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Understanding the Stiffness of Soils in Singapore from Pressuremeter Testing

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ABSTRACT: The stiffness of soil is an important parameter that affects the prediction of ground deformation and impact on adjacent structures due to construction activities such as deep excavations and tunnelling. Whilst constitutive models and analytical methods have been derived to predict soil deformation from its stiffness, engineers face a difficult task of identifying soil stiffness from routine site investigations. This paper discusses the use of pressuremeter testing in site investigations to estimate the soil modulus for design.

In recent years, an intensive regime of pressuremeter testing was implemented along with conventional soil investigation works for the land transportation infrastructure construction in Singapore. These include the investigations in the Downtown Line project on Kallang Formation and the Old Alluvium soils, investigations in the North-South Expressway and Thomson Line projects on the Bukit Timah Granite Formation, and investigations in the Tuas West Extension project on the Jurong Formation. This paper reports on the use of various types of pressuremeter testing in Singapore – namely the Menard pressuremeter, the OYO pressuremeter and the self-boring pressuremeter – in terms of the practical experience and the interpretation of pressuremeter test results to understand the stiffness of local soils.

The paper begins by summarising the applications and limitations for various types of pressuremeters in in-situ testing, before discussing the lessons learned from using these pressuremeters in Singapore. Some of the improvements include relating the pressuremeter modulus to the corresponding strains from which they are derived, as well as developing guidance for operators on when to start the unloading cycle. Empirical relationships using SPT-N correlations would also be recommended based on the pressuremeter tests for the various local soils. Other than its elastic modulus, the small strain stiffness of soil has also been investigated to various extents depending on the type of pressuremeter test. These in-situ investigations will improve on the understanding of soil stiffness in Singapore.

1. INTRODUCTION

In a densely built-up urban environment such as Singapore, one of the biggest issues for underground construction is the ground deformations induced and their impact on existing buildings and facilities adjacent to the construction. At the design stage, it is increasingly important to make good predictions of ground deformations in order to evaluate the adequacy of the construction method proposed and assess the impact on the adjacent structures. This is usually done using numerical modelling, such as finite element models.

The stiffness of soil is an important parameter used in constitutive models of soil to predict the deformation of ground and adjacent structures due to such construction activities. To obtain the stiffness of soil, an intensive regime of pressuremeter testing was implemented along with conventional soil investigation works for the land transportation infrastructure construction projects in Singapore. This paper presents the use of various types of pressuremeter tests in Singapore – namely the Menard pressuremeter, the Oyo pressuremeter and the self-boring pressuremeter – in terms of the practical experience and the interpretation of pressuremeter test results to understand the stiffness of local soils.

2. TYPES OF PRESSUREMETER TESTS

The pressuremeter is a long cylindrical device placed into a borehole and radially expanded into the surrounding ground. Measurements of the applied pressure and the corresponding expansion of the cavity would be taken during pressuremeter testing so that these may be interpreted into ground properties. Figure 1 (as extracted from BRE, 2003) shows the three main types of pressuremeter testing that are available – (a) the pre-bored pressuremeter which is installed in pre-formed boreholes, (b) the self-boring pressuremeter which is able to form its own hole with minimal disturbance on the ground, and (c) the full displacement pressuremeters which is inserted into the ground without soil removal and the ground is displaced by the passage of the pressuremeter. More details on the various types of pressuremeter test methods and interpretation can be found in Mair and Wood (1987) and Briaud (1992). The tests are usually conducted to procedures described in ASTM D4719 (2000) and BS 5930 (1999).

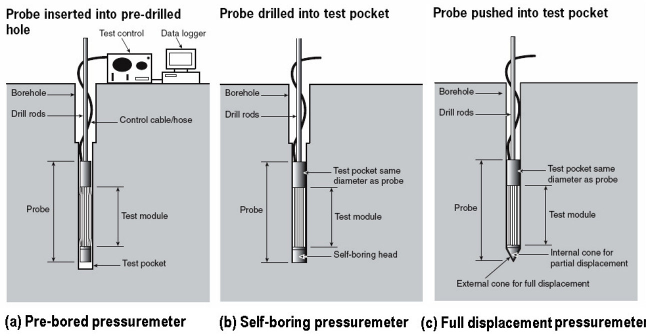

Figure 1 Three main types of pressuremeter testing (after BRE, 2003)

In Singapore, the most commonly used tests are conducted using the pre-bored pressuremeter type, specifically the Menard pressuremeter and the Oyo pressuremeter. These two types of pre-bored pressuremeter tests differ mainly in the measurements and interpretation of the test data. The Menard pressuremeter measures the volumetric expansion of the cavity, whilst the Oyo pressuremeter measures the radial expansion of the cavity by using displacement transducers (LVDTs). However, both types suffer from the same deficiency of pre-bored pressuremeters – that is the significant disturbance to the ground by installation even before conducting the pressuremeter tests. To illustrate, Figure 2 shows an idealized pressuremeter curve obtained using a pre-bored pressuremeter. The initial part of the curve OAB usually shows a high increase in radial strain before the pressure starts to increase. This is due to the pressuremeter tube expanding onto the borehole which was left open before the pressuremeter device is installed. Once this has been achieved, the pressuremeter starts to load the soil along the primary compression curve (BCE), sometimes described as the pseudo-elastic range in literature (Mair and Wood, 1987). However, due to soil relaxation and significant disturbance introduced during the borehole installation stage, the soil response is usually not representative of its in-situ behaviour even after the initial inflation stage – this limitation can be mitigated by minimising soil disturbance in a self-boring pressuremeter. Thus, for pre-bored pressuremeters, estimates on earth pressures at-rest, undrained shear strength and modulus within the initial loading curve have to be treated with great caution and suspicion.

