Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)

Interpretation of the instrumented DMT (iDMT): a more accurate estimation of p_0

H. Shen, W. Haegeman, H. Peiffer
Laboratory of Geotechnics, Department of Civil Engineering, Ghent University, Ghent, Belgium

ABSTRACT: Based on the pioneering conceptual framework of the Marchetti DMT, a number of iDMTs have been developed to produce a full pressure-displacement curve, giving the opportunities to improve interpretation techniques such as the determination of the corrected first pressure reading p_0 (contact pressure at zero displacement). A novel p_0 interpretation technique is thus presented in this paper to reduce the potential errors caused by an invalid assumption of the linear pressure-displacement relation. The analytical procedure involves the determination of the yield point and then the estimation of p_0 from the post-yield curve. With the algorithm programmed in Matlab, the procedure is applied to field data and calibration chamber data, showing better estimated p_0 values using this new technique.

1 INTRODUCTION

The flat dilatometer (DMT) invented by Marchetti more than 30 years ago has been widely used as a routine site characterization device. It provides geotechnical engineers a simple, effective tool to get accurate, reliable soil properties such as operative moduli and stress history (Marchetti et al. 2001, Marchetti 2015). Following the global popularity of the DMT use, various modified DMTs have been developed for different purposes, these modifications have been reviewed by Shen et al. (2015). Among these modified apparatuses, iDMTs capable of producing a full pressure-displacement curve have been prototyped and investigated by a number of researchers (Akbar & Clarke 2001, Bellotti et al. 1997, Benoit & Stetson 2003, Campanella & Robertson 1991, Colcott & Lehane 2012, Fretti et al. 1992, Stetson et al. 2003, Shen et al. 2016). Compared to pressure readings at two [illegible] displacement curve in the iDMT can not only provide a better understanding of the standard DMT but also shows promising improvements in the estimation of the soil properties. An ongoing iDMT project using 3D (metal) printing technology for the probe fabrication has been carried out at UGent and Gesound.be with the following objectives: to consider non-linear soil behaviour by a sufficient large expansion of a loading piston; to perform an effective stress analysis by an additional pore-pressure sensor (Shen et al. 2016).

The corrected first reading p_0 is of importance in the DMT, since it is a necessary input for all three "intermediate" DMT parameters I_D, K_D, and E_D which are then used to derive common soil parameters. Therefore, any error in the determination of p_0 can lead to the misinterpretation of soil properties.

This paper aims to improve the determination of p_0 when a full pressure-displacement curve of the iDMT is available. The p_0 determination technique in the standard DMT is firstly reviewed along with the analysis of its possible errors. Then, to reduce these errors, a new p_0 interpretation technique is presented and applied to various types of iDMT pressure-displacement curves.

2 ESTIMATION OF p_0 IN THE DMT

In the standard DMT, p_0 derives from the assump- [illegible] acement relation and is back-extrapolated from the pressure readings at 0.05 mm and 1.10 mm, as shown in the following formula:

$$p_0 = 1.05(A - Z_M + \Delta A) - 0.05(B - Z_M - \Delta B) \quad (1)$$

where ΔA, ΔB = corrections determined by membrane calibration, Z_M = gage zero offset.

According to this definition, p_0 cannot be measured directly but is de facto a corrected pressure value at zero displacement. This method can provide accurate and repeatable p_0 as long as a linear relation of pressure-displacement is appropriate. However, it will definitely be a biased estimation if a highly non-linear pressure-displacement relation is presented in a soil. This can only be checked by evaluating the full pressure-displacement curve from iDMT data.

3 PRESSURE-DISPLACEMENT CURVE IN THE iDMT

Using an iDMT incorporated with a pressure sensor and a displacement sensor, a full pressure-displacement curve can be obtained. However, various shapes of the curves are produced in different soils based on a review in the literature. In Figure 1, there are 4 types of typical loading curves illustrated and the common feature is that an initial stiff response occurs at the start of the membrane expansion. Specifically, in the first three sub-figures, Figure 1 (a)-(c), an abrupt change in slope is seen in most of the calibration chamber tests (Bellotti et al. 1997, Fretti et al. 1992) and in a few in-situ tests (Akbar & Clarke 2001, Akbar et al. 2005; Benoit & Stetson 2003, Campanella & Robertson 1991, Stetson et al. 2003). Also, there is a fourth type of curve which does not show an apparent abrupt change in slope, as demonstrated in Figure 1 (d). This type of curve has not yet been observed in any calibration chamber test but only in in-situ tests (Benoit & Stetson 2003, Campanella & Robertson 1991, Stetson et al. 2003). It is likely due to the lack of excess pore-water pressure during the tests in sands, while the presence of high pore-water pressure in clays and the dissipation of pore-water pressure in silts may both present difficulties to see the abrupt change in slope.

