Hao Shen,¹ Wim Haegeman,² and Herman Peiffer²

Design, Use, and Interpretation of an Instrumented Flat Dilatometer Test

Reference

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ABSTRACT

The flat dilatometer test (DMT) has been increasingly used as a routine geotechnical site characterization tool in numerous parts of the world for over 30 years. In the meantime, with the rapidly growing metal 3D printing technique, engineers now can design robust, durable devices that are impossible to make by traditional means. This paper presents the development of an instrumented dilatometer (iDilatometer) that has continuous measurements of a piston expansion up to 2.35 mm and pore pressure at the piston center with the assistance of a metal 3D printing technique. A field-testing program consisting of an instrumented flat dilatometer test (iDMT), a DMT, and a cone penetration test (CPT) positioned 1 m apart from each other was carried out in a site in Belgium composed of soil that ranged from silty sands to sandy silts. Interpretation techniques are provided to evaluate the test results, such as the conceptual contact pressure p_c based on the full pressure-displacement curve in the iDMT as an alternative for p_0 in the DMT. The pressure required for a 0.56-mm piston expansion is found to be equivalent to that of a 11-mm central membrane displacement, based on a finite element method (FEM) simulation approach with the assumption of linear elastic soils and a modified displacement boundary. A comparison made between test results from the iDMT, the DMT, and the CPT shows reasonable trends and suggests the use of the iDMT in future soil investigation.

Keywords

flat dilatometer test, instrumentation, rigid piston, metal 3D printing, in situ, flat dilatometer test indices

Introduction

The flat dilatometer test (DMT) has gained acceptance as a routine site characterization tool to estimate various soil properties. Marchetti (1975, 1980) first introduced the DMT and a set of empirical correlations between test results and soil parameters based on the observations at over 40 sites. Since then, a great number of studies have been performed to improve the original correlations and to develop new correlations based on data all over the world (Marchetti 2015; Marchetti et al. 2001).

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¹ Laboratory of Geotechnics, Ghent University, Technologiepark 905, Zwijnaarde B-9052, Belgium (Corresponding author), e-mail: shenhao.geo@gmail.com, <https://orcid.org/0000-0003-2505-7698>

² Laboratory of Geotechnics, Ghent University, Technologiepark 905, Zwijnaarde B-9052, Belgium

Schnaid (2009) foresees a growing trend in favor of the use of a range of sensors incorporated within a single penetration probe. In the flat dilatometer, continuous measurements of the applied pressure and the membrane displacement can be permitted by installing the necessary sensors, which contribute to a better understanding of the DMT mechanics (Fretti, Lo Presti, and Salgado 1992; Bellotti et al. 1997; Benoit and Stetson 2003; Stetson, Benoit, and Carter 2003). The research dilatometer developed by Campanella and Robertson (1981, 1991) allows measurements of not only the applied pressure and the displacement but also the pore pressure at the center of the membrane by attaching a mini porous filter on the face with a pore pressure sensor and a mini water cavity behind. Although the instrumentation on the expandable membrane may reduce the robustness of the tool, the research dilatometer has revealed many significant findings, such as that the pore pressure generated during the penetration in soft clays predominantly controls the DMT pressures, which, however, corresponds to fully drained conditions in clean sands. In addition, modifications are also conducted to enable the device to work in difficult soil conditions. Akbar and Clarke (2001) used a rigid piston instead of the flexible membrane in glacial tills and a pore pressure cell directly installed in the rigid piston; however, it was acknowledged later that this pore pressure cell is not able to perform consistently and thus has been eliminated (Khan 2012). Schnaid et al. (2016) developed a pore pressure instrumented flat dilatometer, which replaces the membrane with a porous element for tests in intermediate soils. This allows pore pressure to be recorded during blade penetration and dissipation tests when the blade is stopped but not during the membrane expansion. In general, instrumentation of the probe offers good opportunities for better interpretation; nevertheless, complexity introduced by instrumentation may present challenges in probe development and even degrade probe robustness.

Rapidly growing manufacturing techniques such as metal 3D printing can help during the development of a geotechnical testing device. Shen, Haegeman, and Peiffer (2016) 3D printed an instrumented dilatometer (idilatometer) prototype in allumide with a rigid piston instead of the flexible membrane. This device allows initial testing in a calibration chamber without the penetration procedure, as the blade is in place before the sample preparation. With the experience gained from this proof-of-concept prototype and the assistance from a novel metal 3D printing technique, a more advanced probe has been developed to allow field testing, pore pressure measurements at the piston center, and thrust measurements during the penetration.

The objective of this paper is to present the development, use, and testing results of a new instrumented flat dilatometer in an effort to enable a better interpretation based on more measurements of the soil response during the tests. The work focuses on basic parameters identified from the measurements, such as the DMT contact pressure p_0 and the DMT indices, which form the

basis for interpretation of the soil properties. Comparisons are made with results from the adjacent DMT and cone penetration test (CPT) soundings.

The Instrumented Flat Dilatometer Test

EQUIPMENT AND WORKING PRINCIPLE

In terms of working principle, the DMT blade originally introduced by Marchetti works as an electrical switch (on/off) without using any complex instrument (Marchetti 1975). This pioneering design enjoys the benefits of simplicity and does the job of obtaining pressure readings at two displacement levels of the membrane center: 0.05 mm and 1.1 mm. However, redesign of the blade and the system is technically needed if more accurate measurements of soil response are required.

Fig. 1 shows the basic layout of the instrumented flat dilatometer test (iDMT). The installation of the idilatometer at various depths in the ground can be done with the same field equipment used in the DMT, such as a truck-based penetrometer and push rods to provide and transfer downward thrust, respectively. Major modifications compared with the DMT system include the replacement of the flexible membrane with a rigid piston, instrumentation of the blade, and an electro-pneumatic system to allow automatic control and continuous measurements rather than manual.

