EFFECT OF TEST PROCEDURE ON SHEAR STRENGTH OBTAINED USING THE NEWCASTLE DILATOMETER

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ABSTRACT

A new dilatometer for in-situ soil testing has been developed which uses a rigid piston to load the soil. The new dilatometer 'called the Newcastle Dilatometer (*NDMT*)' uses a Hall effect transducer and a magnet system to measure the penetration of the piston during loading of the soil. The pressure required to penetrate the piston is recorded using a pressure transducer. The two transducers together can produce applied pressure-displacement curves for obtaining soil parameters which can be more reliable than those obtained based on just one or two contact pressures values as in the Marchetti dilatometer.

Since the *NDMT* allows more control during in-situ testing, the same was carried out employing two test procedures, 'the stress increment controlled' and 'the constant rate of stress' at a site consisting of firm to stiff clay. This paper presents a comparison of the data obtained from the two test procedures and the effect the test procedure has on the various soil properties, in general and the shear strength, in particular.

INTRODUCTION

The Marchetti dilatometer (*MDMT*) is a simple device that can be used to determine in-situ stress, stiffness and strength of a soil with some degree of confidence. During a test the *MDMT* furnishes only two data points consisting of displacement and the corresponding pressure at two different displacement position of its membrane. This device, therefore, lacks in providing any information between the two displacement positions and the only two data points are interpreted to establish the various in-situ soil properties.

The *NDMT* uses displacement and pressure transducers which can record the data throughout the penetration of its piston into the soil. The stress-strain curve thus produced can be studied and analysed with more confidence. Furthermore, the test procedure can be varied easily to suit the nature of the soil parameter required in the design.

KEY DESIGN FEATURES OF THE NEWCASTLE DILATOMETER (NDMT)

Fig. 1 shows the *NDMT* blade (i) whose geometry is the same as that of the Marchetti Dilatometer. The membrane of the *MDMT* is replaced with the piston assembly (ii) shown in Figs. 1 and 2. The use of the wave spring washer (iii in Fig. 2) between the piston flange (ii) and the retaining ring (iv) keeps the piston flush with the blade until the piston is pressurized using dry N_2 gas and brings the piston back when depressurized. Two O-rings are incorporated in the *NDMT* to keep the assembly air and water tight. The applied gas pressure is recorded using a pressure transducer.

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A magnet has been glued inside a hole at the centre of the piston (vi in Fig. 2). An *HET* (v) has been glued to the blade facing this magnet. This system of a Hall effect transducer (*HET*) and a magnet is used for measuring the displacement of the piston. When the piston moves by internally pressurising the blade, the *HET* produces a change in its output according to the flux intensity. This output is non-linear but non-hysteretic and a second-degree curve fits the data (Akbar, 2001). Access to the connections between the *HET* and the cable is via steel cover plate (iii in Fig. 1).

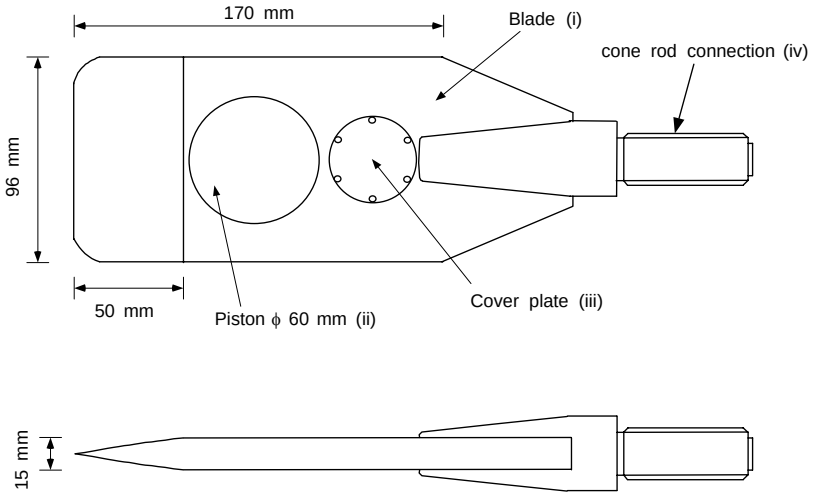


Figure 1 The Newcastle flat rigid dilatometer (*NDMT*)