This initial stiff response shown in the data of iDMT is an unload-reload effect: soil elements are unloaded in a wedge cavity expansion by the blade tip during the probe installation; then these soil elements are reloaded as the membrane expands during the test. The soil unloading has been quantitatively evaluated in the three-dimensional numerical solutions presented by Finno (1993) and Kouretzis et al. (2015) in saturated cohesive soils. A decline in strain levels of soil elements from the blade shoulder to the membrane during the blade penetration is observed. So it is reasonable to assume the occurrence of a reloading phase for the membrane expansion during the test.

A schematic pressure-displacement curve along with an initial stiff soil response on the loading curve is illustrated in Figure 2. There are several important points to consider during the loading phase: O, the lift-off point where the membrane starts to move; Y, the onset of yield; A, the pressure reading at the displacement of 0.05 mm; B, the pressure reading at the displacement of 1.10 mm.

As pressure readings at point A and B are obtained in the standard DMT, p_0 is derived via Equation 1 based on the assumption of a linear relationship, as illustrated by the dashed line in Figure 2. In other words, the post-yield curve is assumed to be linear from A to B in the standard DMT interpretation technique. So in case of a non-linear post yield curve or/and a large initial stiff response beyond the displacement of 0.05 mm, the estimation of p_0 can be erratic using this standard method.