Typically, it is common practice to carry out at least one unload-reload cycle within the pressuremeter test (section CDC in Figure 2) from which the unloading stiffness may be obtained. This is increasingly recommended for two reasons. Firstly, the unloading curves are less sensitive to imperfections in the pressuremeter installation process, and hence the results can be representative of in-situ soil behaviour. Secondly, the unloading curves could give important information about the elastic behaviour of soil, which geotechnical analysis to predict ground deformations is dependent upon. Once the unload-reload cycle has been overcome, the pressuremeter curve continues its path along the primary loading line until the end of the test with a final unloading cycle (section CEF in Figure 2).

Occasionally, self-boring pressuremeter tests are conducted to investigate the behaviour of soft clays. These are better than the pre-bored pressuremeter in that there is minimal disturbance of the in-situ soil and consequently more properties of the soil may be obtained.

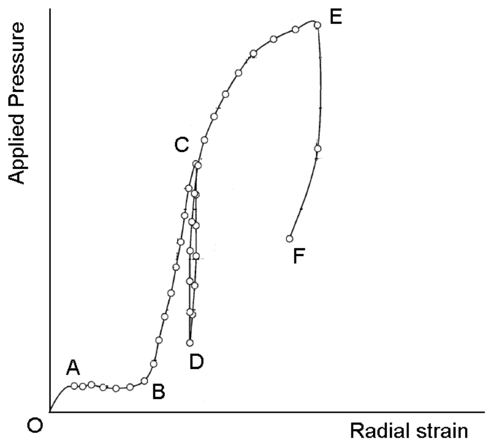

Figure 2 Typical pressure-strain curve for pre-bored pressuremeter

3. OYO-TYPE PRESSUREMETER TESTS

3.1 Interpretation of pressuremeter curve

Due to reasons explained in the earlier section, only the unload-reload portion of pressuremeter curves should be analysed for pre-bored pressuremeters. The slope of the pressuremeter curve gives an indication on the shear modulus of soil during the pressuremeter test. For the Oyo-type pressuremeters where cavity expansion is measured directly using LVDTs, the pressuremeter modulus (E_p) can be calculated as follows:-

$$E_p = (1+\nu)*\Delta p \,/\, (\Delta R/Ro) \qquad (1)$$

where ν is the Poisson's ratio, Δp is the increase in the applied pressure, ΔR is the increase in the cavity radius and Ro is the initial radius of the cavity. The radial strain ΔR/R of the pressuremeter would be equal to half the shear strain in the cavity wall as explained in Mair and Wood (1987).

Furthermore, it should be noted that the pressuremeter test measures shear modulus from the slope of the pressuremeter curve, and that the pressuremeter modulus is actually deduced depending on the drainage conditions to which that value of E_p would be used in design. A Poisson's ratio of 0.3 is usually assumed when reporting the pressuremeter modulus and this would make it comparable to the elastic modulus of the soil under drained condition – even though the pressuremeter is usually considered to be testing the soil undrained. Based on the recommendations in ASTM D4719 (2000), the pressuremeter modulus would be calculated by assuming a best-fit-line for the initial loading curve (line BC in Figure 2) and a best-fit-line for the unload-reload curve (line DC in Figure 2). These would usually be provided in the soil investigation reports and denoted as initial modulus and unloading modulus respectively.

The pressuremeter modulus may be correlated to SPT-N values to derive relationships for design. SPT-N value is a useful parameter for correlations not only because it gives a rough indication on soil stiffness, but also because it is routinely tested for the entire length of all the boreholes in soil investigation works so that the correlations can be used to estimate soil modulus in geotechnical analysis even where there is no pressuremeter test conducted. Figure 3 plots the initial and unloading pressuremeter moduli against the nearest SPT-N value within the same borehole. It should be noted that these SPT-N values were obtained directly from standard penetration tests carried out in accordance to BS 1377-9 (1990), and taking the number of blow counts required to effect a 300mm penetration of a 50mm diameter split spoon sampler driven by a 63.5kg hammer dropped from a free fall height of 760mm. Typically, this nearest SPT-N value would be within 3m depth from the pressuremeter test in the same borehole – this is to ensure that the correlations are made for the same type and same depth of soil as much as possible. Furthermore, all these data points are obtained from a total of 115 pressuremeter tests that were conducted in the residual and completely weathered soils of Bukit Timah Granite (GV and GVI) in 3 different locations in Singapore – Gambas Avenue, Ang Mo Kio Avenue 6 and Thomson Road.

As expected, there is a significant difference between the stiffness of the initial (or primary) loading curve with the stiffness of the unload-reload curve. As seen in Figure 3, the initial modulus are generally lower than the correlation Ep = 1.5N (in MPa) whereas the unloading modulus are much higher. This is due partly to the primary loading behaviour of soils being less stiff than the unload-reload behaviour of soils, but also influenced by the relaxation in the borehole before the pressuremeter test. Furthermore, there is a significant scatter in the plot of unloading modulus versus SPT-N, where the unloading modulus can range between 1.5N to 15N with a mean correlation of Ep=5.2N based on linear regression. With such a large scatter in the pressuremeter test results, it can be quite a challenge to identify a suitable soil modulus for analysis and design.