Similar to the DMT, the expansion stage follows the blade penetration stage in the iDMT. But it is a rigid piston competing against the surrounding soils by means of internal gas (i.e., Nitrogen) pressure in the iDMT. In addition, the pore pressure is continuously measured via a pore-water intake filter located at the piston center. The rigid piston is favored in the iDMT design because of the following: (1) The rigid piston can protrude further out of the blade surface (as far as 2.35 mm uniform displacement) compared to the DMT, which allows 1.1 mm of central membrane displacement. The edges of the flexible membrane are fixed to the blade, which causes difficulties to further increasing the maximum displacement of the membrane due to the stiffness of the membrane and boundary effects. In interpretation, it can be an erroneous assumption that the membrane movement is a process of uniform loading when displacement increases. (2) Practically, it is easier and more robust to install a pore-water intake filter on the rigid piston than on a thin (normally 0.02 mm thick) flexible membrane. Moreover, the stiffness of the membrane is changed by any modification of the membrane and thus is under further calibration requirements. (3) The calibration of the membrane may change during a sounding due to soil abrasion, whereas the calibration of the rigid piston system is more consistent throughout a sounding because the source of the calibration is inside the blade. (4) The rigid piston can be used in a larger variety of soil types because of its robustness, especially in

FIG. 1

The basic layout of the idMT.

soils in which the membrane may be easily scratched or even damaged.

The idilatometer allows direct measurements of the piston displacement and pore pressure at the piston center while the applied pressure is measured on the ground surface using a sealed gauge pressure sensor (model MLH, made by Honeywell, Morris Plains, NJ). By providing real-time feedback of these measurements to the control system, the pressure regulator (model QB2, made by Proportion Air, McCordsville, IN) can automatically adjust the applied pressure using proportional-integral-derivative mechanics to achieve different loading paths, such as a constant rate of stress or a constant rate of strain. Meanwhile, all measurements are recorded in a portable computer via a data acquisition device (model USB-6009, made by National Instruments, Austin, TX), which facilitates an on-site real-time check of the data.

DESIGN AND FABRICATION OF THE IDILATOMETER

Design

The starting point of the idilatometer design is that the external dimensions comply with the nominal dimensions of the standard dilatometer, which are a 95-mm width and a 15-mm thickness with an approximately 16° cutting edge (the tapered section 50 mm in length). Note that the total length of the dilatometer is not considered as a nominal dimension by Marchetti (1980) and Marchetti et al. (2001) but is specified to be between 220 and 230 mm by ISO standard 22476-11:2017(E), *Geotechnical Investigation and Testing—Field Testing—Part 11: Flat Dilatometer Test* (2017). In principle, a longer dilatometer will not influence the test results as long as the wedge-shaped section of the blade below the membrane remains unchanged, because the disturbance of the soil adjacent to the membrane is mainly subject to this section, which opens

a flat cavity during the penetration. This allows the soils around the idilatometer to suffer the same level of disturbance during the installation as that of the dilatometer.

The idilatometer has two blade surfaces meeting at a blade end. The blade includes a displaceable 40-mm diameter rigid piston in line with the first blade surface at rest condition. Note that the change of the loading from the flexible membrane to the rigid piston does not alter the level of soil disturbance during the blade penetration stage, because both are in line with the blade surface. During the piston/membrane expansion stage, a uniform displacement is applied by the rigid piston, whereas an assumed uniform pressure is applied by the flexible membrane. Considering this difference, the diameter of the piston is not necessarily the same as the 60-mm diameter of the membrane, so a smaller piston is adopted in this design to increase the robustness of the idilatometer. However, this can reduce the range of soils suitable for testing because the soil grains shall be small compared to the piston diameter (40 mm). Fig. 2 shows an exploded view generated in computer-aided design to illustrate the assembly. Specifically, the main blade body comprises three chambers, wherein three covers along with O-rings lodged in specifically dimensioned grooves are used to seal the chambers and shield the elements within the chambers from outside influence. In the chamber close to the blade tip, an inductive distance sensor (model BAW-R03, made by Balluff, Florence, KY) is installed to measure the piston

movement up to 3 mm. The piston itself is the metal target influencing the sensor output with its movement. Note that this piston comprises a porous disk mounted at its center, which allows the intake of pore water. A single turn wave spring is positioned on the flange of the piston to keep the piston in line with the first blade surface at rest condition. A flexible drainage lead is used to connect the pore-water intake filter in the piston with a tunnel going from this chamber to the adjacent chamber. This adjacent chamber is a pore pressure cell comprising a pore pressure sensor (model 4LC, made by Keller Group, London, England) to measure a pressure range of 0 to 1 MPa. Prior to in-situ tests, this cell together with the drainage lead, the tunnel, and the pore-water intake filter must be saturated with viscous silicone oil to reduce the possibility of saturation loss. This way, a fixed and stable environment is created to have a consistent performance of the pore pressure measurements. The third chamber of the idilatometer is necessarily configured to house circuitry and to provide space during assembly and maintenance.

Fabrication

Given the complexity inside the idilatometer, the fabrication is challenging for traditional manufacturing means. With standard machining tools, the irregular tunnels and the hidden grooves inside the blade cannot be built. In comparison, metal 3D printing does not suffer any of the aforesaid geometrical limitations and

FIG. 2
Exploded view of the idilatometer.