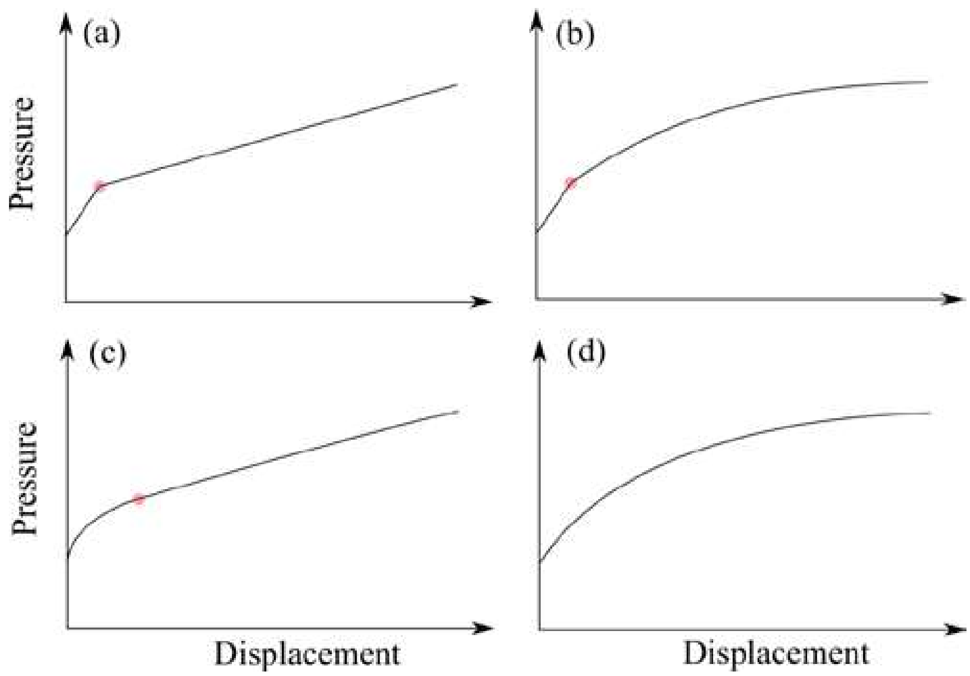

Figure 1. Schematic diagrams of typical pressure-displacement curves

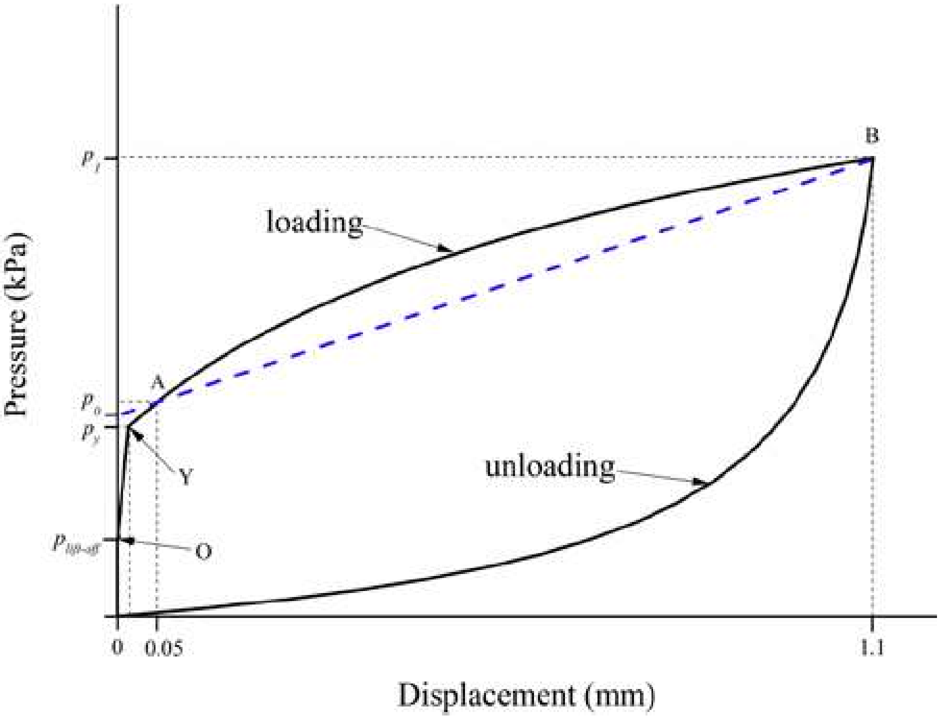

Figure 2. Schematic diagram of a full pressure-displacement curve

p_0 has been determined in different ways when a full pressure-displacement curve is available. Bellotti et al. (1997) and Fretti et al. (1992) use the pressure p_y at the onset of yield while Campanella & Robertson (1991) and Colcott & Lehane (2012) use the pressure $p_{lift\text{-}off}$ when the membrane starts to move. These methods chose specific points on the loading curve but can still bring errors.

4 A NEW INTERPRETATION TECHNIQUE

A new interpretation technique for p_0 is thus proposed to reduce the aforementioned errors. The technique finds the corrected pressure at zero displacement from the full pressure-displacement curve.

To deal with the four types of loading curves shown in Figure 1, the newly proposed solution involves two steps: (1) The determination of the yield point Y to distinguish the reloading phase O-Y from the post-yield phase Y-A-B, as shown in Figure 2; (2) The estimation of p_0 based on the post-yield phase of the loading curve.

4.1 *Determination of the point of yield*

In Figure 1(a, b, c), the point of yield is clearly identified by the circles. These results are found in calibration chamber tests with clean and uniform sand being tested as well as in a few in-situ tests. Then, this point of abrupt change in slope is readily determined as the onset point of yield Y. In most cases of in-situ testing results, a clear yield point Y cannot be found since a smoothed curve is observed, as shown in Figure 1(d).

In the one-dimensional consolidation test, the preconsolidation pressure cannot be measured directly, but can be estimated with a satisfactory degree of accuracy by means of the empirical graphical methods such as the widely used method proposed by Casagrande (1936). Likewise, in the DMT tests, an unloading phase during the blade penetration precedes an initial reloading phase during the membrane/piston expansion. Considering the similarity of the reloading process, a resemblant graphical method may also be of use in the determination of the yield point in the iDMT pressure-displacement curve, despite the fact that sufficient experience is still needed for the validation.

