# Instrumented DMT: Review and Analysis

Hao Shen
*Laboratory of Geotechnics, Ghent University, Ghent, Belgium. E-mail: Hao.Shen@UGent.be*
Wim Haegeman
*Laboratory of Geotechnics, Ghent University, Ghent, Belgium. E-mail: Wim.Haegeman@UGent.be*
Herman Peiffer
*Laboratory of Geotechnics, Ghent University, Ghent, Belgium. E-mail: Herman.Peiffer@UGent.be*

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ABSTRACT: Following the research of the Marchetti DMT, instrumented DMTs have been fabricated and investigated for different purposes such as automatic data acquisition, better understanding of the standard Marchetti DMT, dealing with difficult soils or achieving soil stiffness at additional strain levels. In this article, the modification to the displacement measurement and pore-pressure system are reviewed, and a quantitative research on pressure-displacement curves and unload-reload modulus is presented, showing how far the research of instrumented DMTs has gone. Furthermore, a descriptive review of these modifications and data analysis provide deeper understanding of the standard Marchetti DMT and the instrumented DMT, and indicate if a further development of a new device and corresponding interpretation is required.

## 1 INTRODUCTION

The Flat Dilatometer test (DMT) is a quick, simple, economical, routine in-situ testing device, which can provide highly reproducible and reliable information in geotechnical design, particularly in in-situ soil compressibility for settlement prediction (Marchetti 1980; Marchetti et al. 2001). Meanwhile, following the concept of spade-like in-situ testing probes, instrumented DMTs have been fabricated and investigated for different purposes.

The most simple and straightforward modification was allowing automatic control and measurements to replace the manual steps in the standard Marchetti DMT (Failmezger and Nolan 2006).

To better understand the measurements and interpretation of the standard Marchetti DMT, full and continuous pressure-displacement measurements are normally involved in the instrumented DMTs and pore-pressure measurements are sometimes included. It is noted that the instrumented DMTs herein are identical in dimension to a standard Marchetti DMT for reasons of comparison (Campanella and Robertson 1991; Udakara 2000; Fretti et al. 1992; Kaggwa et al. 1996; Liu et al. 2013; Motan and Khan; Stetson et al. 2003).

In an effort to deal with difficult soils, modifications of the standard Marchetti DMT are also performed. The 'Newcastle DMT' is developed for the application in glacial tills by using a rigid piston instead of a flexible membrane to load the soil (Akbar and Clarke 2001). The "ΔDMT" is developed to facilitate in-situ measurements of a reservoir mud under more than 40m of water by incorporating a differential pressure sensor (Lee et al. 2013). The "mIDMT" is designed to assess the elastic behavior of shallow cohesive sediments by using smaller size probe, automatic measurements and automatic control (Barry et al. 2012). The "Dual DMT" is developed for in-situ testing in fibrous peats employing two membranes where the second membrane is mounted in the upper part of the blade with twice the thickness than the standard blade (Rahardjo et al. 2004).

To obtain more information on the soil modulus at different strain levels, it is important to measure the pressure and displacement development in wide ranges. An expansion of 3 mm is allowed to obtain the soil modulus at higher strain level in the instrumented DMT developed by Colcott and Lehane (2012). The unload-reload modulus is taken into account to evaluate elastic deformation properties by incorporating unload-reload loops in the expansion curves, similar as in the pressuremeter tests (Bellotti et al. 1997; Benoit and Stetson 2003; Fretti et al. 1992).

In line with the ongoing research on instrumented DMTs, a review of the modifications of the displacement measurement system to obtain full pressure-displacement curves and the adding of pore-pressure measurement during the test is presented in section 2. Quantitative investigations on the pressure-displacement development and the unload-reload loops are included in section 3. This provides insight into measurements and mechanics of instrumented DMTs and indicates where further development of the instrumented DMT and corresponding interpretation is needed.