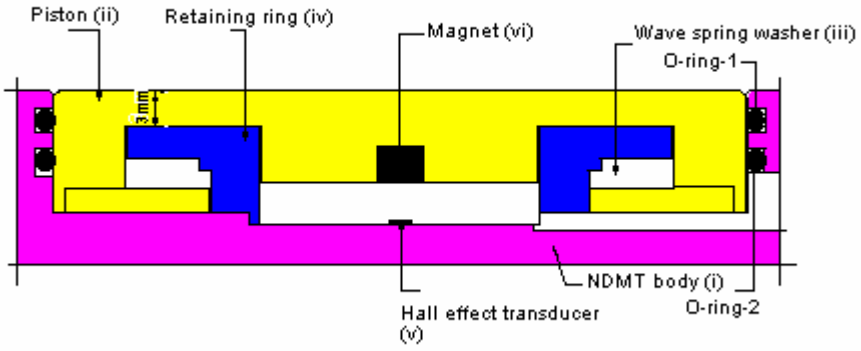


Figure 2 Piston assembly of the *NDMT*.

SITE OPERATIONS

The *NDMT* equipment was assembled on-site as shown in Fig. 3. As two test procedures were to be employed to load the subsoils during in-situ testing, the calibration for the system compliance was carried out accordingly. The two procedures were:

(i) Stress increment controlled (SIC) procedure: In this procedure, the gas pressure was increased in increments, maintaining each increment for 30 seconds.

(ii) Constant rate of stress (CRS) procedure: The pressure was increased at a constant rate similar to that used for testing with the Marchetti dilatometer. For this purpose, the Marchetti *DMT* pressure regulator, which has a needle valve system, was engaged.

From the data for the both procedures, the displacement of the piston (in mm) was plotted against the pressure applied (in kPa) as shown in Fig. 4. The two procedures produce different shape curves with about similar pressures at 1.1 mm displacement. Similar pressures at 1.1 mm penetration indicate that the stiffness of the wave spring washer is independent of the test procedure followed.

The different initial characteristics from the two procedures may be due to the time lag between the pressure increase and the same pressure to be effective and activate the piston. When the pressure is increased, it is recorded immediately because the pressure transducer is adjacent to the pressure regulator. The same pressure takes some time to reach the probe and activate the piston. The time is a function of the length of the hose (about 25 m in this case). In the SIC procedure, equilibrium is reached between the pressure applied and the piston movement due to that pressure in 30 seconds. In the CRS procedure, since the load is increased/decreased continuously, equilibrium between the applied pressure and the piston movement due to that pressure is never reached. As a result, in the CRS procedure, lower penetration values are recorded compared to the SIC procedure at the same pressures, as is evident in Fig. 4.

In the SIC procedure, data points prior to load increments/decrements are considered. It is possible to determine the slope of the loading and unloading parts of the curve to correct the field curve for system compliance. In the CRS procedure, finding the best-fit curve to the loading curve only is possible, as the unloading curve does not have a regular shape due to fast unloading.

After the calibration, the probe was pushed into the ground using a mechanical jack. The in-situ testing was carried out at two adjacent locations. At one location, the CRS procedure was used, at the other location, the SIC procedure was employed.

Tests were conducted immediately after the blade reached a test depth to perform tests under undrained conditions. As a test takes longer to complete with the SIC procedure, tests were carried out at 40 cm intervals to obtain a deeper profile. Using the CRS procedure, tests were carried out at every 20 cm interval, as recommended by Marchetti (1980).

Using the SIC test procedure, the tests were carried out by increasing the pressure at a constant rate up to the lift-off pressure and thereafter the pressure was increased in increments, maintaining each increment for 30 seconds.

Using the CRS procedure, the pressure was applied through the Marchetti *DMT* pressure regulator. After attaining 1.1 mm penetration of the piston, the pressure was vented off. Each test took between 1 and 3 minutes. At the end of the test, the instrument was withdrawn and calibrated for system compliance. The calibrations before and after the in-situ testing were averaged. The in-situ test curves were then corrected for system compliance.

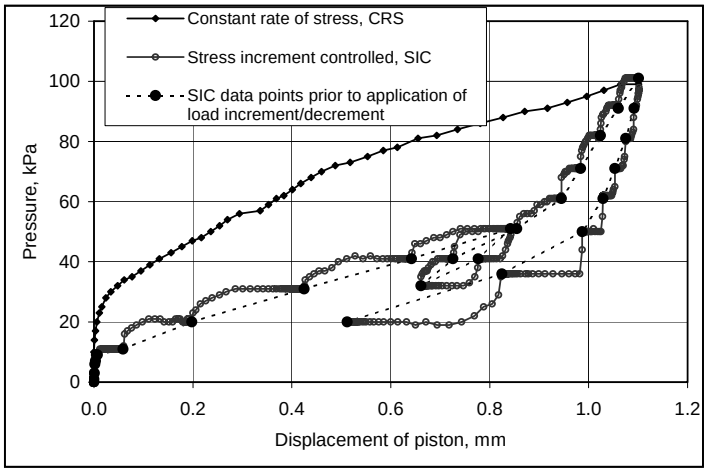


Figure 4 Typical calibration data plot for the NDMT system compliance.