In addition, implementation of a manual graphical method is time consuming and inconvenient. Therefore, an algorithm has been developed and programmed in Matlab to automate the procedure. The specific steps are as follows: (One may refer to Figure 4 of an example, for better understanding of this technique)

1. Arrangement of the iDMT data on a semi-log plot of the displacement with a linear scale for the *x*-axis and the pressure with a logarithmic scale for the *y*-axis. Note that this presentation is typical in iDMT curves for a clear demonstration of the stress-strain relation.
2. Curve fitting of the data points from the lift-off point till the end of loading to a power function:

$$y = ax^b + c \quad (2)$$

3. Estimation of the point of maximum curvature on the fitted curve. Using the mathematical definition of the radius of curvature R, as shown in the Equation 3, the R determination for a power function is obtained in the Equation 4. As the curvature is the reciprocal of the radius of curvature, the point of maximum curvature is given by the minimum value of the radius.

$$R = (1 + (dy/dx)^2)^{3/2} / (d^2y/dx^2) \quad (3)$$

$$R = x^{2-b}[(a^2b^2x^{(2b-2)} + 1)^{3/2}]/[ab(b-1)] \quad (4)$$

4. Determination of the bisector line from the vertical line and tangent line at the point of maximum curvature.
5. Linear fitting of the straight portion of the post-yield curve.
6. The point where the lines in part 4 and part 5 intersect is used to obtain the displacement of the yield point.

In the last step, the displacement of the intersection is used to deduce the yield point, which is different from the Casagrande's method using the pressure of the intersection as the preconsolidation pressure. The rationale of this is that the DMT test can be regarded as a displacement-controlled test as the soil elements are loaded by an expansion of the membrane until a displacement of 1.1 mm is attained. So the pressure required to achieve this displacement varies in different soils. A one-dimensional consolidation test is a pressure-controlled test as the specimen is subjected to increments of pressure until the final pressure being equal to or greater than four times the preconsolidation pressure. Therefore, a large enough pressure in the DMT test is not likely to be attained in some soils but the final maximum displacement of 1.10 mm is normally higher than multiple times the displacement of the intersection.

4.2 *Back-extrapolation of p_0*

Once the yield point Y is identified, the start of the post-yield loading curve is determined. Then, p_0 at zero displacement can be back-extrapolated from a regression model fitting the post-yield loading curve.

Concerning the characteristics of the post-yield loading curve, a limit pressure p_L may be approached with increasing displacement, which has been found in some iDMT curves (Benoit & Stetson 2003, Colcott & Lehane 2012). However, this is not valid in every iDMT curve since a fixed displacement level, such as 1.1 mm in the standard DMT, may correspond to different strain levels in different soils. Therefore, a regression model which can take into account possible non-linear, asymptotic behaviours is proposed:

$$Y = c' + a'X - b'd'^X \quad (5)$$

where a' and c' are the parameters for a linear asymptote line representing a potential boundary associated with the limit pressure p_L, b' indicates the range of the non-linear part and d' is the rate of the non-linearity. It is noted that the model is valid when $b' \geq 0$ and $0 < d' < 1$.

5 EXAMPLES

An iDMT test was performed at a depth of 13.72 m in soft varved clay by Benoit & Stetson (2003). Note that the test is carried out after the full pore-pressure dissipation so the curve is not influenced by the dissipation of pore-pressure generated by probe installation. This issue is important since the performance of an unload-reload loop may require a longer time than in the standard DMT test. The partial drainage condition, which is more difficult to interpret, rather than the undrained condition may be met if the excess pore-pressure is not fully dissipated. The digitalized data points of the loading curve are shown in Figure 3.

For the standard Marchetti method, the point at the maximum displacement of 1.04 mm and the linear interpolated point at the displacement of 0.05 mm are used to obtain a p_0 value of 194 kPa. However, as shown in the graphical illustration of this method in Figure 3, the straight line linking the two points is significantly biased from the real measurements, with only an R-squared value of 0.45. This is due to the large initial stiff response in the curve which covers a range beyond the displacement of 0.05 mm.