## 2 REVIEW OF INSTRUMENTED DMTS

### 2.1 *Modification of the displacement measurement system*

The Marchetti DMT measures pressures at prescribed displacement of 0.05 mm and 1.1 mm at the center of the membrane. In addition, it is assumed that the pressure-displacement relation is linear provided that the displacement is below 1.1mm, and then linear elasticity theory is employed to interpret the soil stress-strain behavior during the membrane expansion. However, the linearity of pressure-displacement curves can vary in different types of soils and deviation can be seen if the displacement measurement range is over 1.1 mm in an instrumented DMT. Therefore, most of the researchers working on instrumentation of DMTs are committed to attain a continuous pressure and displacement measurement.

Campanella and Robertson (1991) and Fretti et al. (1992) both choose spring arms with strain gages to obtain the displacement measurements ranging from 0 to 1.0 mm. Strain gages are also used in devices developed at the University of Adelaide (Kaggwa et al. 1996), University of Hong Kong (Udakara 2000) and University of Newcastle (Akbar and Clarke 2001) featured by using a rigid piston as the penetrating element instead of a flexible steel membrane. In the later version of the Newcastle DMT, a system of a Hall Effect Transducer (HET) and a magnet is used to measure the displacement of the rigid piston.(Akbar et al. 2005, 2006) However, it is recognized that Hall Effect sensors are traditionally used as contact-less switches and not as linear sensing devices because of the limited accuracy, which can presumably be a problem if the unload-reload loop is studied. Furthermore, concerning the output signals from above-mentioned displacement sensors are amplified on the ground surface, so the impact on the measurement accuracy induced by the signal noise can be significant when a long cable has to be used for the sounding at a large depth. For the device developed at the University of New Hampshire, a displacement-tunable electronic oscillator is employed to produce a sinusoidal output voltage varying in frequency, which can avoid the influence of voltage drop (Stetson et al. 2003).

Other than the aforesaid direct measuring techniques, the displacement can be indirectly determined by measuring the volume of the pressurized medium as well. In the design of a mIDMT, the displaced membrane volume is obtained based on Boyle's law by measuring the air pressure applied during the loading phase (Barry et al. 2012). Similarly, determining the displacement by measuring the volume of oil pumped to the device was proved feasible in an instrumented DMT (Colcott and Lehane 2012).

It is concluded that, in terms of displacement measurement, many methods are available, but the following criteria are considered important based on the above review: *(a)* the measurements should be accurate and precise over the expansion curve and unload-reload loop; *(b)* the signals should be amplified near the blade so as to avoid the noise; *(c)* a direct measurement of displacement is preferred, rather than inferring displacements from measured volume changes of the pressuring medium which can bring in a number of potential sources of error. For example, there is no unique relation between the displacement and the change of the volume, which is due to the fact that the deforming shape of membrane varies with applied pressure. The change of the inside diameter of the pneumatic tubing can also make a difference.

### 2.2 *Pore-pressure measurements*

Marchetti DMT does not include pore-pressure measurements, but some of the instrumented DMTs incorporate pore-pressure cells to perform quantitative or qualitative investigations. Pore-pressure measurements at the center of the membrane are performed by Campanella and Robertson (1991). The results showed no excess pore-pressure generation during the penetration and membrane expansion in clean sands but large excess pore-pressure in soft clays. However, it is noted that the design of attaching the pore-pressure sensor and the porous element to the expendable and easy-damaged membrane is feasible for a research device but not sufficiently robust and practical for the routine in-situ testing device. In the design of the Newcastle DMT, a porous stone is screwed into the piston together with a differential transducer measuring the difference between the applied pressure and pore-pressure at the center of the piston, but no data was shown (Akbar and Clarke 2001). Since performing pore-pressure measurements at the center of the membrane/ piston requires delicate fabrication, the porous elements are expediently mounted nearby the membrane/ piston in other devices. (Benoit and Stetson 2003; Liu et al. 2013; Stetson et al. 2003) Because pore-pressure measurements are not done at the center of membrane/ piston, they can only be considered as a qualitative investigations. However, qualitative findings, such as the partially drained condition during the expansion of the membrane and the influence of excess pore-pressure dissipation on the unload–reload shear modulus, provide valuable information if a further quantitative research is required.