reduces the production time by orders of magnitude. However, objects normally require a minimal thickness (1 to 3 mm, depending on material) to be metal 3D printed, and they require an even greater thickness to form a suitable stiffness and strength, because the process is creating an object by laying down successive layers of material. So certain 3D-printed parts with small thicknesses cannot safely withstand the pushing thrust during penetration, such as the blade tip and the threads on the rod-blade connector. Therefore, a hybrid of manufacturing technologies is used in the idilatometer fabrication: the main blade body and the rigid piston are metal 3D printed; the blade tip and the rod-blade connector are machined; then the parts are welded. This hybrid method is de facto a compromise between the traditional machining process and the metal 3D printing technique, which not only enables the fabrication of the iDMT probe, which is too complex for traditional machining, but also fortifies the parts such as the threads and the blade tip, which are less robust when fabricated with the 3D printing techniques. The key to success of this hybrid method is a good welding process to bond the two distinct parts together. In this case, a tungsten inert gas (TIG) welding process was conducted by depositing the silicone-bronze (CuSi_3) filler layer by layer and allowing a slow cooling process to the atmosphere temperature between two successive layers. These cooling down intervals allow the heat generated during the TIG welding to be dissipated evenly to prevent any crack formation due to the different thermal properties between the 3D-printed parts and the

machining parts. Note that at the end of welding, the CuSi_3 filler is in line with the iDMT blade surface in the transitional zone between the blade body and the blade tip, which is slightly different from the streamlined shape in the DMT blade. This is likely to result in a sharper change in horizontal stress in soils during the iDMT installation than that of the DMT. Fig. 3 shows the assembly of the idilatometer components and use of the setup in field testing.

There are various methods of metal 3D printing; the goal of this project was to fabricate sufficiently robust parts in an accurate manner at a low cost. So, it was decided to use the binder jetting technique to produce a matrix metal material—420 stainless steel infiltrated with bronze. The binder jetting technology was originally developed at Massachusetts Institute of Technology (Sachs, Cima, and Cornie 1990), but it only became one of the commercial 3D printing technologies around 2010. Binder jetting in 420 stainless steel infiltrated with bronze typically involves the following steps: printing, curing, sintering and infiltration, and, finally, cooling down (ExOne 2014). The printing is a process of a liquid binder being selectively deposited to join stainless steel (alloy 420) powder particles, and this process is repeated layer by layer to form a complete object. This object is then cured in an oven to enable the handleability. Following the curing, the objects are sintered and infiltrated with bronze (90 % Cu and 10 % Sn) above $1,100^\circ\text{C}$. In the last step, the object can be cooled down in a nonannealed way to retain its best strength and hardness.

FIG. 3 Idilatometer: (a) the first blade surface with the piston protruding out; (b) the uncovered second blade surface; (c) at the end of a sounding with a truck-based penetrometer.

TABLE 1 Main properties of nonannealed 420 stainless steel infiltrated with bronze (ExOne 2014).

Ultimate Tensile Strength, MPa	Yield Tensile Strength (0.2 % Offset), MPa	Elastic Modulus, GPa	Elongation, %	Hardness, HRb
496	427	147	2.3	97

The finished object is composed of 60 % stainless steel and 40 % bronze infiltrant with the main properties shown in Table 1. It is worth noting that the whole production process of the dilatometer parts takes only two days and costs approximately €300, excluding value-added tax, which is by no means feasible using traditional machining or casting techniques. In terms of geometrical accuracy of the finished products, the main blade body has a width of 95.4 mm (+0.42 % error), a thickness of 15.3 mm (+2 % error), and a length of 259.7 mm (−0.12 % error); the rigid piston is 40.04 mm (+0.1 % error) in diameter. The error (in percentage) of the blade thickness is generally one order of magnitude larger than the rest because the layer-by-layer printing orientation is along the axis of thickness and a single layer thickness is 0.1 mm.

CALIBRATION

Two types of calibration are required to obtain a correct soil response from the iDMT: calibration of the instrument recording system and determination of the internal resistance during the piston movement.

In terms of calibration of the instrument recording system, first, the piston-displacement calibration is performed to measure the output of the noncontact displacement sensor in function of the displacement of the target (piston) made of the nonstandard material (420 stainless steel infiltrated with bronze). The piston displacement is measured using a dial gauge (model $\mu 233$, made by Sylvac, Crissier, Switzerland) at the same sampling rate as the inductive displacement sensor. Fig. 4 illustrates this setup along with the relationship between the voltage output of the sensor and

FIG. 4 Piston-displacement calibration.

the piston displacement measured by the dial gauge. Note that this voltage-displacement relationship is generally dependent on the type of metal used. Based on the sensor manual, the curve is supposed to be linear if the target is made of 100 % stainless steel while in the case of a matrix metal made of 60 % 420 stainless steel and 40 % bronze, a nonlinear relationship is expected. Still, a high coefficient of correlation of 0.97 can be obtained by a best-fit line. Therefore, linear interpolation is adopted to estimate the displacement value at any given voltage using the two adjacent known data points. Furthermore, for all components of the instrument recording system, zero-offset calibration recording the value at zero load should be performed routinely in the field prior to each field test, because ambient temperature or atmospheric pressure shifts can result in errors.

Considering that the raw data from field tests consist of not only the soil response but also the system's internal resistance, which is the sum of the force exerted by a wave spring, the friction of the O-ring, and the system compliance, calibrations mimicking the field-testing procedure are performed in air. Note that although the piston can be displaced up to 2.35 mm, a maximum displacement of 2.0 mm is configured in the program to avoid the relatively large pressure required for the displacement due to stiffness behavior of the wave spring. Fig. 5 shows nonlinear hysteretic loading-unloading loops from all calibrations of this type. Hysteresis may be an issue of major concern if it is rate-dependent. Thus, three different pressurization/depressurization rates are used in the calibrations: the maximum, the minimum, and the mean pressurization/depressurization rates in the allowed

FIG. 5 Wave spring stiffness and O-ring friction calibrations.

range given in the following section. Considering a ± 8.5 -kPa accuracy of the instrument system, no significant difference between the loading curves is found, whereas the unloading curve with the maximum rate shows a slight lag in displacement. This confirms that the calibration is rate-independent in the given pressurization/depressurization range. Furthermore, although the wave spring and the O-ring do not suffer the influence of soil abrasion during the tests, which is the usual cause of a change of the flexible membrane calibration curve in the standard DMT tests, the calibration at the mean rate is repeated after the in-situ tests. The repeatability is considered sufficiently good, as divergence between the two is generally smaller than 17 kPa. With these calibration data available, the soil response—corrected pressure-displacement curve—can be readily produced by a subtraction from the raw field data.