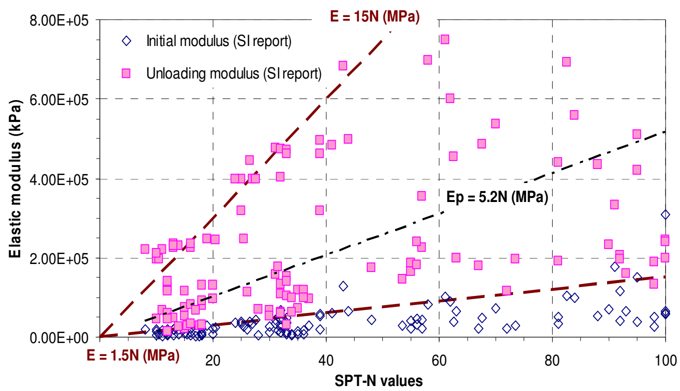

Figure 3 Relationship of pressuremeter modulus to SPT-N value by fitting linear slopes to pressuremeter curves

3.2 An alternative approach to interpret pressuremeter modulus

Instead of assuming a linear function to work out a single unloading stiffness, an alternative method of interpreting the unload-reload portion of the pressuremeter would be to examine the elastic secant modulus in relation to the corresponding strains. Figure 4 shows the unload-reload portion of a typical pressuremeter test, where the nonlinear behaviour of soil can be clearly seen from the pressuremeter curve. The conventional approach of assuming a slope cutting through the unload-reload loop and calculating the pressuremeter modulus as a single value is flawed as the secant modulus can be clearly observed to decrease when the cavity strain increases. An alternative method of analysis would be to estimate the pressuremeter modulus of the reload cycle for various cavity strains, with the lowest recorded value of stress and strain becoming the origin for subsequent data points until the original loading path is rejoined. The slope decreases and this indicates a reduction in the pressuremeter modulus as the cavity strain increases.

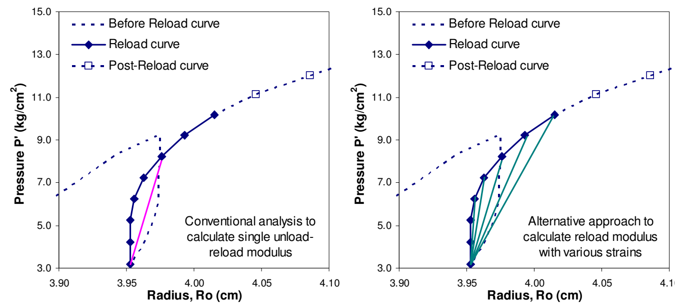

Figure 4 Non-linear behaviour of soil from unload-reload cycle of pressuremeter test

Figure 5 shows the secant modulus of a particular pressuremeter curve (E_p) plotted against its corresponding radial strains (ΔR/Ro). When the radial strain is increased from 0.2% to 1% within the reloading curve, the elastic modulus dropped from 208 MPa to 77 MPa. This is consistently observed when the same 115 Oyo-type pressuremeter curves reported earlier, were analysed using the same methodology. Figure 6 shows the compilation of all the analysed data, where the rapid degradation of pressuremeter stiffness with radial strains may be observed. It is possible to fit in an empirical power correlation between the pressuremeter modulus to radial strains, i.e.

$$E_p / N = A*(\Delta R/Ro)^B \qquad (2)$$

where A and B are empirical constants, N is the SPT-N blowcount value,ΔR/Ro is the radial strain of the cavity and pressuremeter unload modulus E_p is in MPa. Although the data is rather scattered from the suggested design correlation, such expressions can still be used for preliminary stages in the geotechnical design for local soils.

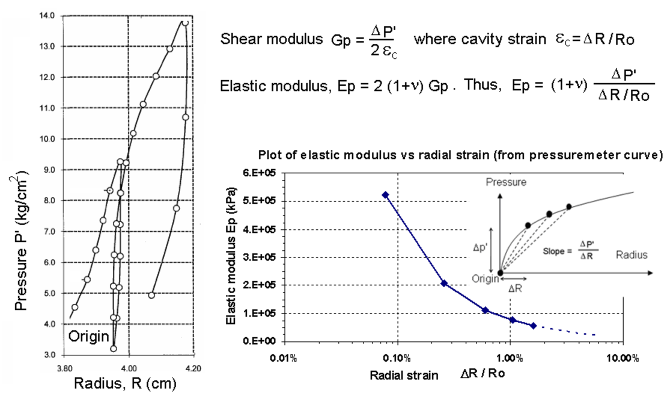

Figure 5 Strain dependent behaviour of pressuremeter modulus

One limitation of using pressuremeters to estimate the small strain stiffness of soil is the accuracy in measuring radial displacements. For an Oyo-type pressuremeter, the accuracy of displacement detection using the LVDT is 0.001 cm. For an initial radius of say 3.8 cm, the error in estimating the strains would be in the range of 0.05% strain. As a result, there is a high scatter in the pressuremeter modulus for the low strain (0.1%) cases. However at arger strains (say 0.5% and 1%), the scatter in the pressuremeter modulus is attributed to non-homogeneous sampling and on the use of SPT-N correlations as an indirect measure of soil stiffness.

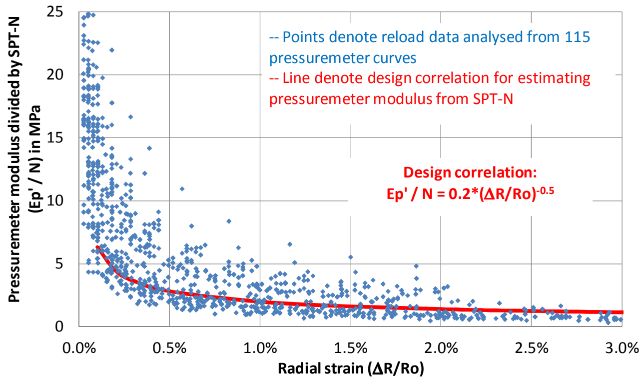

Figure 6 Variation of pressuremeter modulus with radial strains

Figure 7 presents another plot to compare the relationships between pressuremeter modulus and SPT-N value for the conventional analysis and for the alternative approach corresponding to 0.1%, 0.5% and 1.0% radial strains. It can be seen that the scatter was reduced considerably for 0.5% and 1.0% radial strains.