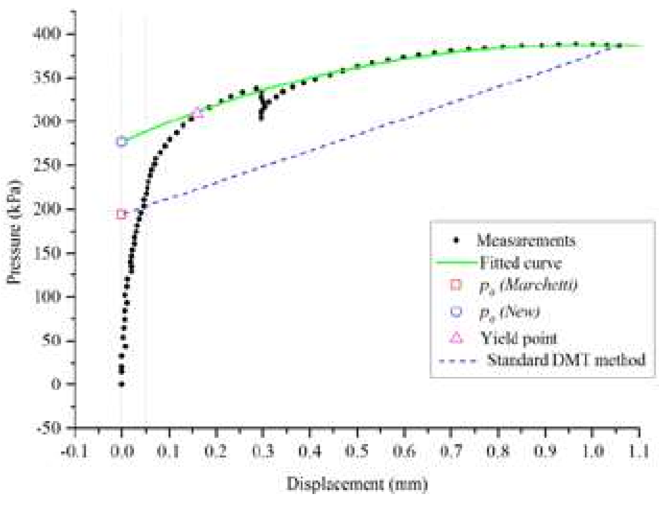

Figure 3. Test data of Benoit & Stetson (2003): application of the new p_0 interpretation technique in comparison with the Marchetti method

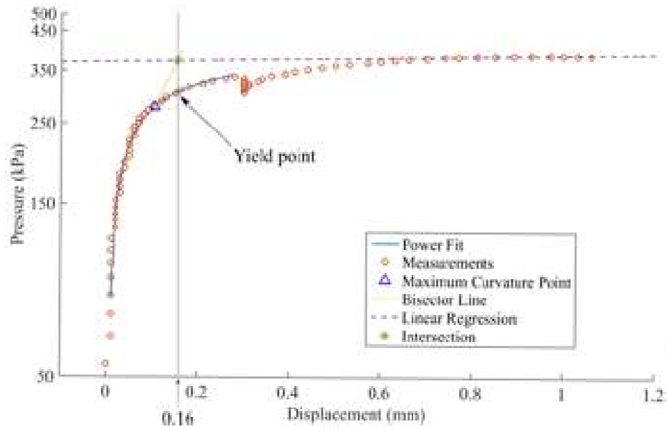

Figure 4. Determination of the yield point

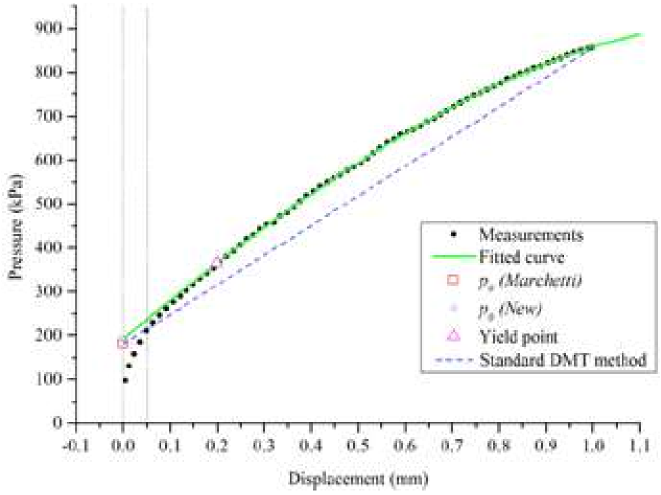

Figure 5. Test data of Campanella & Robertson (1991): application of the new p_0 interpretation technique in comparison with the Marchetti method

Therefore, the use of the standard DMT method is inappropriate in this case. To address this issue, the newly proposed interpretation technique is applied accordingly.

As a smoothed curve is seen in this data rather than an abrupt change in slope, the aforementioned algorithm based on the graphical method for the determination of the yield point is applied in Matlab, and the analytical procedure is illustrated in Figure 4. Given the location of the intersection point, the yield point on the curve is positioned at a displacement of 0.16 mm and a pressure of 309.4 kPa. Note that this displacement value is much higher than the predefined value of 0.05 mm in the standard DMT. Then, with the yield point determined, the post-yield data points (with the unload-reload loop omitted) are selected to carry out the curve fitting based on the regression model of Equation 5, estimating a p_0 of 277 kPa in Figure 3.

Following the first example, there are more measured curves analysed and discussed. The main difference is the determination of the yield point. The smoothed curve in Figure 5 requires the application of the newly developed algorithm. The yield point in Figure 6 and Figure 7 can be directly determined by the abrupt changes in slope.

