig. 7 indicates that the *A*-decay is significant, the test occurs in partially drained conditions, *B* is probably too low and the tests cannot be interpreted in order to derive soil parameters.

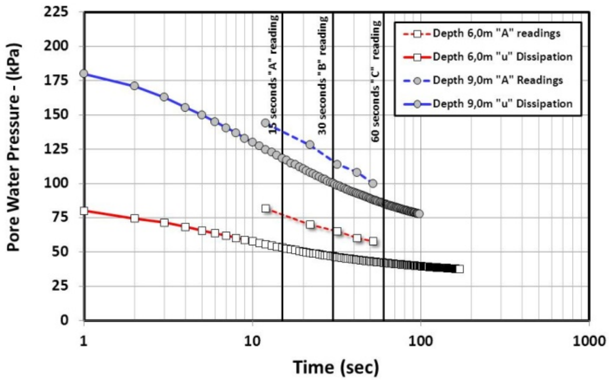

Fig. 7. Pore pressure during DMT dissipation tests in Gold tailings.

A summary of the evidences provided by monitoring the after penetration DMT pore pressure dissipation is shown in Fig. 8 for tests carried out in the different geo-materials tested in the present work (sand, silty-sand, clay and gold tailings). In this figure, all tests were carried out at a standard penetration rate of 20mm/s and pore pressure dissipation is expressed in percentage as:

$$Disspation\ \% = \left(\frac{u_{max} - u_i}{u_{max} - u_{eq}}\right)100 \qquad (1)$$

where u_{max} is maximum penetration pore pressure generated at the testing depth; u_i the pore pressure at any instant during inflation (i = 15 seconds for A Reading; i = 30 seconds for B reading) and u_{eq} is the hydrostatic pore pressure at the testing depth.

Within the 60s required for DMT readings, the test is undrained in clay, drained in sand and partially drained in intermediate permeability soils. The main research question is how to produce a unified interpretation criterion that allows drainage conditions to be identified or (even better) to be controlled in the DMT.

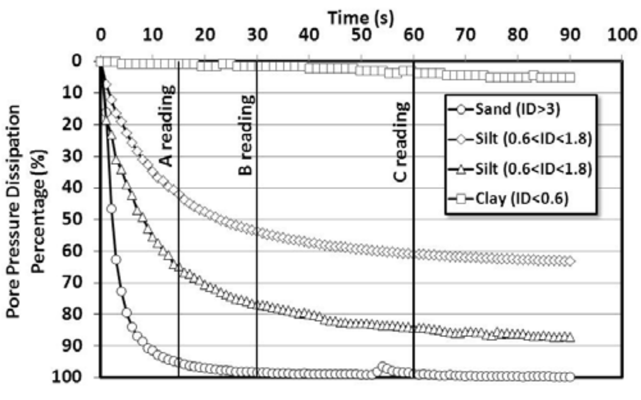

Fig. 8. Pore pressure dissipation with time for different geo-materials.

In the literature, transition penetration rates are identified by accounting for probe size and soil compressibility (e.g. Randolph and Hope, 2004). Normalization of penetration results are represented by an analytical backbone curve of penetration resistance against normalized penetration velocity *V* (= vd/c_h, where v is the penetrometer velocity, d is the penetrometer diameter (in this case the piezocone diameter), and c_h is the horizontal coefficient of consolidation obtained from piezocone dissipation tests. These concepts are adapted here by plotting simultaneously penetration pore pressure, dissipation pore pressure and soil type I_D versus normalized velocity (Fig. 9). Despite the scatter, it is possible to identify a region in these plots where partial drainage occurs during both DMT penetration and dissipation. This region is defined by normalized velocities *V* in the range of 1 to 100 that, in turn, are associated to I_D values typically ranging from 0.6 to 1.8.