Field Tests

A field-testing program consisting of an iDMT, a DMT, and a CPT was conducted at Ghent University located at Technologiepark, Zwijnaarde, in Belgium. The three soundings using three different devices were carried out at adjacent locations only 1 m apart from each other and employed a common truck-based penetrometer to allow the probes to be statically pushed to a depth of 7.0 m below the ground surface at a constant rate of 20 mm/s. The site was mostly composed of soil that ranged from sandy silts to silty sands, and the groundwater table was about 2.8 m below the ground surface during this testing program.

In terms of the iDMT, the testing procedure is devised to minimize the difference from the DMT testing procedure to allow a comparison. In addition, during the penetration stage, the thrust on top of the rods is measured by a load cell, and a friction reducer is installed just above the blade to prevent damage of the equipment as well as to estimate the blade penetration resistance.

Once the piston reaches the desired testing depth, pressurization starts immediately. The pressurization continues until at least a piston displacement of 2.0 mm or a pressure of 3.4 MPa (the maximum capacity of the system) is reached before an immediate depressurization or a controlled depressurization is performed. Though the iDMT is capable of carrying out additional small unload-reload (or reload-unload) loops to enhance estimation of soil stiffness, this is not adopted in this test to avoid influencing the comparison with the DMT. Before the penetration, the pore pressure cell and the pore-water intake filter at the piston center are fully saturated using viscous silicone oil.

In the DMT, the pressurization rate is normally controlled by acquiring sequential pressure readings within the required time ranges. In terms of a complete expansion sequence (A-pressure at 0.05 mm and B-pressure at 1.1 mm), Marchetti et al. (2001) indicates that it generally takes about 1 min and pressure readings

are reached slowly; ASTM D6635-15, *Standard Test Method for Performing the Flat Plate Dilatometer* (2015), suggests that the A-pressure is obtained within 15 to 30 s after beginning the gas flow and the B-pressure is obtained after 15 to 30 s after beginning the gas flow; Eurocode7, *Geotechnical Design—Part 3: Design Assisted by Field Testing—Section 9: Flat Dilatometer Test (DMT)* (1997), recommends that the A-pressure is obtained within 20 s after beginning the gas flow and the B-pressure within 20 s after the A-pressure; ISO 22476-11:2017(E) suggests that the A-pressure should be obtained within approximately 15 s of reaching the test depth and the B-pressure within approximately 15 s of the A-reading. Taking the difference between these popular standard testing methods into account, the time generally required for a complete expansion sequence (A-pressure and B-pressure) is within 30 to 60 s. Similarly, the time required for a slow, controlled depressurization for the C-pressure is within approximately 15 to 30 s (ASTM D6635-15; ISO 22476-11:2017(E)). This pressurization/depressurization rate requirement with respect to time and its corresponding 1.1-mm membrane expansion at its center can be regarded as a displacement-controlled procedure. Since a rigid piston is used in iDMT, it is possible to compare the piston displacement rate and the membrane displacement rate based on the expanding cavity volume. Fig. 6 shows that the expansion of the flexible membrane and the rigid piston are modelled as an expanding spherical cap and an expanding cylindrical element, respectively. The volume of this spherical cap is expressed as the following:

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

where V_m is the membrane volume, h is the membrane displacement at the center, and $a = 30$ mm = the membrane radius.

The volume of this cylindrical element can be expressed as the following:

$$V_p = \pi r^2 \cdot h' \quad (2)$$

FIG. 6 Expanding cavity volume of (a) a flexible membrane and (b) a rigid piston.

where V_p is the piston volume, $r = 20 \text{ mm}$ = the piston radius, and $h^0 =$ is the piston displacement.

Thus, the maximum cavity volume of the rigid piston ($r = 20 \text{ mm}$, $h^0 = 2.0 \text{ mm}$) is $2,512 \text{ mm}^3$, which is larger than $1,555 \text{ mm}^3$ of the flexible membrane ($a = 30 \text{ mm}$, $h = 1.1 \text{ mm}$). So the DMT pressurization/depressurization rate with respect to the aforementioned time range can be expressed as a volume-per-time range of 26 to $52 \text{ mm}^3/\text{s}$ for pressurization and 13 to $26 \text{ mm}^3/\text{s}$ for controlled depressurization. Then, the time required for the iDMT can be derived from this volume-per-time range to a range of 48 to 97 s and 24 to 48 s for pressurization and controlled depressurization, respectively. Nevertheless, an immediate depressurization is performed in this sounding, rather than a controlled depressurization for the sake of a simple comparison in these initial tests.

Interpretation and Test Results

REVIEW OF THE DMT INTERPRETATION

The dilatometer field readings A-pressure and B-pressure are used in the determination of the basic DMT parameters p_0 and p_1 in the following equations:

$$p_0 = 1.05\Delta A - Z_m + \Delta A - 0.05\Delta B - Z_m - \Delta B \quad (3)$$

$$p_1 = B - Z_m - \Delta B \quad (4)$$

where ΔA and ΔB are corrections determined by calibration and Z_m is the gage zero offset.

Note that p_0 is conceptually the initial contact pressure and is calculated using a linear extrapolation from the B-pressure at 1.1 mm displacement through the A-pressure at 0.05 mm displacement to a zero displacement. Then p_0 can be normalized to the dimensionless horizontal stress index, $K_D = \frac{\sigma_h}{\sigma_v} = \frac{p_0}{p_0 + u_0}$, where u_0 is the in-situ equilibrium pore pressure at the depth of testing and σ_v is the in-situ effective overburden stress. Together with p_1 , the material index, $I_D = \frac{p_1}{p_0} = \frac{B - Z_m - \Delta B}{p_0 + u_0}$ and the dilatometer modulus, $E_D = 34.7\frac{p_1}{I_D} - p_0$ can be derived. It is seen that p_0 is crucial for identifying K_D , I_D , and E_D and

thus of paramount importance in deriving common soil parameters based on these DMT indices. Therefore, it is of interest to improve the p_0 determination technique because now a full pressure-displacement curve is available rather than just pressure readings at two fixed displacements.