In Figure 5, the results of an iDMT test performed at a depth of 9 m in sand by Campanella & Robertson (1991) are shown. Compared to the foregoing example also with a smoothed curve, a smaller difference is found between p_0 of 181 kPa using the standard DMT method and p_0 of 192 kPa using the new technique. It is due to a smaller non-linearity of the curve and the fact that the initial stiff range is lower than the displacement of 0.05 mm.

The iDMT developed by Akbar & Clarke (2001) is featured by using a rigid piston instead of a flexible membrane as loading element. In Figure 6, the testing result of this iDMT in a cohesive soil is shown (Akbar et al. 2005). It is interesting to point out that the post-yield curve is linear while the initial stiff phase covers a large range of displacement till around 0.3 mm. Thus the standard DMT method is invalid because of the large initial stiff response. The assessment based on the full pressure-displacement curve is therefore necessary to obtain a reasonable p_0. The p_0 estimated by the standard Marchetti method and the newly proposed method is 416 kPa and 483 kPa, respectively.

In Figure 7, the results of an iDMT test carried out at a depth of 70 cm in a calibration chamber on Toyoura sand by Bellotti et al. (1997) are illustrated. An initial stiff response occurs at the displacement lower than 0.05 mm, however, the standard Marchetti method is still invalid due to the non-linearity of the post-yield curve. This is also illustrated by the difference between the dashed line of the standard DMT method and the measured post-yield data points. The p_0 estimated by the standard Marchetti method and the new technique is 857 kPa and 694 kPa, respectively.

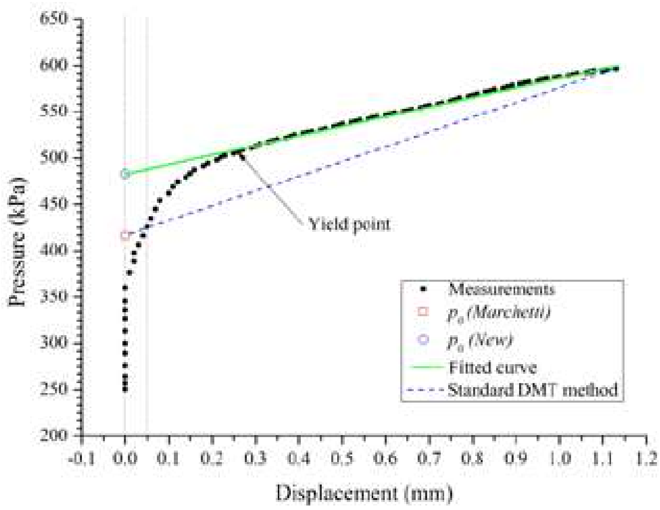

Figure 6. Test data of Akbar et al. (2005): application of the new p_0 interpretation technique in comparison with the Marchetti method

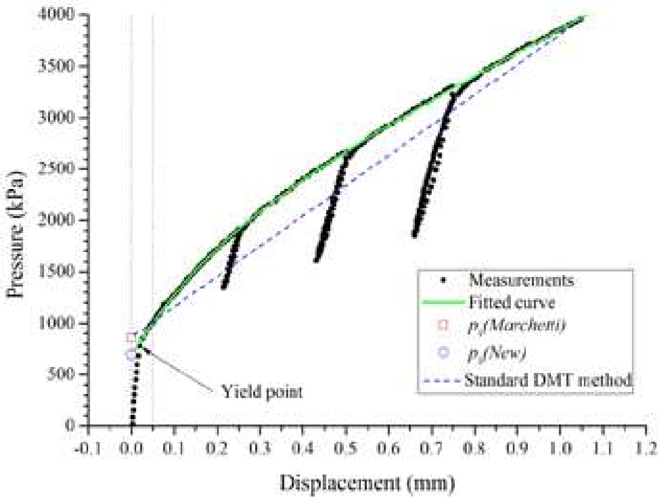

Figure 7. Test data of Bellotti et al. (1997): application of the new p_0 interpretation technique in comparison with the Marchetti method

6 CONCLUSION

A full pressure-displacement curve using an iDMT can provide a number of opportunities to improve the interpretation of soil properties. This paper specifically addresses the errors in the p_0 interpretation as non-linear measured curves may be found and so the standard DMT method, with the assumption of a linear pressure-displacement relation, is by no means sufficiently accurate. Then a new interpretation technique with the determination of the yield point and the estimation of p_0 from the post-yield curve is presented to reduce these errors. The corresponding algorithm is programmed in Matlab to automate the analytical procedure.