Some conclusions can be drawn from these observations. There is similarity in properties of coarse tailings and loose to medium dense natural sands, whereas fine tailings behave as clay. In silts pore pressures decrease considerably during test and, in this case, the DMT requires specific recommendations because A and B readings, being total stress measurements, are sensitive to variations in testing rate. It appears that drainage conditions can be inferred directly from soil type I_D and that tests can be only used to assess soil parameters for I_D<0.6 (undrained) and I_D>1.8 (drained). In the intermediate I_D range (corresponding to 1<*V*<100), penetration and inflation rates may have to be adjusted to reduce consolidation effects on both penetration and dissipation pore pressures. In this respect, a possible advantage of the DMT over other driven tools (such as the CPT) is that adjustments in inflation rate – if required – can be made during the actual tests when monitoring A readings.

5 SOIL PROPERTIES

Once the uncertainties associated to rate effects in silty tailings are assessed, one can turn to the problem of interpreting DMT in order to predict soil parameters. Let us take the constrained modulus as an example, given the fact that we can rely on Elastic Theory.

The original Marchetti's work in the 1980s has already explored the possibility of correlating the constrained modulus M and E_D through an empirical coefficient R_M. We reviewed the original concept to isolate the influence of parameters controlling drainage. From Elastic Theory, the volumetric strain of an element is simply calculated as:

$$\frac{\Delta V}{V} = \varepsilon_x + \varepsilon_y + \varepsilon_z \quad (2)$$

Considering that stresses and strains are linked by the Coefficient of Poisson μ and *by* the Young Modulus *E*:

$$\frac{\Delta V}{V} = \frac{1}{E}\{(1-2\mu)(\Delta\sigma_x + \Delta\sigma_y + \Delta\sigma_z)\} \quad (3)$$

where ε_x, ε_y, ε_z and σ_x, σ_y, σ_z are strains and stresses in the x, y and z direction respectively.

Assuming the DMT expanding in the x direction, perpendicular to the blade, $\Delta\sigma_y = \Delta\sigma_z$ = zero and $\Delta\sigma_x = (p_1 - p_0)$:

$$\frac{\Delta V}{V} = \frac{(1-2\mu)}{E}(p_1 - p_0) \quad (4)$$

If $\varepsilon_y = \varepsilon_z = 0$, equation 3 can be expressed as:

$$\frac{1}{E} = \frac{(1-\mu)}{M(1+\mu)(1-2\mu)} \quad (5)$$

where M is the constrained modulus, ΔV the membrane volume for the p_1 reading and V deformed soil volume. By isolating the constrained modulus:

$$M = \frac{(1-\mu)}{(1+\mu)}(p_1 - p_0)\frac{\Delta V}{V} \quad (6)$$

Note that $\Delta V = V_f - V_o$ can be easily obtained: the initial volume V_o is zero and the final volume V_f is expressed as (see Fig. 10).

$$V_f = \frac{1}{6}\pi \cdot h(3a^2 + h^2) \quad (7)$$

For the DMT *a*=3cm (6cm/2), *h*=1,1 mm and the final volume is 1.555×10^{-6} m^3.