## 3 DATA ANALYSIS

### 3.1 *Linear regression of pressure-displacement curves*

The use of linear elasticity is one of the advantages of the DMT interpretation, so the soil modulus is obtained in a straightforward and convenient way. It is assumed that the relation between applied pressure and displacement at the center of membrane is linear regardless of the soil type. Therefore, pressures are measured at only two prescribed displacements in the Marchetti DMT. To better understand these measurements from the Marchetti DMT, full and continuous pressure-displacement curves are acquired by most instrumented DMTs. Using these results, we perform a quantitative analysis on the development of the pressure-displacement curves.

The published data is digitized and then analyzed by linear regression using the least squares method to investigate how well the data fits the linear relation. Then, adjusted R-square values, indicating the percentage of the response variable variation are computed and shown in Fig. 1.

As far as different instrumented DMTs are concerned, the maximum displacement at the center of the flexible membrane or the rigid piston varies and is taken into account. The 1.1 mm, found in the Marchetti DMT, is prescribed in instrumented DMTs of Liu et al. (2013), Stetson et al. (2003), Akbar & Clarke (2001), Udakara (2000) and Kaggwa et al. (1996). The devices of Campanella & Robertson(1991) and Fretti et al. (1992) can only reach 1.0 mm as the maximum displacement. Colcott & Lehane (2012) fabricated an instrumented DMT allowing the rigid piston to expand up to 3 mm which is significantly larger than other devices. Thus, the adjusted R-squared values, computed from 4 curves in field tests, are relatively lower than the values of other instrumented DMTs averaging 98.57%. However, all of them are claimed to be acceptable for using the linear theory in practical engineering design if only the adjusted R-square values are looked upon. In addition, a typical linear fit curve based on the field test from R. Colcott (2012) is shown in Fig. 2.

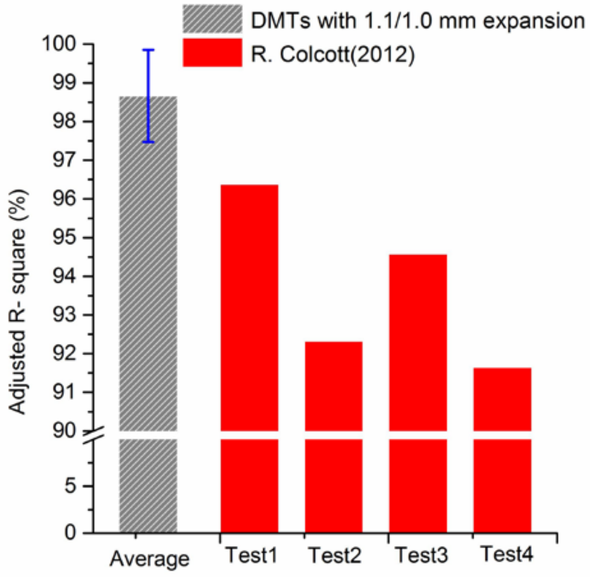

Fig. 1. Adjusted R-square values

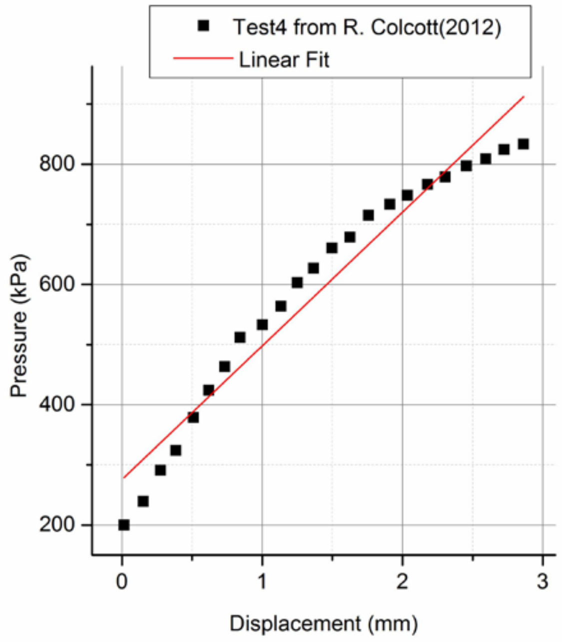

Fig. 2. Typical curve of linear fit.