3.3 Implication on geotechnical analysis

Conventional geotechnical analyses use the linear elastic and perfectly plastic, Mohr-Coulomb model for numerical modelling. Although more advanced soil constitutive models have been developed to address some of the non-linearity, there are not many back-analyses of actual excavations in Singapore using such advanced constitutive models and this results in a lack of confidence on the appropriate soil parameters to use. On the other hand, the immense experiences accumulated from the use of linear-elastic models provide confidence on the soil parameters assumed, and facilitate communication between the designer, the checker and the approving authorities. Linear-elastic model is still the most commonly used constitutive model in geotechnical analysis.

For linear elastic models, an important decision to be made in deformation prediction is the selection of an appropriate modulus. Actual soil stiffness will change with strains, and soil modulus decreases with increasing strain even within the elastic range. Specifically, Mair (1993) had highlighted that the ranges of soil strains encountered in typical geotechnical works would occur over the range where there is the greatest variation of soil stiffness with strain. For a linear elastic model, it could be quite erroneous (and/or onerous) if the analysis is based on a stiffness parameter that is not corresponding to the anticipated strains in the geotechnical works.

Linear elastic models can be used by selecting a stiffness parameter corresponding to the anticipated soil strains, rather than the conventional approach of selecting a single stiffness. For example, if the desired outcome is to limit the shear strains in the ground to less than 0.5%, then the elastic stiffness used for the geotechnical model should correspond to modulus at 0.5% shear strains. Or if the results of the analysis shows that the strain level in the soil had reached 1%, then the stiffness used for the soil model should be capped at the stiffness corresponding to 1% strain. A more relevant representation of soil stiffness will purportedly lead to better predictions of deformations.

To provide guidance on the variation of soil stiffness with strains, Goh et al. (2011) reported an earlier study of analysing the Oyo-type pressuremeter curves on other types of soils in Singapore, including 136 tests in the Old Alluvium and 40 tests in soils of the Jurong Formation. Table 1 summarises their recommendations on the variation of pressuremeter modulus for major types of soils in Singapore.