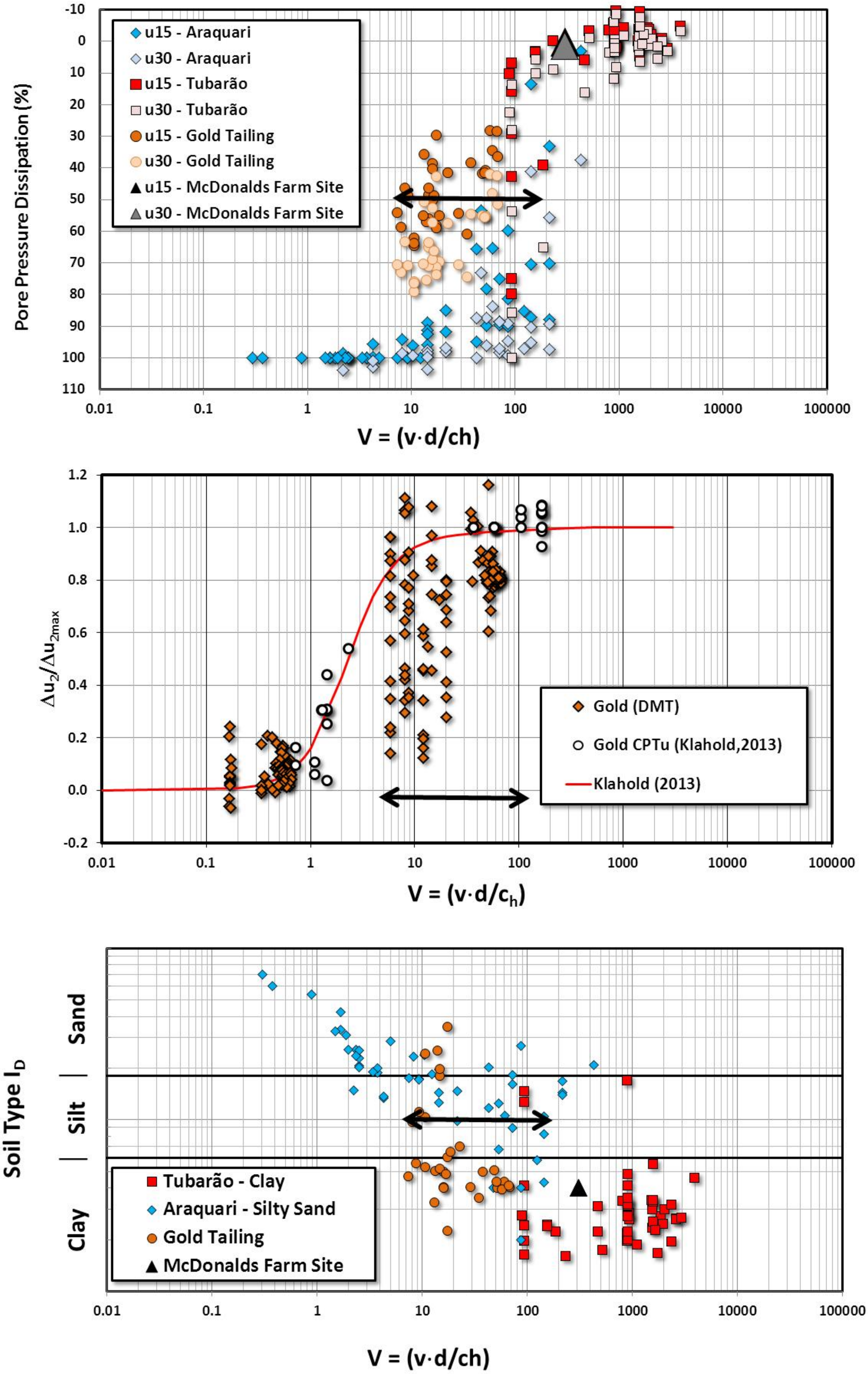

Fig. 9. Normalized DMT penetration pore pressure for gold tailings.

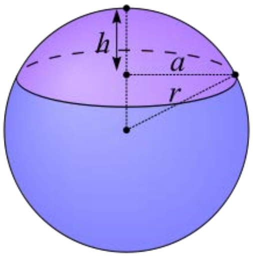

Fig. 10. Volume around an expanding elliptical element.

The deformed soil volume V can be obtain by assuming a semi-ellipse (half the volume of an ellipse) with $a=b=3$cm (6cm/2) and $c=7$cm.

$V=(4/3)\pi(a\cdot b\cdot c)/2 = (4/3)\pi(0.03\cdot 0.03\cdot 0.07)/2 = 2.26\cdot 10^{-4}/2 = 1.13\cdot 10^{-4}$ m^3.

Equation 5 is a ready to use expression derived to calculate the constrained modulus from DMT p_0 and p_1 measurements, but requires the Coefficient of Poisson to be selected in each specific case. In the experimental clay testing site of Tubarão, equation 5 yields a constrained modulus *M* that is in close agreement with results from oedometer tests and in tune with the original correlation proposed by Marchetti (1980). In this case tests are undrained and the Coefficient of Poisson is taken as 0.49.