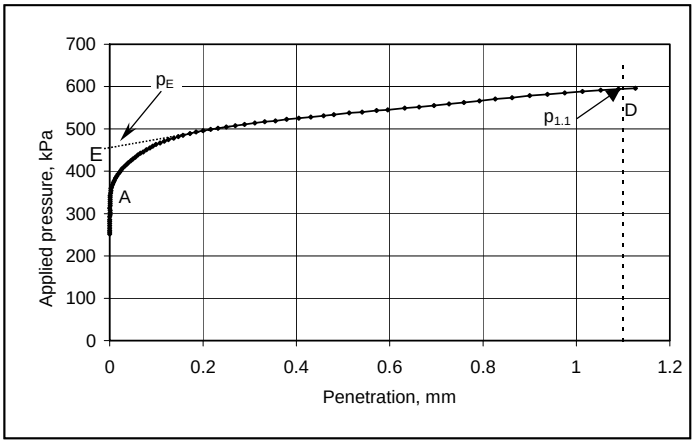


Figure 5 A typical in-situ test curve.

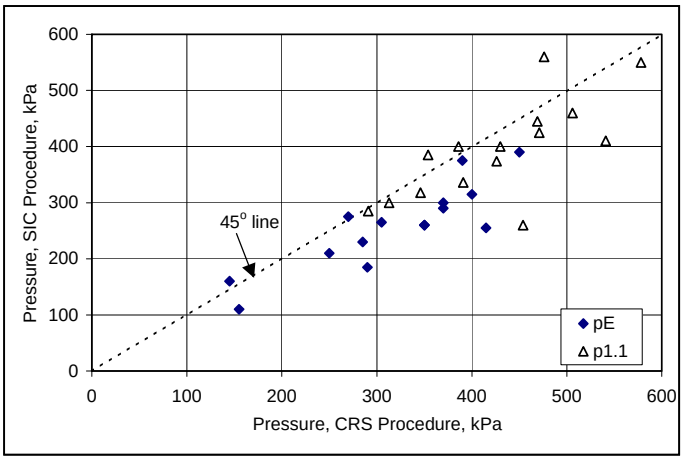


Figure 6 Comparison of *NDMT* pressures from SIC and CRS tests.

INTERPRETATION OF THE DATA

For the SIC test procedure only data points prior to a pressure increment/decrement were used to obtain the stress-strain curve for the tests. For the CRS test procedure, all the data points were plotted.

Fig. 5 shows a typical test curve. The yield pressure p_E (equivalent to Marchetti *DMT* p_o pressure) has been determined by tracing back the trend of (or tangent to) the initial part of the plastic loading curve to intercept the pressure axis at point *E*. This pressure corresponds to zero displacement of the piston. Note that pushing the blade into the soil causes the soil to yield, which implies the initial pressure on the piston should be p_E. The fact that the initial pressure (pressure corresponding to point A) is less than p_E is a result of unloading that occurs as the soil is unloaded as it moves past the shoulder of the blade.

The piston is forced to move by at least 1.1 mm to D. The pressure corresponding to point D is $p_{1.1}$.

Fig. 6 presents a comparison of p_E and $p_{1.1}$ pressures derived from the CRS and the SIC test procedures. The CRS procedure records values of p_E about 20% on average higher than the SIC method. The $p_{1.1}$ pressures recorded by the CRS procedure are about 10% higher than those from the SIC method, as expected. This is due to the time lag between the pressure increase and the pressure becoming effective, as explained during the calibration above.

The two pressures (p_E and $p_{1.1}$) together with the test depth, are converted to a dilatometer modulus (E_D), a horizontal stress index (K_D), and a material index (I_D), using the following equations:

$$K_D = \frac{p_E - u_0}{\sigma'_v} \quad (1)$$

$$I_D = \frac{p_E - u_0}{\sigma'_v} \quad (2)$$

$$E_D = 42.8\,(p_{1.1} - p_E) \quad (3)$$

where u_o is the in-situ pore water pressure.

K_D is a very useful parameter in understanding the stress history (*OCR* profile) of a deposit. $K_D \approx 2$ corresponds to OCR ≈ 1 (Marchetti 1997).

I_D is related to the prevailing grain size. E_D is a function of the soil stiffness and is based on the loading of a rigid, circular plate on elastic soil.