The dilatometer modulus is calculated using the theory of elasticity because the space surrounding the dilatometer blade is assumed as two elastic half spaces in contact along the plane of symmetry of the blade (Fig. 7a) (Marchetti 1980). The solution of this problem complies with the general form of distributed loads on the surface of a semi-infinite elastic half space (Poulos and Davis 1974). Using this solution with the influence factor (Mayne and Poulos 1999), the dilatometer modulus is as follows:

$$E_D = \frac{E}{\delta(1 - \nu^2)} = \frac{qD}{s} \quad (5)$$

where E = Young's modulus; q = the applied pressure; D = diameter of the loaded area; ν = Poisson's ratio; l = influence factor; and s = the piston displacement or the displacement at the center of the membrane. For the simple case of a flexible circular footing over a semi-infinite elastic half space and the dilatometer setup with the additional condition of zero settlement external to the loaded area, $l = 1$ and $2/\pi$, respectively. l is $\pi/4$ as an exact solution for a rigid circular footing situated on an elastic half-space, but the problem of rigid piston expansion in iDMTs is not usable because of the presence of discontinuities (displacement jump) at the edge of the loaded area (Fig. 7b); thus, the development of an alternative approach is required.

THE IDMT CONTACT PRESSURE

Observations and Analysis

Two types of loading curves are typically seen in an iDMT sounding, which then requires different techniques to estimate the contact pressure. Fig. 8 shows a first result using the measurements of an iDMT at a depth of 4.0 m. As immediate depressurization is carried out, only the loading part of the measurements is corrected using the calibration data. The corrected loading curve

FIG. 7 Modelling (a) the flexible membrane expansion and (b) the rigid piston expansion.

FIG. 8 Typical testing results with distinct phases in the loading curve.

is therefore used to interpret soil response during the loading stage, which consists of three distinct phases. In phase 1, the piston begins to move outward when the pressure reaches around 100 kPa. Then an initial stiff piston expansion follows until the pressure-displacement relationship becomes linear. This linear piston expansion may be regarded as a pseudoelastic phase (hereinafter phase 2) prior to phase 3 where plastic behavior becomes dominant. In this particular testing curve, phase 2 starts at around 0.08 mm and ends at the initiation of yielding at about 0.65 mm where the increase in pressure reaches the strength of the soils adjacent to the piston. In phase 3, it appears that a limiting pressure is approached. This may be reasonable for this sand-silt mixture, considering that the rigid piston expansion with a uniform displacement results in a more significant plastic soil response than that of the flexible membrane expansion with the same displacement magnitude measured at the membrane center. Note that Campanella and Robertson (1991) indicate that the slope of the DMT expansion curve from p_0 to p_1 , (i.e., E_D) represents a measure of the "elastic-plastic" response of the sand. Followed by a depressurization stage, phase 3 ends at 2.08 mm displacement; however, the maximum displacement of 2.13 mm is reached during the depressurization. This implies time-dependent deformations such as soil creep. Additionally, pore pressure is measured through the test at the piston center and shows a slight increase over the equilibrium water pressure during the expansion and a gentle decline before reaching the maximum displacement. This generation of excess pore pressure is possibly due, to some extent, to fines in the soils while the dissipation in the meantime is expected as well. However, the magnitude of the pore pressure development is negligible compared to the total pressure of soil response. Fig. 9 shows another result

FIG. 9 A typical smooth loading curve.

using the test data at a depth of 5.8 m. Though an identical testing procedure is applied in all the tests of this sounding, the soils here respond in a smooth curve rather than in the aforementioned distinct phases. However, the general trend remains the same: that the lift-off at around 180 kPa is followed by a piston expansion at a decreasing rate until the maximum system capacity of 3,400 kPa is reached. The trend of the pore pressure development resembles that shown in Fig. 9, such as the decrease prior to the full piston expansion. The magnitude of the maximum pore pressure is higher than that in Fig. 9; however, it is still considerably lower than the total stresses.

Furthermore, it is common to see in all tests that the soil response under 0.1-mm piston displacement is significantly stiffer than the ensuing part of the curve. In general, this soil response depends not only on the preinsertion in-situ horizontal stress but also on the amount of disturbance associated with the blade penetration. In saturated cohesive soils, this disturbance during blade penetration can be evaluated numerically. Finno (1993) employed the strain path method to compute the strain field developing around the DMT blade during the penetration through saturated cohesive soil and then evaluated stresses based on the computed strain fields by use of an anisotropic bounding surface model. Kouretzis et al. (2015) developed a 3D finite-element model simulating the penetration of the DMT blade into saturated clays to obtain the average horizontal stress acting on the membrane. Both of these works are in line with a finding that the maximum value of the total horizontal stresses of the soil elements close to the blade surface is attained near the blade shoulder, which is the geometrical transition point of the blade surface. Once this point has been passed during the penetration, the total horizontal stresses may decrease to 0.6 times the maximum value that is approximately constant at the membrane (Finno 1993) or still

undergo a continued reduction at the membrane (Kouretzis et al. 2015). The difference may be due to the larger 50-mm-long tapered section of the blade used by Kouretzis et al. (2015) compared to the 40-mm one by Finno (1993). Therefore, in reality, the initial soil response during the expansion stage follows the unloading from the penetration and is in fact a reloading. While these numerical findings are only in saturated cohesive soils, it is likely that the unloading-reloading effect also takes place in sandy soils, in which the same initial soil response is spotted in the measurements.