In the sand tailings from Zelany Most Dam in Poland, the modulus *M* can be probably assessed by assuming a drained Coefficient of Poisson of about 0.25. In this case equation 6 yields values in the same range of the well-established Marchetti´s correlation (Fig. 11). By moving to the gold tailings of *Fazenda Brasileiro* where consolidation impacts the A (p_0) and B (p_1) measurements, we can assume an average μ value of about 0.3. In this case some discrepancy is observed between methods in the lower silty sand layer (see Fig. 13).

It is premature to speculate on the accuracy in assessing the constrained modulus M (or any other constitutive parameter) in tailings. Materials tested here are all normally consolidated to slightly overconsolidated where the effect of soil stress history is not dominant and the DMT provides indication of M. For a more general application, the Poisson Coefficient and the deformed soil volume (V) could be probably expressed in terms of soil type and have different values in one profile. Rate effects may have to be better controlled and understood before making general practical recommendations.

6 STATIC LIQUEFACTION

In the past, tailings dams have failed due to various causes such as slope instability, piping, weak foundations and static and seismic liquefaction. For assessing liquefaction potential the first step is identifying whether a material compresses or dilates under shear.

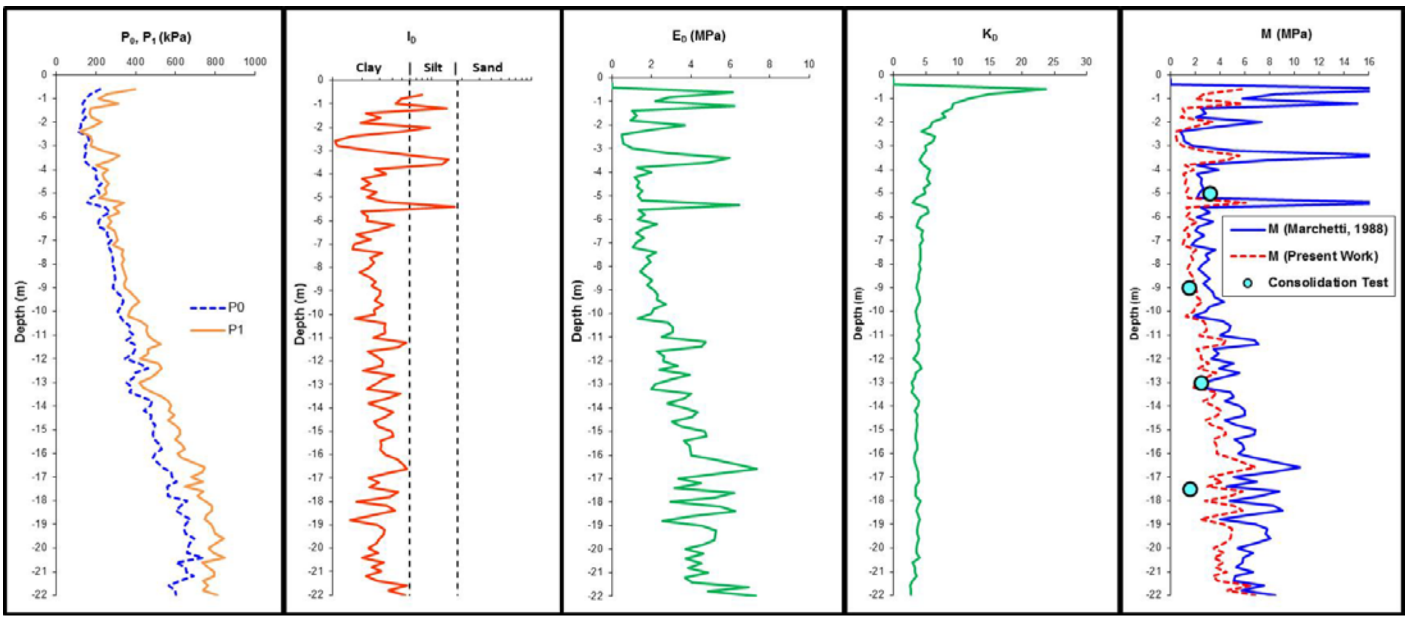

Fig. 11. Constrained modulus D for the Tubarão clay site (μ= 0,49).