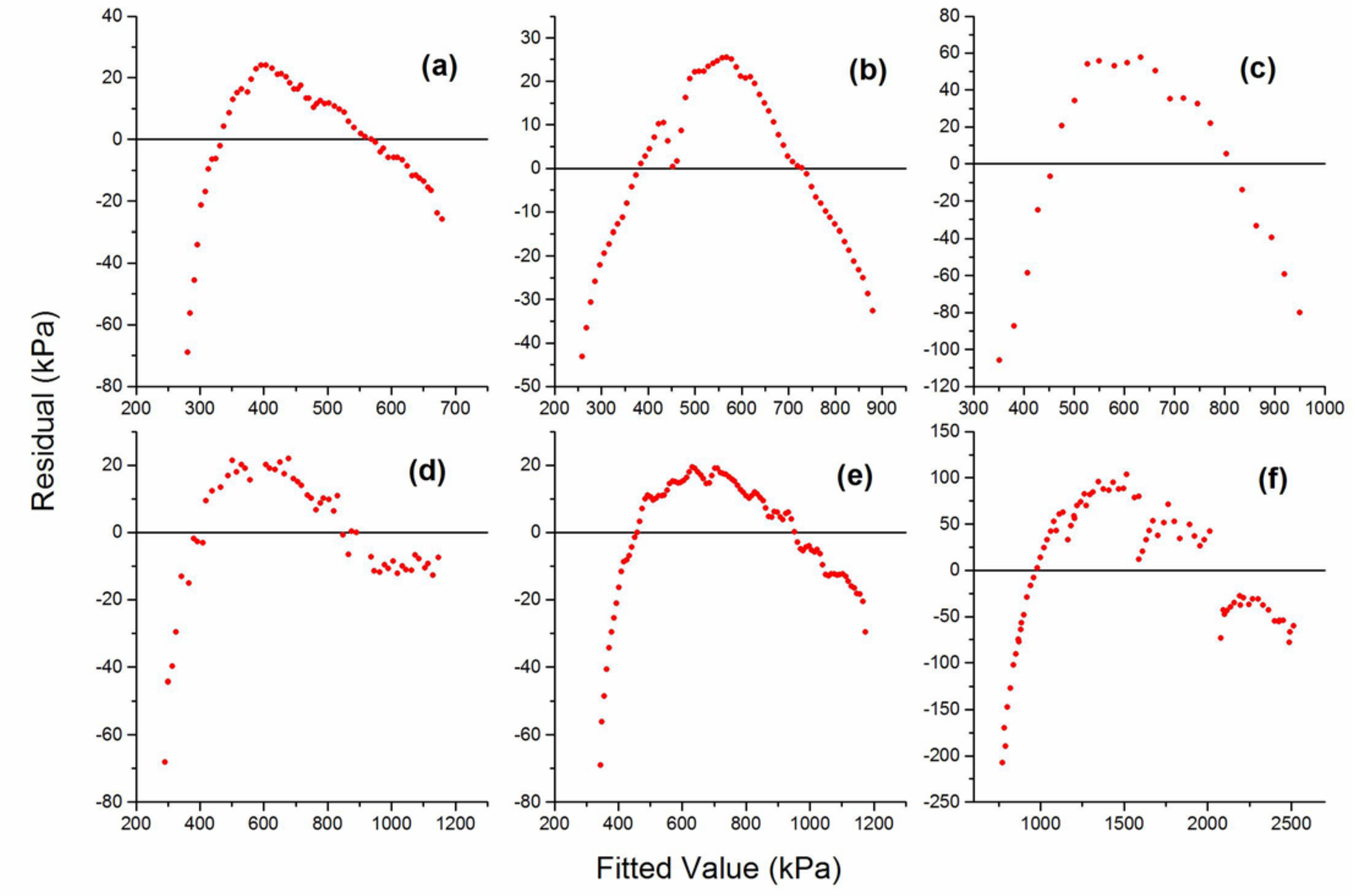

Fig. 3. Residual plots: (a) The maximum displacement of rigid piston: 1.1mm, from Akbar et al. (2006), (b) The maximum displacement of flexible membrane: 1.0mm, from Campanella and Robertson (1991), (c) The maximum displacement of rigid piston: 3.0mm, from R. Colcott and B. M. Lehane(2012), (d) The maximum displacement of flexible membrane: 1.0mm, from C. Fretti et al.(1992), (e) The maximum displacement of flexible membrane: 1.1mm, from W. S. Kaggwa et al. (1996), (f) The maximum displacement of flexible membrane: 1.1mm, from R. Belloit et al. (1997).

Nevertheless, concerning reasonable linear regression analysis, both the adjusted R-squared values and the residual values shall be investigated. As residual is the difference between the observed value and the fitted value(Residual = Observed value - Fitted value), the data points of a good linear fit shall be randomly dispersed in the residual plot showing the residual values versus fitted values. In Fig. 3, the non-random patterns of inverted U shape are found in all six typical residual plots, suggesting a better fit for a non-linear regression. It explicitly indicates the simplification of using linear elasticity to describe the non-linear soil behavior.

Furthermore, no recognized difference in adjusted R-squared values and residual plots are found between the devices using a rigid piston and a flexible membrane as the penetrating element. The data from instrumented DMTs capable of performing expansion larger than 1.1mm in displacement is still limited, so further research on the best fitting procedure is needed.

### 3.2 *Analysis of unload-reload modulus*

Performing an unload-reload loop is technically not feasible in a Marchetti DMT but is frequently investigated in instrumented DMTs. The theory of linear elasticity is used to interpret the unload-reload modulus $E_{DUR}$ from the unload-reload loop, in a similar way of the interpretation of the dilatometer modulus $E_D$. It is commonly observed that $E_{DUR}$ is significantly larger than $E_D$, indicating that $E_{DUR}$ is representative for the quasi-elastic behavior of soils within the current yield surface while $E_D$ reflects the elasto-plastic response of soils (Bellotti et al. 1997; Benoit and Stetson 2003; Campanella and Robertson 1991; Fretti et al. 1992).