Therefore, the p_0 estimated using Eq 3 is, in fact, not the "real" lift-off pressure but a conceptual contact pressure at zero displacement neglecting the initial stiff reloading phase. In the case of the reloading phase going beyond 0.05 mm, the pressure-displacement relationship is likely to be nonlinear between the A-pressure and the B-pressure because the initial elastic reloading is normally much stiffer than the ensuing phase. This can possibly lead to noticeable errors using Eq 3 to obtain p_0 . Furthermore, it has been observed that the slope of the expansion curve represents some elastic-plastic response in sands and is largely controlled by the excess pore pressure generated during penetration in clays (Campanella and Robertson 1991). The soils tend to behave nonlinearly in either case, so an approximation to some extent can be expected under the assumption of a linear relationship. To eliminate these possible errors, a new estimation technique for p_0 based on the full expansion curve is a necessity.

New Approach and Results

In terms of this conceptual contact pressure, p_c is used for the iDMT to distinguish from p_0 in the DMT. To address the first type of loading curve, such as the one shown in Fig. 8, phase 2 is adopted to back-extrapolate p_c at zero displacement by simply using a linear regression. This method can prevent potential errors, including parts of phase 1 or 3 in the prefixed displacement range such as that of the DMT. In the case of the result of the smooth loading curve as shown in Fig. 9, an approach to estimate p_c is presented in Appendix A. With this approach, the iDMT expansion curve at a testing depth of 5.8 m can be addressed by means of first identifying the transitional "yield" point that is the intersection point at 0.278 mm in displacement, as shown in Fig. 10. Then, a value of $p_c = 674$ kPa is obtained by the back-extrapolation to zero displacement, as shown in Fig. 9.

In this way p_c can be interpreted from each iDMT pressure-displacement curve using either of the aforementioned techniques. Fig. 11 shows the pressure profile from the iDMT and the DMT, in which a comparison can be made between p_c and p_0 . The general trends appear to agree with each other, with a mean ratio p_c/p_0 of 1.01. However, p_c may be significantly different from p_0 at certain depths, with a standard deviation of 0.3 for the set of p_c/p_0 values. Moreover p_0 is found to be mostly larger than p_c in the depth range from 4 m to 6.4 m. For example, p_c and p_0 are estimated as 674 kPa and 997 kPa, respectively, at a

FIG. 10 Estimation of the transitional "yield" point (Intersection point).

depth of 5.8 m. Although it is not possible to measure a full pressure-displacement curve from the DMT, a linear fit is drawn from the point at maximum displacement on the post-yield part of the dilatometer expansion curve in Fig. 9, thus allowing a perception on this difference, as the linear fit may excessively overestimate p_0 in spite of a high adjusted R^2 .

THE RIGID PISTON EXPANSION

Because of the aforementioned displacement discontinuity, the rigid piston expansion problem is not tractable using the theory of elasticity, and the soils at the piston edge must be broken. Thus, a modified displacement boundary is proposed to allow continuity of displacement at the piston edge and a gradual transition of displacement from the piston edge to the piston center. Fig. 7b shows this assumed displacement boundary characterized by a semi-ellipse. The difference in reaction of elastic soils is assumed to be small if the cavity volume resulting from the elliptical boundary and the ideal cylindrical boundary are identical. Using this elliptical displacement boundary, an FEM simulation by means of Abaqus software is feasible.

To gain faith in the validity of the numerical results, a benchmark is first performed to the flexible membrane expansion in the DMT where an exact solution exists as $l = 2/\pi$ for Eq 5. An axisymmetric model (the radius of the loaded area of 1 m, the mesh size of 200 by 200 m, and the element type of three-node linear axisymmetric triangle) is built with the material properties of 5 MPa in Young's modulus (E) and 0.3 in Poisson's ratio (ν). This benchmark gives 0.43 % error compared to the exact solution. A sensitivity study of these model parameters is also conducted showing that the accuracy is mainly sensitive to the mesh size, as demonstrated in Table 2. This may be reasonable, considering the fact that an elastic half-space is simulated.

Fig. 12 shows the model for the piston expansion using the elliptical displacement boundary and the prescribed displacement u equal to $s_0 \left(1 - x^2/r^2\right)$, where s_0 is the displacement at the center

FIG. 11 The pressure profile of the flat dilatometer test (DMT) and the instrumented flat dilatometer test (iDMT) results.

TABLE 2 Errors of meshes in various sizes.

Mesh Dimensions	Errors
50 × 50	3.83 %
100 × 100	1.56 %
200 × 200	0.43 %

(the vertex of the ellipse along the minor axis) and r is the radius of the loaded area. The vertical reaction force acting on the nodes of the loaded area is recorded at each increment during the loading stage. Then the applied pressure is calculated as the sum of the vertical force divided by the loaded area. Fig. 13 shows the results from the FEM simulations. Taking the assumption of the equivalent cavity volume into account, s_0 is 1.5 times the uniform displacement of the piston expansion. Then I can be back-calculated as 0.49 from the linear fit based on Eq 5. Seeking a relation between the flexible membrane expansion in the DMT and the rigid piston expansion in the iDMT, the pressure required for a 1.1-mm central movement of the membrane only results in an approximately 0.56-mm piston displacement, if the soil behavior is completely elastic. Fig. 11 shows the profiles of p_l from the DMT and $p_{0.56}$ from the iDMT in a comparison. The trends of p_l and $p_{0.56}$ pressure profiles appear similar, with a mean $p_{0.56}/p_l$ ratio of 1.18 and a corresponding standard deviation of 0.3. The

divergence is mainly attributed to greater $p_{0.56}$ values in the depth range of 1.6 to 3.6 m. This may imply that the rigid piston competes with a larger plastic soil response than the flexible membrane. Furthermore, it is necessary to pay attention to the limitation of these comparisons due to the influence of the partial drainage conditions. The scatter could also possibly be attributed to the variation in soil stratigraphy, which results in different soils being measured at the same depth in adjacent in-situ soundings.