As described above and illustrated in Fig. 6, the p_E pressures are higher for the CRS procedure, therefore, soil parameters (K_D, K_o, *OCR*) based on this pressure should be slightly higher for the CRS procedure compared to those based on the SIC test procedure in identical soil conditions. The Marchetti (1980) classification is based on a range of I_D values, a little difference in I_D values from both the procedures is not relevant. The dilatometer modulus, E_D values from both procedures should also be similar in identical soil conditions.

UNDRAINED SHEAR STRENGTH

Since the slope of the loading curve is a function of the strength of the soil, the same part has been analysed to estimate the undrained strength, s_u as explained below:

Figs. 7(a) and 7(b) show typical plots to determine the undrained shear strength for the CRS and SIC test data respectively. The applied pressure has been plotted against the natural logarithm of the cavity strain. The cavity strain, which is not a true cavity strain as defined in expanding cavities, is defined as the penetration of the piston divided by half the thickness of the blade (7.5 mm), expressed in percentage.

The slope of the initial part of the curve (after the yield) between cavity strain 0.7 and 5.7%, for SIC procedure and 1 and 3% for CRS procedure have been considered appropriate for estimating the undrained strength for the following reasons:

- There should be a negligible effect of the pore pressure dissipation over this early strain range.
- These strain ranges give s_u values comparable with those from the Marchetti *DMT* for the in-situ testing carried out during this research.
- A similar approach has been used to determine the undrained strength from the self-boring and pre–boring pressure meters curves (Clarke, 1995). The disadvantage with the SIC procedure used is that the only data point prior to a load increment is used to plot the curve, which misses the data points in between the load increments. For this reason, it is difficult to adhere to a particular strain range for deducing s_u. This is possible with the CSR procedure used with the *NDMT*.

Beyond the initial yield (after pressure p_E in Fig. 5), the undrained strength is assumed to be a constant. This is because the mean effective stress in a cohesive soil does not change after the soil has yielded (Campanella et al. 1991; Clarke, 1995). The increase in the applied pressure increases the excess pore pressure only. However, the gradient of the curve for the SIC test data (Fig. 7b) seems increasing with expansion indicating an increase in the strength with cavity expansion. This may be due to:

- The test procedure followed (i.e. stress increment controlled, SIC) during which partial dissipation of the excess pore pressure developed may take place with time. This partial dissipation of excess pore pressure increases the effective stress and hence the strength and stiffness as the cavity strain increases. In general, all tests show a similar behaviour but tests including an unload-reload cycle show slightly steeper gradient after the cycle as in Fig. 7(b). This is due to the time spent to carry out the cycle during which pore pressure developed can dissipate more than a test without a cycle. With a constant stress rate (CSR) test procedure, the gradient after the initial yield point remains nearly linear, indicating undrained condition during a test, as shown in Fig. 7(a).
- The gradient of the line can also vary depending upon the strain level as most soils are not perfectly plastic (Clarke, 1995).

The above explanation shows that a correct assessment of the reference datum is very important to determine the undrained strength from this curve fitting method. The *MDMT* has been the only device used to calibrate the *NDMT* results. There is a need to verify the *NDMT* results with the other field and laboratory methods such as field vane, triaxial UU etc.

Fig. 8 shows that there is some scatter in the strength values obtained by the two test procedures. It may be due to the inability in adhering to a certain strain range with the SIC test curve, and the fact that soils vary.

Based on the shape of the test curves (Fig. 7), the following conclusions may be drawn:

- If the undrained shear strength only is required, the test should be carried out using the CRS procedure. It is much quicker and provides a convenient way to determine the strength by adhering to a certain strain range.
- The undrained shear strength is affected by an unload/reload cycle (Clarke, 1995). If the cycle is to be included to determine the stiffness of the soil, it should be performed after about 4% cavity strain (about 0.3 mm penetration of the piston). The pressure should be applied at a constant rate before and after performing the cycle. The cycle needs to be performed by the SIC procedure in order to allow the soil to record its response to unloading and reloading. Alternatively, since tests can be performed at a closer spacing (like 20 cm), one or two tests exclusively (within one meter range) using the SIC procedure may be adequate to provide the stiffness profile.

CONCLUSIONS

The Newcastle Dilatometer allows tests to be performed employing either stress increment controlled or constant rate of stress increase test procedures. However, the data obtained by the constant rate of stress increase test procedure are analyzed more conveniently to obtain the undrained shear strength of clays. The strength parameter based on the test curve can be more reliable than that derived based on just one or two contact pressure values as in the *MDMT*. However, this instrument has undergone limited testing. More in-situ testing is required before making rigorous comments.

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