$E_{DUR}$ is a function of several factors: stress level of the soils near the membrane/ piston, soil properties, the shape of the unload-reload loop. Therefore, without a proper control of the aforementioned variables in the tests, both interpretation and application of $E_{DUR}$ in engineering design is difficult.

The ratio $E_{DUR}/E_D$ is expected to increase with the increase of stress level at which the unload-reload loop is performed. Fretti et al. (1992) observed this trend by performing two unload-reload loops during a single expansion, the $E_{DUR}$ *(2'loop)* measured at higher displacement appeared larger, due to the fact that the mean effective stress on the membrane increases for an increasing of the displacement of membrane. The same variation of $E_{DUR}$ versus the average mean effective stress was also found from data points of 5 DMT profiles but not from the single expansion curve by Bellotti et al. (1997), since the unload-reload loops in a single expansion curve varied significantly in both displacement amplitude and pressure amplitude.

Instrumented DMTs, as well as Marchetti DMT, can also obtain intermediate DMT parameters $I_D$ and $K_D$ containing information of soil properties. Although effects from variables other than $I_D$ and $K_D$ cannot be ignored, $E_{DUR}/E_D$ is mostly analysed in relation to $I_D$ and $K_D$. Specific trends are known if the $I_D$ and $K_D$ are the only major influence factors. The published data was reorganized in Fig. 4 showing the influence of $I_D$ and $K_D$ on $E_{DUR}/E_D$ (Bellotti et al. 1997; Benoit and Stetson 2003; Fretti et al. 1992). Recognizable trends are: *(a)* According to the soil classification criteria from Marchetti et al. (2001), the soil types are identified as clay ($0.1 < I_D < 0.6$), silt ($0.6 < I_D < 1.8$), sand ($1.8 < I_D < 10$), and then, it is concluded that $E_{DUR}/E_D$ is mostly in the range of 4 to 10 for sand, 10 to 60 for clay and 18 to 90 for the soils classified as soft clay ($I_D$ is less than 0.1), but without information for silt. *(b)* The largest variation of $E_{DUR}/E_D$ is found in soft clay, then in clay, smallest in sand. *(c)* As far as normally consolidated clays are concerned, the range of $K_D$ from 1.8 to 2.4 is presumably specified. $E_{DUR}/E_D$ tends to decrease with degree of overconsolidation in both clay and soft clay.