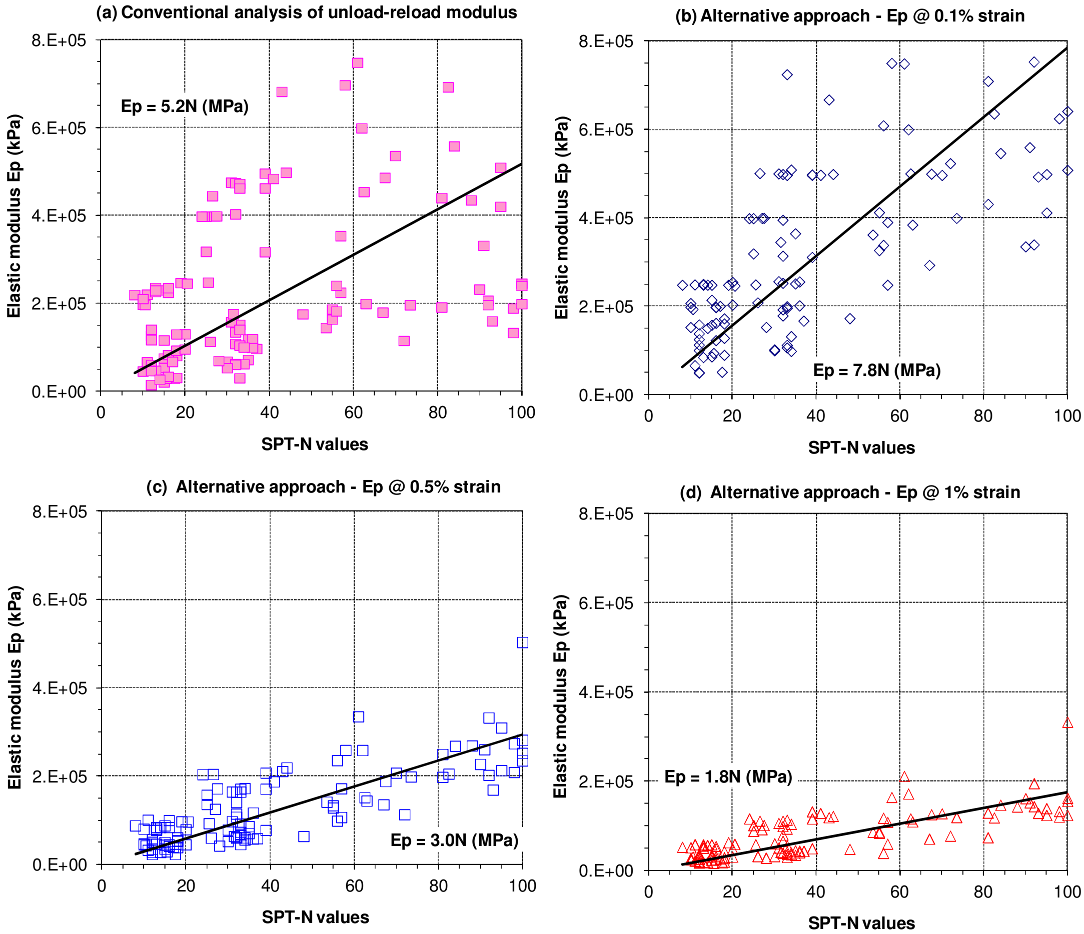

Figure 7 Pressuremeter modulus of reload curves at various radial strains

Table 1 Pressuremeter modulus for different types of soils in Singapore

	Elastic modulus interpreted from reload portion of pressuremeter curve		
	Reload modulus at 1% radial strain	Reload modulus at 0.5% radial strain	Reload modulus at 0.1% radial strain
	Pressuremeter moduli correlated to SPT-N (in MPa)		
Soils of Bukit Timah granite (GV, GVI)	1.8*N	3.0*N	7.8*N
Old Alluvium of various grades of weathering	2.5*N	3.7*N	9.6*N
Soils of Jurong Formation (SV, SVI)	1.6*N	2.8*N	8.4*N

Furthermore, it should be noted that pressuremeter tests were performed in the horizontal direction and the elastic modulus was derived assuming that soil behaves as an isotropic material. In reality, soils are not isotropic and any deformation modulus derived from a pressuremeter test (be it shear modulus or elastic modulus) is strictly a pressuremeter modulus. In heavily over-consolidated clays and weak rocks, allowance should be made for the pressuremeter modulus measured in the horizontal direction being greater than the deformation modulus relevant to the vertical loading.

4. MENARD-TYPE PRESSUREMETER TESTS

4.1 Interpretation of pressuremeter curve

The interpretation of pressuremeter modulus for Menard type pressuremeters is slightly different from that of Oyo type pressuremeters, due to the cavity expansion being measured by volume rather than radial displacements. Shear strain at cavity wall could then be calculated by $\Delta V/(Vo+Vm)$ where ΔV is the volumetric increment during pressuremeter testing and $Vo+Vm$ is the initial volume of the probe. The Menard pressuremeter modulus (E_{pm}) can thus be calculated as follows:-

$$E_{pm} = 2(1+\nu)*\Delta p / [\Delta V/(Vo+Vm)] \quad (3)$$

The pressuremeter curve is constructed by plotting the measured volume with its corresponding pressure measurements which are both calibrated for volume loss and pressure loss. Figure 8 shows an example of a pressuremeter curve obtained from a Menard-type pressuremeter test in Singapore, where two unload-reload cycles were conducted within the pseudo-elastic range (or primary loading curve). The pseudo-elastic range can be defined by monitoring the creeping behaviour of volumetric measurements at various time intervals up to 60 sec or 120 sec. This is translated into a “creep curve” which measures the volume increment through the time increments, and as shown in the figure. At the beginning of the test, the volume would increase when the pressure is held steady at a constant value – this is due to the pressuremeter membrane embedding itself into the disturbed cavity. The pseudo-elastic range of the curve begins when the volume remains constant at subsequent pressure increments and the creep curve drops to zero volume increment. The end of the pseudo-elastic range of the curve occurs when the volume starts to increase with pressure increment being held constant for 60 sec (or 120 sec) and the creep curve rises.

From Figure 8, it can be observed that there was a difference in the slopes of the two reload-curves. When the unload-reload cycle was conducted near the start of the pseudo-elastic range, the reload modulus (~139 MPa) was observed to be lower than the reload modulus (~197 MPa) from a unload-reload curve conducted near the end of the pseudo-elastic range. While the 2nd reload curve resembles the elastic behaviour for soil during an unload-reload loop, the 1st unload-reload curve seemed to be tracing back the primary loading curve.

There is no guidance on when to conduct the unload-reload cycle in ASTM D4719 (2000), so long as it is within the pseudo-elastic range. From Figure 8, the reload modulus could be sensitive to the location of the unload-reload cycle within the pseudo-elastic range of the pressuremeter curve. To understand this further, pressuremeter tests were conducted with the unload-reload cycles conducted just before and just after the pseudo-elastic range as shown in Figure 9. It was found that the slope of the 1st unload-reload cycle conducted just before the end of pseudo-elastic range was similar as that for the 2nd unload-reload cycle conducted just after the pseudo-elastic range.

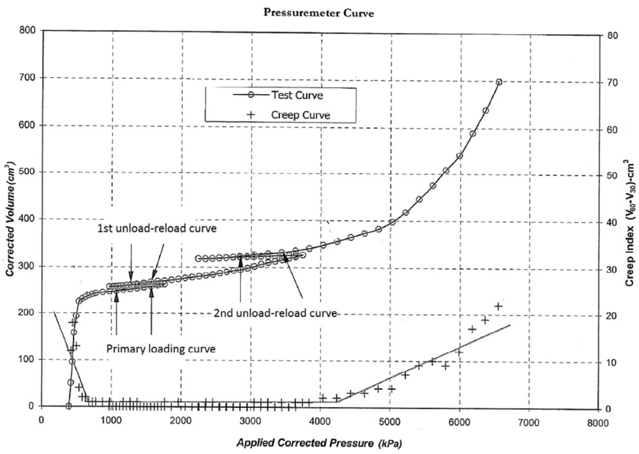

Figure 8 Menard pressuremeter curve with unload-reload cycles at the start and at the end of the pseudo-elastic range