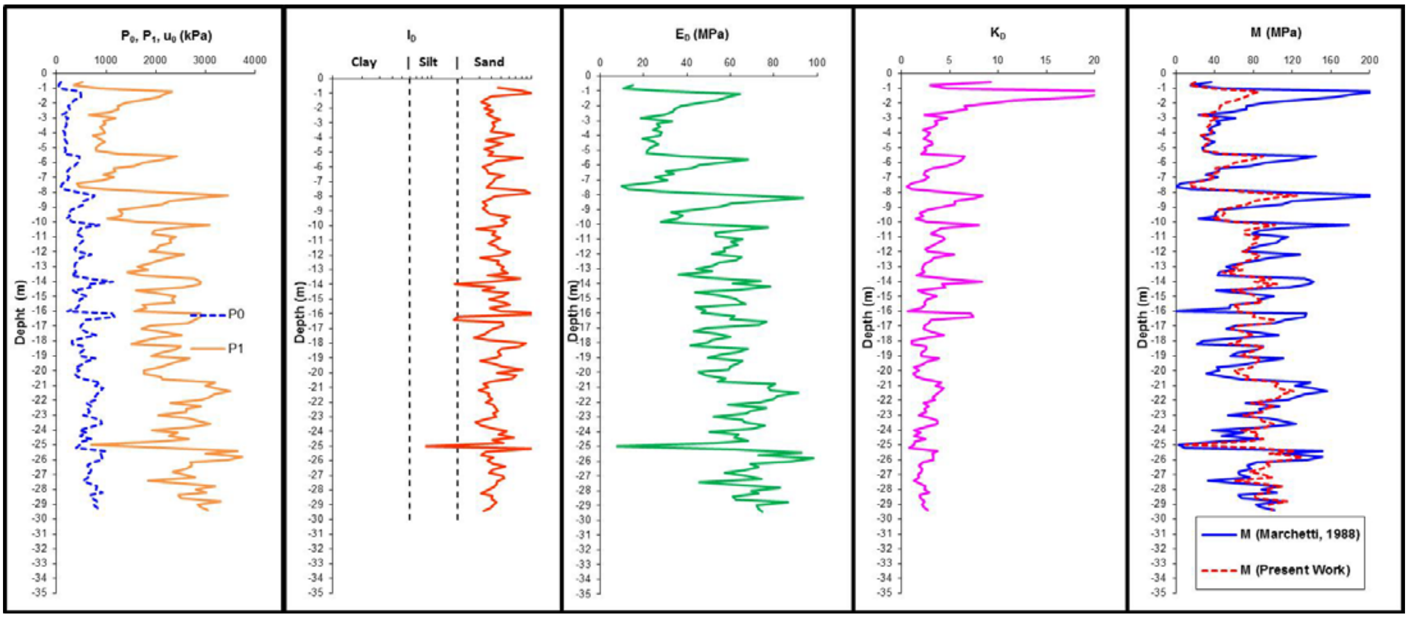

Fig. 13. Zelany Most Dam in Poland (μ=0.25) – *data granted by Silvano Marchetti*.