IDMT INDICES AND COMPARISON WITH DMT INDICES

Calculated from p_0 and p_l , three DMT indices can be identified, namely I_D , E_D , and K_D , using the aforementioned formulae established by Marchetti et al. (2001). These DMT indices are then used to derive common soil parameters. Therefore, it is of great interest to identify the iDMT indices in a similar way. In the iDMT, p_c and $p_{0.56}$ may be considered as alternatives of p_0 and p_l , so the iDMT indices are expressed as the following:

$$I_D = \bar{\alpha}_{0.56} - p_c / \bar{\alpha}_c - u_0 \quad (6)$$

$$E_D = 34.7 \bar{\alpha}_{0.56} - p_c \quad (7)$$

$$K_D = \bar{\alpha}_c - u_0 / \alpha_{v0}^0 \quad (8)$$

Note that the constant of 34.7 in the calculation of E_D in the iDMT remains the same as that of the DMT because the

FIG. 12 Finite element method (FEM) simulation for the piston expansion.

FIG. 13 (a) Contour of vertical displacement around the loaded area and (b) the load-displacement curves.

displacement of 0.56 mm of $p_{0.56}$ is already "equivalent" to 1.1 mm of p_1 based on Eq 5. The soil unit weight is estimated in the same way as that in the DMT using the solution chart of E_D versus K_D (Marchetti et al. 2001).

Robertson (2009) proposed CPT-DMT correlations based on a great number of sites where adjacent CPT and DMT data are available. Thus, the DMT indices (I_D , E_D , and K_D) can be predicted from the CPT parameters (the normalized cone resistance Q_{t1} and the normalized friction ratio F_r). The correlations for sand-like soils ($I_c \leq 2.6$) are as follows:

$$I_D = 10^{0.67-0.67I_c} p \quad (9)$$

$$E_D / \sigma'_{v0} = \alpha Q_{t1} \quad (10)$$

$$K_D = \alpha / 34.7 p Q_{t1} / 10^{0.67-0.67I_c} \left[\frac{F_r}{Q_{t1}} \right] \quad (11)$$

where $I_c = 1.847 - \log Q_{t1} + \log F_r + 1.22 \left[\frac{F_r}{Q_{t1}} \right]$ is the CPT soil behavior type index; α = a factor varying with soil type, relative density, age, and stress history, in a range from 2 to 10. Since I_c ranges from 1.84 to 2.51 in this CPT sounding, the soils are

FIG. 14 Profile of I_D , E_D , K_D , and the penetration resistance.

classified as sand-like soils ($I_C \leq 2.60$), so Eqs 9–11 are used accordingly to predict the DMT indices.

Fig. 14 shows a comparison among the measured DMT indices, the CPT-predicted DMT indices, and the iDMT indices based on the three individual soundings 1 m apart from each other. The plots for I_D and E_D are presented on log scales for a clearer illustration of the range of values. It appears that I_D and E_D based on the iDMT can give slightly larger values than that of the DMT, since mostly either p_c may be smaller than p_0 or $p_{0.56}$ may go higher than p_1 . Nevertheless, in general, I_D from both tests describes similar soil classification of sands and silts, and the difference between the two is considered smaller than that between the DMT-measured I_D and the CPT-predicted I_D using Eq 9. In terms of E_D in the DMT and the iDMT, the derivation simply assumes that the soils are purely elastic while, in reality, E_D is essentially a large strain response (Campanella and Robertson 1991; Robertson 2009). Thus, scatter to some extent resulting from elastoplastic soil response is reasonably expected between the DMT-measured E_D and the iDMT-measured E_D . Predicting E_D and K_D from the CPT data requires selecting an appropriate α , which depends on soil type, relative density, age, and stress history. But α is not unique to all soils, thus bands bounded by α are alternatively used in the comparison plots of E_D and K_D . Robertson (2009) suggests that α is in a range from 2 to 10, with an average of 5 for most soils. In this case, the selected α values are 2 and 8.3 for a good capture of the trends and variation in both E_D and K_D . Furthermore, the comparison of K_D between the DMT and the iDMT shows reasonable agreement, which is essentially the normalized comparison of p_c and p_0 in Fig. 11. The " K_D crusts" possibly resulting from shallow desiccation crusts in sands (Marchetti 1997) are fairly captured by both K_D profiles, as sharp reductions are seen from 1 to 2.5 m.

THE THRUST MEASUREMENTS

Houlsby and Wroth (1989) pointed out that the thrust required to advance the DMT blade in sands is linearly related to the p_0 pressure. This has been confirmed by Smith (1993) and Bellotti et al. (1997) in calibration chamber tests and by Campanella and Robertson (1991) in in-situ tests. Thus, from the interpretation point of view, the thrust measurements are redundant with respect to the p_0 pressure. However, the thrust measurements can still help to prevent potential damage to the equipment, especially considering that the dilatometer has multiple sensors inside. Compared to the p_0 pressure, the thrust provides a faster measure of the soil strength and the stress level. This can be helpful for withdrawing the blade in time when a significant stiff soil layer is detected by the thrust measurements but not yet by the p_0 pressure. Schmertmann (1982) and Schmertmann and Crapps (2016) suggested that the thrust measurements made during the DMT sounding can provide an estimation of the blade penetration resistance q_D . Ideally, the thrust should be directly measured just above the blade using a load cell, like that of the cone tip load cell. However, this creates significant extra cost for redesigning of the blade-rod connector. Alternatively, the thrust can be measured above the ground at the top of the string of rods with an assumption that friction on the rods can be neglected if a friction reducer is used just above the blade. This assumption has been proved reasonable for sounding in sand provided that testing depth is less than 15 m (Bullock 2015; Campanella and Robertson 1991).