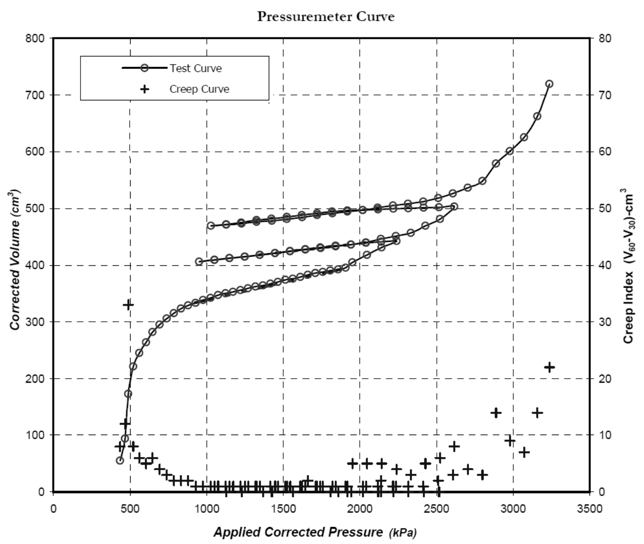

Figure 9 Menard pressuremeter curve with both unload-reload cycles near the end of the pseudo-elastic range

This is similar as the elasto-plastic behaviour of soil under compressive loading. Initially when soil is loaded, its behaviour is elastic – meaning that unloading and reloading will allow the soil to trace back the original loading path. When it is loaded further into the plastic range, any unloading will result in some irrecoverable deformation. The unload-reload path will be different from the primary loading path, but any subsequent unloading-reloading within the elastic range will follow similar path and this characteristic is usually described by an elastic modulus.

To investigate the difference between carrying out the unload-reload modulus near the start of the pseudo-elastic range compared to near the end of the pseudo-elastic range, two sets of Menard pressuremeter tests were conducted – first set of eight tests involved carrying out one unload-reload cycle at the start of the pseudo-elastic range and another unload-reload cycle near the end of the pseudo-elastic range within the same pressuremeter test (as illustrated in Figure 8), and second set of nine tests involved carrying out two unload-reload cycles within the same pressuremeter test near the end of the pseudo-elastic range (as illustrated in Figure 9). Figure 10 plots the 1st reload modulus against the 2nd reload modulus from these two sets of pressuremeter tests.

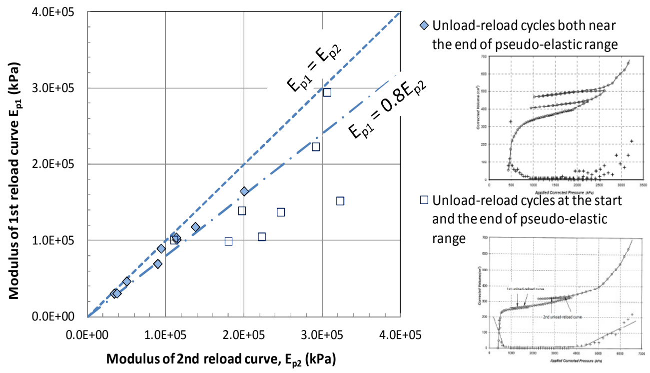

Figure 10 Menard pressuremeter modulus with both unload-reload cycles near the end of the pseudo-elastic range

As seen in Figure 10, when the first unload-reload cycle is carried out at the start of the pseudo-elastic range, the 1st reload modulus (E_{p1}) was found to be consistently much lower than the 2nd reload modulus (E_{p2}). This is due to the 1st unload-reload cycle being influenced by the primary loading behaviour rather than the true reload behaviour that is captured by the 2nd unload-reload cycle. On the other hand, when the two unload-reload cycles are carried out just before and just after the pseudo-elastic range, the 1st reload modulus (E_{p1}) was found to be similar and within 20% difference from the 2nd reload modulus (E_{p2}). This suggests that the reload modulus is affected by where the unload-reload cycle is carried out and the unload-reload cycle should be carried out well-within the elasto-plastic range of the soil after the pressuremeter has overcome the initial relaxation of the pre-bored cavity.

For pre-bored type pressuremeters, the primary loading curve would not provide meaningful information about the soil due to the significant disturbance during borehole installation. Therefore, the pressuremeter modulus from an unload-reload cycle that traces the primary loading curve would not be useful. On the other hand, the pressuremeter modulus from an unload-reload cycle that is well into the pseudo-elastic zone of the pressuremeter curve could reflect the elastic unload-reload behaviour of the in-situ soil. It is therefore important to distinguish the unload-reload modulus based on the location of the unload-reload cycle.

However, most of the pressuremeter tests were usually done with one unload-reload cycle with no other basis for comparison. Operators of Oyo-type pressuremeters in Singapore tend to conduct the unloading cycle near to the end of the pseudo-elastic range whereas operators of Menard-type pressuremeters in Singapore tend to conduct the unloading cycle near to the start of the pseudo-elastic range. However, the examples in Figure 8 and Figure 9 (and observations of other similar type of pressuremeter tests) do suggest that the reload modulus is sensitive to the location of the unload-reload cycle. This could have contributed to a common observation in Singapore that the unload-reload modulus from Oyo-pressuremeters is higher than those from Menard-pressuremeters.

4.2 Reload modulus using Menard-type pressuremeters

With these in mind, the modulus of Menard type pressuremeter curves which had unload-reload cycles well within the primary loading curve, were analysed using the same approach to correlate with the corresponding strains. These were normalised using the appropriate SPT-N value, and plotted against the cavity strains (which is twice the volumetric strain) as shown in Figure 11.