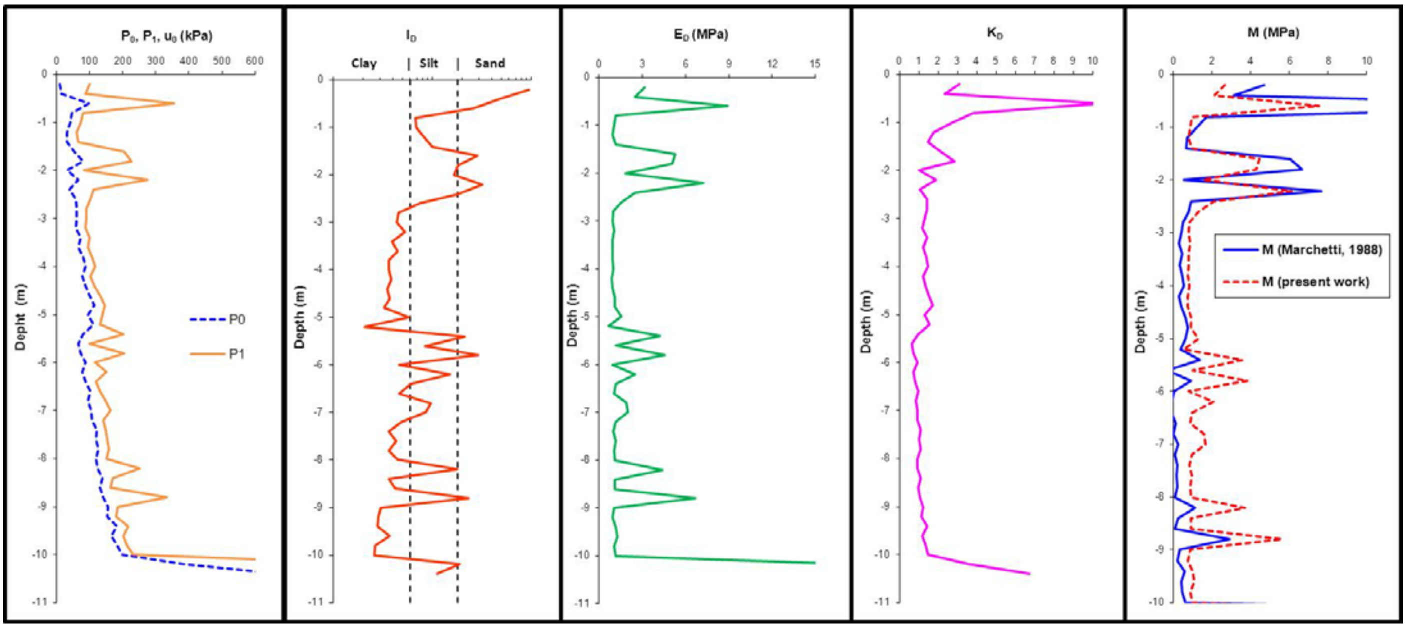

Fig. 14. *Fazenda Brasileira* Gold Tailing Dam in Brazil (μ=0.3).

Approaches based on CPTU data appear to give some insights in this respect and can be used in combination with the database gathered for tailings (see Schnaid et al, 2015). An approach developed by Robertson and Fair (1995) correlating G_o/q_c and Q_t is shown in Fig. 14, where the ratio of the elastic stiffness to penetration tip resistance (G_o/q_c) follows the concept that a material that is stiffer in deformation may be stronger in strength. A similar plot has been suggested by Schnaid et al (2004) and Schnaid (2005) in which the the G_o/q_c ratio is related to the normalized dimensionless parameter q_{c1}, defined as:

$$q_{c1} = \left(\frac{q_c}{P_a}\right)\sqrt{\frac{P_a}{\sigma'_v}} \qquad (8)$$

where P_a is the atmospheric pressure. Results from Fazenda Brasileiro shown in Fig. 15 define a specific region in the G_o/q_c *versus* q_{c1} space that falls outside, above and to the left of the region established for sand. Both classification methods provide consistent indication of tailings exhibiting strong strain softening, in agreement to laboratory data reported by Schnaid *et al*, (2013; 2015). DMT data (courtesy from Marchetti) combined to CPTU reported by Tschuschke (2014) on copper ore tailing at Zelanzny Most Dam, western Poland, are in contrast to gold tailings, falling in the same zone as stable, clean uncemented sand.