The application of the new p_0 interpretation technique on non-linear measured curves shows more reasonable estimation, compared to the use of the standard DMT method. Furthermore, it is the first time in the DMT/iDMT interpretation to address the soil unload-reload effects upon the estimation of p_0.

However, further research is still necessary and currently underway on validating this new technique by comparing with other in-situ data and theoretical back analysis of p_0.

A useful guideline based on this research is that p_0 obtained by the standard DMT method can be up to 30% lower or 23% higher than those using the new p_0 interpretation technique. This does not indicate a compulsory correction to apply but gives rise to awareness of possible inaccuracy in case of non-linear pressure-displacement curves. To eliminate these uncertainties, the performance of iDMT tests for a full pressure-displacement curve along with the use of this newly proposed p_0 interpretation technique are suggested.

7 AKNOWLEDGEMENTS

H. Shen acknowledges the financial support from the China Scholarships Council (No. 201306320157).

8 REFERENCES

Akbar, A., and Clarke, B. G. (2001). “A flat dilatometer to operate in glacial tills.” *Geotechnical Testing Journal*, 24(1), 51–60.

Akbar, A., Kibria, S., and Clarke, B. G. (2005). “The Newcastle Dilatorneter testing in Lahore cohesive soils.” *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*, Rotterdam, 651–654.

Bellotti, R., Benoît, J., Fretti, C., and Jamiolkowski, M. (1997). “Stiffness of Toyoura sand from dilatometer tests.” *Journal of geotechnical and geoenvironmental engineering*, 123(9), 836–846.

Benoit, J., and Stetson, K. P. (2003). “Use of an instrumented flat dilatometer in soft varved clay.” *Journal of geotechnical and geoenvironmental engineering*, 129(12), 1159–1167.

Campanella, R. G., and Robertson, P. K. (1991). “Use and interpretation of a research dilatometer.” *Canadian Geotechnical Journal*, 28(1), 113–126.

Casagrande, A. (1936). “The determination of the preconsolidation load and its practical significance.” *Proceedings of the 1st International Conference on Soil Mechanics and Foundation Engineering*, Harvard, 60–64.

Colcott, R., and Lehane, B. M. (2012). “The design, development and application of a new DMT.” *Geotechnical and Geophysical Site Characterization 4*, Pernambuco, 565–570.

Finno, R. J. (1993). “Analytical interpretation of dilatometer penetration through saturated cohesive soils.” *Geotechnique*, 43(2), 241–254.

Fretti, C., Presti, D. LO, and Salgado, R. (1992). “The research dilatometer: in-situ and calibration chamber test results.” *Riv. Italiana di Geotecnica*, 26(4), 237–242.

Kouretzis, G. P., Ansari, Y., Pineda, J., Kelly, R., and Sheng, D. (2015). “Numerical evaluation of clay disturbance during blade penetration in the flat dilatometer test.” *Géotechnique Letters*, 5, 91–95.

Marchetti, S. (1980). “In-situ tests by flat dilatometer.” *Journal of the Geotechnical Engineering Division*, 106(3), 299–321.

Marchetti, S. (2015). “Some 2015 Updates to the TC16 DMT Report 2001.” *The 3rd International Conference on the Flat Dilatometer*, Rome, 43–65.

Marchetti, S., Monaco, P., Totani, G., and Calabrese, M. (2001). “The flat dilatometer test (DMT) in soil investigations.” *International Conference on In-situ Measurement of Soil Properties*, Bali, 95–131.

Shen, H., Haegeman, W., and Peiffer, H. (2015). “Instrumented DMT: Review and Analysis.” *The 3rd International Conference on the Flat Dilatometer*, Rome, 377–384.

Shen, H., Haegeman, W., and Peiffer, H. (2016). “3D Printing of an Instrumented DMT: Design, Development, and Initial Testing.” *Geotechnical Testing Journal*, 39(3), 492–499.

Stetson, K. P., Benoit, J., and Carter, M. J. (2003). “Design of an instrumented flat dilatometer.” *Geotechnical Testing Journal*, 26(3), 302–309.