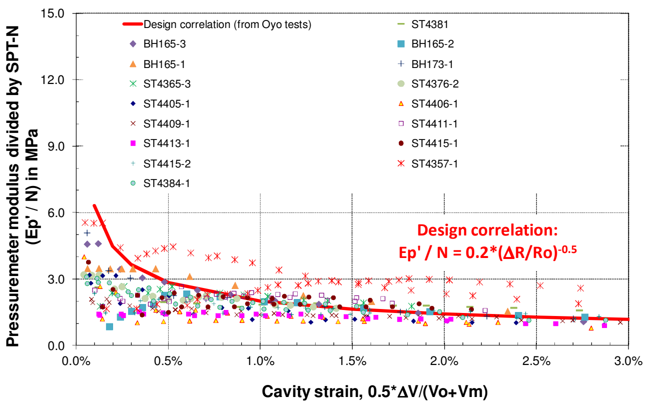

Figure 11 Variation of Menard pressuremeter modulus with cavity strains

These Menard pressuremeter tests (16 nos. in total) were also conducted in the residual and completely weathered soils of the Bukit Timah Formation, in order to compare with the earlier analysis from the Oyo pressuremeters. From Figure 11, it can be observed that the degradation of Menard pressuremeter modulus with strain follows the design correlation obtained using Oyo pressuremeter tests, except for cavity strains lower than 0.5%. The lower Menard pressuremeter modulus could be due to losses as the Menard pressuremeter reloads itself back onto the cavity due to indirect measurement of cavity expansion using volume. Otherwise for cavity strains higher than 0.5%, the Menard pressuremeter results are consistent with those tested using Oyo-type pressuremeters.

4.3 Limitations of using pressuremeter testing on rocks

Attempts were also made to determine the modulus of stiff soils and rocks using the Menard pressuremeter. Figure 12 shows a typical example of pressuremeter curve from a test conducted on the rock of the Bukit Timah granite (slightly weathered grade of granite, GII). The two unload-reload cycles were conducted within the primary loading curve and both curves trace the primary loading behaviour closely. It is observed that after the pressuremeter membrane had embedded itself onto the cavity, the creep curve extended throughout and until the end of the test. These imply that the rock was still not loaded beyond the relaxation induced due to borehole installation, and that the unload-reload cycles would be at best a representation of the primary loading behaviour of the disturbed rock borehole. As a matter of fact, the reload modulus worked out to be between 307 MPa and 620 MPa, which is only a small proportion of the expected modulus of rock. For example, through laboratory testing on more than 600 samples of granitic rock, Zhou (2001) summed up the Young's modulus of intact granite as ranging from 49.3 GPa to 111.3 GPa. Although laboratory testing would be more relevant as an estimate on the intact strength of rock and should result in higher modulus as opposed to insitu testing that estimates the mass properties of the rock, Zhou's estimate of rock modulus is at least 50 times greater than the rock modulus observed from the pressuremeter tests.

It is believed that such a large difference is attributed more to borehole relaxation during pressuremeter testing rather than the mass properties of rock. This phenomenon was also observed consistently for both Oyo and Menard pressuremeter tests on all other weathering grades of granite rock (GI, GII, GIII), and it highlights the limitation of using pressuremeter tests to determine the modulus of rock in-situ.

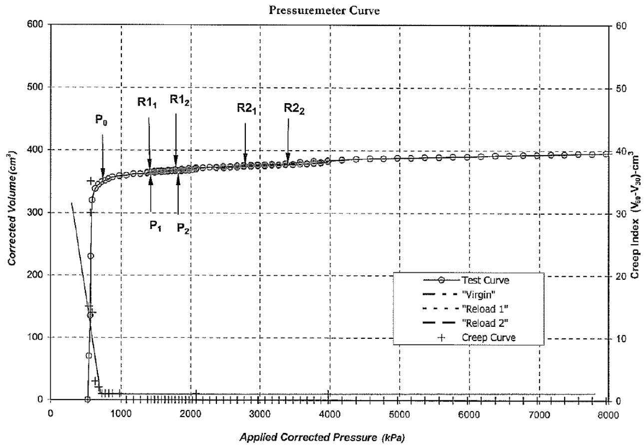

Figure 12 Typical pressuremeter curve for a rock in Bukit Timah Granite

5. SELF-BORING PRESSUREMETER TESTS

For very soft clays such as the Singapore marine clay, self-boring pressuremeter tests were conducted occasionally to estimate the modulus of the soil in-situ. Figure 13 shows an example of the pressuremeter curve conducted by Cambridge Insitu on the Singapore marine clay, which has two unload-reload loops within the primary loading curve. The self-boring pressuremeter by Cambridge Insitu uses a specially developed and self-boring technique which results in the instrument entering the ground with minimum disturbance to the insitu condition of the soil. As a result, more reliable information about the insitu characteristics of the soil (including undrained shear strength, at-rest earth pressure, shear modulus, etc.) can be obtained from the self-boring pressuremeter as compared to pressuremeter tests carried out in a prebored hole.

However, this paper is focusing only on the stiffness property of soil investigated using pressuremeters. As with prebored pressuremeters, the reload shear modulus of the soil (G) may be deduced from the unload-reload slope of the pressuremeter curve. Figure 14 illustrates the variation of shear modulus with shear strains obtained from two particular self-boring pressuremeter tests in Singapore marine clay, but taken at various depths. The shear modulus ranged from 1 MPa to 5.3 MPa at 1% shear strain (or 0.5% radial strain), with the higher modulus obtained at greater depths. This falls in the range of soil stiffness typically assumed in geotechnical analysis for Singapore marine clay locally, i.e. undrained elastic modulus at 20m depth, Eu = 300*Cu = 300*0.25*20*6 = 9000 kPa suggests that shear modulus would be about 3 MPa (since Eu = 3*G). At lower shear strains, there is a steady increase in the shear modulus back-analysed from the pressuremeter curve, and this increased to 7.3 MPa maximum at 0.5% shear strain and to 15.3 MPa maximum at 0.1% shear strain.