In this iDMT sounding, the thrust was measured at the top of the rods with a manometer on which readings were taken every 50 mm for a nearly continuous profile, and a friction reducer was installed just above the blade. Thus, q_D was estimated by correcting the thrust using the approach devised by Schmertmann

(1982). Fig. 14 shows the comparison plot between the profile of q_D and q_C . An average ratio (q_D/q_C) of 1.09 is found to be consistent with the range of 1.1 ± 0.1 given in the literature, yet the ratios vary from 0.25 to 2.37 with a standard deviation of 0.44. This magnitude of dispersion may be due to the inherently variable sandy site, such as the shift of similar large variations in the depth range of around 4.5 to 6.3 m.

Conclusions

The design, development, and field-testing results of the iDMT are presented in this study. The design uses a rigid piston instead of the flexible membrane in the DMT, which allows a displacement of up to 2.35 mm and pore pressure measurements at the piston center. The development mainly involves fabrication of the dilatometer with the assistance of a metal 3D printing approach (the binder jetting technology) and instrumentation of the system for automatic control and continuous measurements during the tests. With the successful field tests in a site composed of soil that ranges from sandy silts to silty sands, the dilatometer has proven robust. Additionally, the adopted metal 3D printing technique appears promising in improving other geotechnical testing devices because the dilatometer has safely withstood penetration stress up to 20.77 MPa during the tests.

With the full pressure-displacement curves, the conceptual contact pressure p_c can be estimated from the iDMT as an alternative of the DMT p_0 . The approach requires identification of two types of the loading curves that are addressed differently: the use of linear extrapolation for a curve with distinct phases or the use of nonlinear extrapolation with an automated Casagrande's method for a smooth curve. This proposed method for p_c generally gives similar values to p_0 or possibly a smaller p_c when the loading curve is highly nonlinear, such as in Fig. 9.

Concerning the piston expansion problem, an FEM simulation approach is used by eliminating the discontinuity at the piston edge with a modified displacement boundary. Then the iDMT modulus is back-calculated as $E_D = 0.49q_D/s$. The pressure required for a piston displacement of 0.56 mm is the same as that for a 1.1-mm central membrane displacement, provided the soils behave purely elastic. A comparison is made between $p_{0.56}$ from the iDMT and p_1 from the DMT showing that $p_{0.56}$ may be larger than p_1 in some soils, possibly due to a larger plastic soil response during the piston expansion.

A comparison made between the measured iDMT indices, the measured DMT indices, and the CPT-predicted DMT indices shows reasonable agreement of the iDMT profiles. The iDMT indices are less different from the DMT indices than from the CPT-predicted DMT indices. Nevertheless, it is important to recognize the limitations of only performing the tests in soils ranging from sandy silts to silty sands because partial drainage effects during the tests are likely to influence the test results and, thus, the

comparison between different testing techniques. Therefore, a large validation program comprising tests in soils under the fully drained condition and the undrained condition is a necessity in further work. In conclusion, the presented work shows promising use of the iDMT with accurate measurements of the piston expansion, the pore pressure, and the thrust in sandy soils.

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Appendix

ESTIMATION OF P_c IN A SMOOTH LOADING CURVE

This approach consists of firstly locating a transitional "yield" point on the curve followed by a nonlinear curve fitting to identify p_c . Specifically, in the first step, a modified method based on the graphical technique developed by Casagrande (1936) for the pre-consolidation pressure in the one-dimensional consolidation test is used considering the resemblant unloading-reloading effects. In addition, considering that the implementation of a manual graphical method is time consuming and inconvenient, a Matlab program has been developed to automate the following steps:

1. Arrangement of the iDMT data on a semilog plot of the displacement with a linear scale for the x-axis and the pressure with a logarithmic scale for the y-axis.
2. Curve fitting of the data points from the lift-off point until the end of loading to a power function:

$$y = ax^b + c \quad (A1)$$

3. Estimation of the point of maximum curvature on this fitted curve. Using the mathematical definition of the radius of curvature R , as shown in Eq A2, the R determination for a power function is obtained in Eq A3. As the curvature is the reciprocal of the radius of curvature, the point of maximum curvature is given by the minimum value of R

$$R = \frac{dy}{dx} \left(1 + \left(\frac{dy}{dx} \right)^2 \right)^{3/2} / \frac{d^2y}{dx^2} \quad (A2)$$

$$R = \frac{x^{2-b} (a-bx^{b-1})}{(b-1)^2 (a^2 - 2abx^{b-1} + b^2x^{2b-2})} + \frac{1}{b^2} \frac{2abx^{b-1} - 1}{a^2 - 2abx^{b-1} + b^2x^{2b-2}} \quad (A3)$$

4. Determination of the bisector line from the vertical line and tangent line at the point of maximum curvature.
5. Extension of the straight portion of the expansion curve near the end of loading.
6. The point where the lines in parts 4 and 5 intersect is used to obtain the displacement of the transitional "yield" point.

In the last step, the displacement of the intersection is used to estimate the transitional "yield" point, which is different from Casagrande's method using the pressure of the intersection as the preconsolidation pressure. The rationale of this is that the membrane/piston expansion can be regarded as a displacement-controlled test, as the soil elements are loaded until the maximum displacement while the one-dimensional consolidation test is a pressure-controlled test as the specimen is subjected to increments of pressure until the final pressure is equal to or greater than four times the preconsolidation pressure.

Once this transitional "yield" point is located, a nonlinear fit is used to back-extrapolate p_c from the post-yield curve. To account for possible nonlinear, asymptotic behaviors if the limit pressure is approached, the following regression model is proposed:

$$Y = c^0 + a^0X - b^0d^X \quad (A4)$$

where a^0 and c^0 are the parameters for a linear asymptote line representing a potential boundary as the curve potentially tends to flatten, b^0 indicates the range of the nonlinear part, and d^0 is the rate of the nonlinearity. It is noted that the model is valid when $b^0 \geq 0$ and $0 \leq d^0 \leq 1$. Then, with a good fit reached, $p_c = c^0 - b^0$.

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