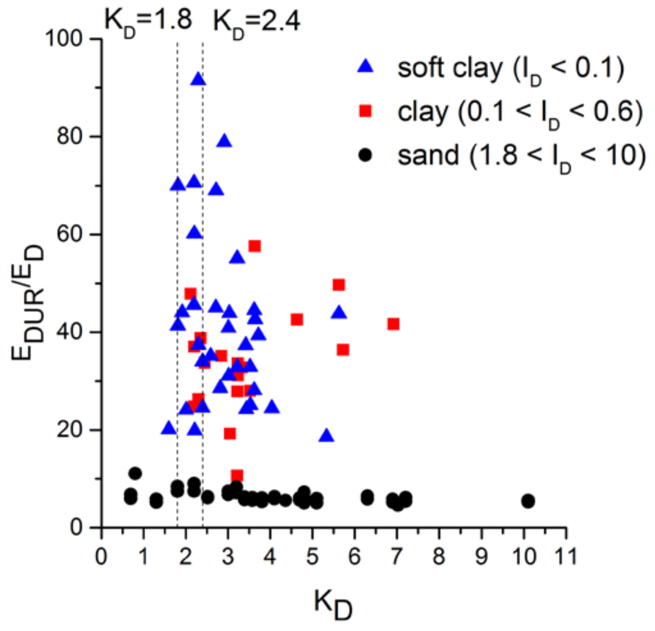

Fig. 4. Ratio $E_{DUR}/E_D$ versus $K_D$ for various soil types grouped by $I_D$ (from Bellotti et al. (1997), Benoit and Stetson (2003), Fretti et al. (1992)).

Note that the pressure reduction in the unload-reload loop should not exceed the elastic limit in extension. Since the elastic limit of clay generally is much smaller than that of sand, there is a higher chance for clay to go beyond the elastic limit. This raises the interest in defining the maximum magnitude of the change in effective stress during the unloading phase in the further research.

The shape of the unload-reload loop has not been taken into account until now. Instrumented DMTs were only capable of manually controlling the unload-reload loop in the pressure controlled procedure. However, precise and accurate controlling the shape of the unload-reload loop is necessary if reliable interpretation of $E_{DUR}$ is to be obtained. Specifically, the sensitivity of $E_{DUR}$ to displacement amplitude and pressure amplitude of the unload-reload loop has to be investigated, as well as the procedure how the loop is performed: pressure controlled or displacement controlled. The slope of the loop is previously calculated by Bellotti et al. (1997), Benoit and Stetson (2003) and Fretti et al. (1992), drawing a single line between the two apexes of the loop. Actually the procedures for the calculation of the slope of the loop can make a difference as the non-linearity of the unload-reload loop is markedly observed. Hence, it will be interesting to compare the soil modulus calculated by different methods.

## 4 CONCLUSION

Instrumented DMTs are fabricated for different aims such as automatic data acquisition, better understanding of the standard Marchetti DMT, dealing with difficult soils or achieving soil stiffness at additional strain levels.

The devices which can provide full pressure-displacement measurements or pore-pressure measurements are reviewed. For a new device to be developed, it is expected that the displacement measurements should be accurate and precise over the full expansion curve and unload-reload loop. Pore-pressure measurements should be located at the center of the membrane/ piston to consider the influence of excess pore-pressure dissipation and partially drained conditions.

The linear regression of the full pressure-displacement measurements shows the possible need of considering a non-linear fit provided that the displacement exceeds 1.1 mm. In addition, the analysis of the unload-reload loops out of literature indicates that further development of instrumented DMT tests with a proper control of all variables is required in order to get reliable values of the unload-reload modulus.

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