It would be possible to conduct more studies on the in-situ stiffness of the marine clay using pressuremeters, but this may require much more samples of self-boring pressuremeter tests in order for the study to be truly conclusive. Potentially, this would result in the characterisation of the complete strain-stiffness degradation function and curve to describe the small strain behaviour of soil and this can be used as input parameters to the more advanced constitutive models in geotechnical analysis.

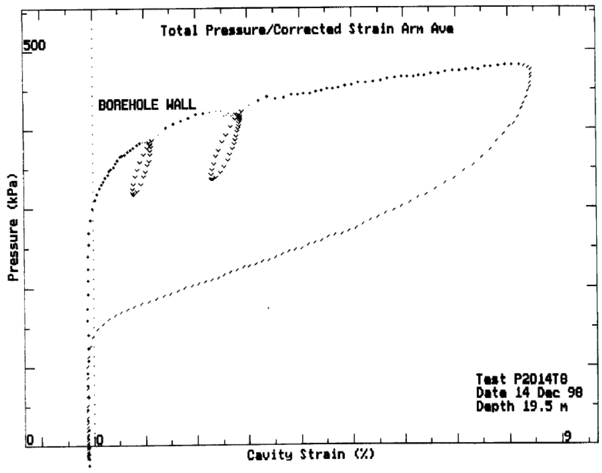

Figure 13 Self-boring pressuremeter curve for marine clay

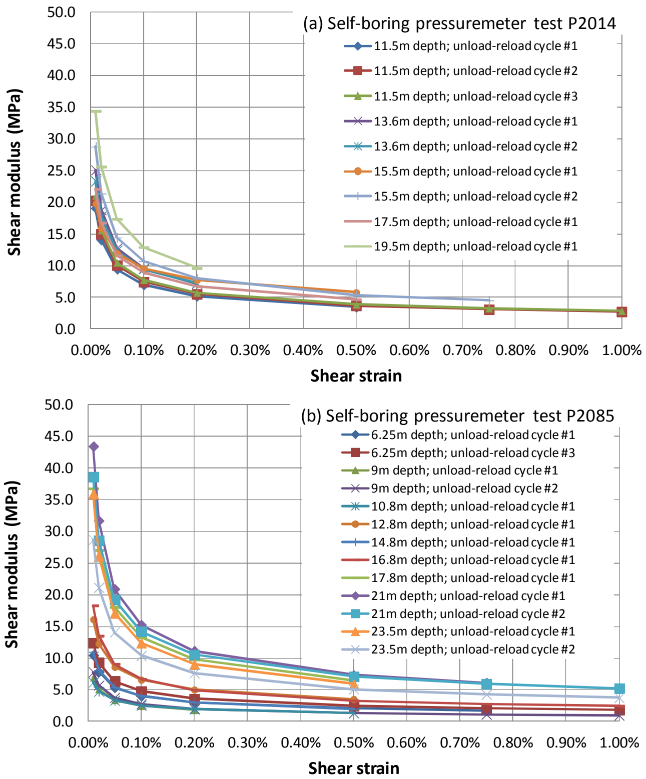

Figure 14 Variation of reload shear modulus with shear strain from self-boring pressuremeter tests P2014 and P2085 in Singapore marine clay

6. CONCLUSION

The practical experience of using various types of pressuremeters to understand the stiffness of soils in Singapore has been presented in this paper. The first part of the paper proposes an alternative way to interpret the pressuremeter modulus in relation to the corresponding cavity strains, and finds that the pressuremeter modulus can be reasonably well-correlated to the SPT-N value using this new interpretation method.

Consequently, it is possible to recommend empirical relationships for the various types of soils in Singapore so that designers can use elastic stiffness corresponding to various anticipated strain levels in their geotechnical models. Although the data from which the SPT-PMT correlations are derived has a very large scatter, the expressions from the best fit profiles can be used for preliminary stages in the geotechnical design for local soils.

The paper then discussed about the influence of location of the unload-reload cycle on the pressuremeter modulus. When the unload-reload cycle is conducted prior to the pressuremeter having loaded the soil into the pseudo-elastic range, the unload-reload curve re-traces the primary loading curve of the pressuremeter, and results in a reload modulus that is more reflective of the disturbed nature of the soil than its actual elastic modulus. This is similarly observed of pressuremeter tests conducted in rocks, where the rock was still not loaded beyond the relaxation induced due to borehole installation and the unload-reload modulus would be only a fraction of the actual rock modulus.

However when the unload-reload cycle is conducted well into the pseudo-elastic range of the pressuremeter curve, it was found that the Oyo-type and the Menard-type pressuremeters give consistent results for cavity strains that are greater than 0.5%. It is recommended that unload-reload cycles of pre-bored pressuremeters should be conducted well into the pseudo-elastic range, and not just at the onset of the pseudo-elastic curve as was the previous practice for operators of Menard-type pressuremeters.

Some results of self-boring pressuremeters conducted in Singapore Marine Clay were also presented. However, due to the few numbers of self-boring pressuremeters conducted, it is not possible to derive conclusive correlations on the stiffness of marine clay. Nevertheless, it may be seen that self-boring pressuremeters causes minimal disturbance during installation and can give insightful information on the stiffness of in-situ soil.

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