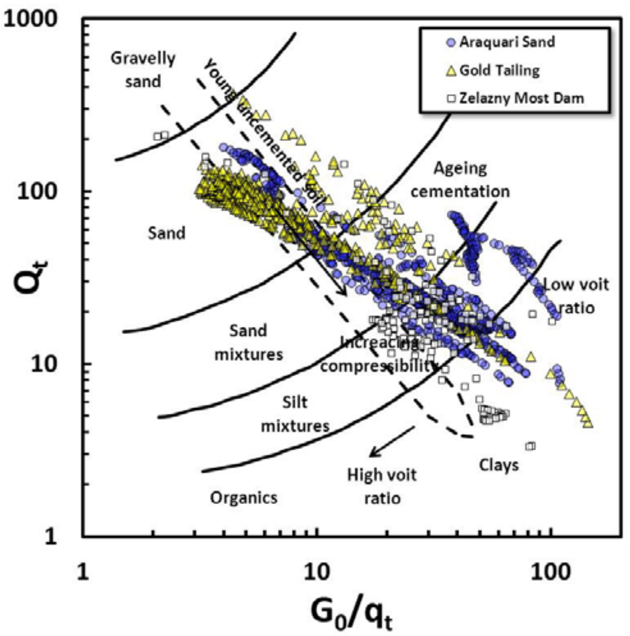

Fig.14. Results from gold tailings and sand (classification chart by Robertson and Fair, 1995).

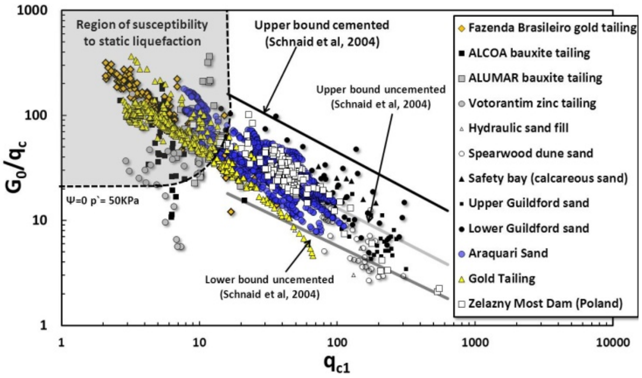

Fig.15. Results from gold tailings and sand (classification chart by Schnaid, 2005).

It is premature to establish an equivalent plot for the DMT. For seismic liquefaction Marchetti (2015) suggests reducing the uncertainty in assessing liquefaction resistance by incorporating Stress History into the liquefaction correlations through K_D. Although the need for Stress History information for better estimates of the liquefaction resistance is recognized, tailing dams are essentially normally consolidated environments.

Undergoing research at UFRGS is exploring the potential of G_o, q_t and K_D correlations, as illustrated in Fig. 16. In general, results from gold tailings exhibit higher G_o/q_t ratios when compared to Araquari sand and Zelazny Most Dam which is characteristic of metastable sols.

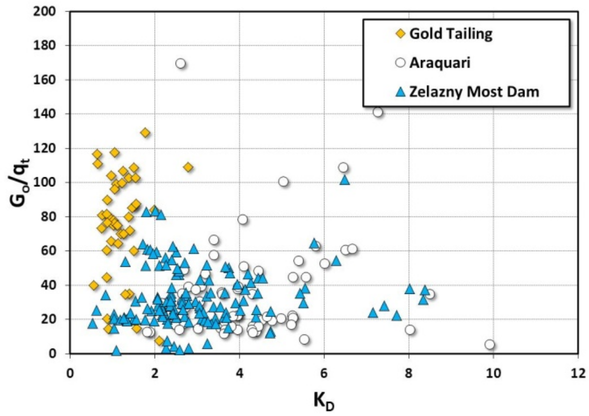

Fig. 16. G_o/q_t *vs* K_D correlation.

7 CONCLUSIONS

The purpose of the research efforts described herein is to gain insights into the interpretation of DMT testing data in tailings and hence to assess their mechanical properties (permeability, stiffness and strength) for geotechnical design of dams and impoundments. The particle size of tailings varies from medium sand to silt or clay, producing materials in the intermediate permeability range and requiring the rate of DMT penetration and inflation to be linked to drainage effects. DMT data from various tests have been compared in a space that correlates dimensionless velocity *V* to degree of drainage *U*. In this space it is possible to evaluate whether partial drainage is taking place, allowing the rational interpretation of short and long term properties of the tailings to be determined. In addition, the SDMT provide indication of liquefaction potential in tailing dams.

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