

# IN SITU DISSIPATION TESTING OF SOFT SOIL UNDER RECLAMATION FILLS

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## ABSTRACT

*In situ* dissipation tests provide a means of evaluating the *in situ* coefficient of consolidation and hydraulic conductivity of soft clays due to horizontal flow. Dissipation tests using piezocone (CPTU), dilatometer (DMT), self-boring pressuremeter (SBPT) and BAT permeameter (BAT) were utilized in the characterization of the coefficient of horizontal consolidation and horizontal hydraulic conductivity of Singapore marine clay at Changi in a land reclamation project. Dissipation tests were carried out to compare the changes in the coefficient of consolidation and hydraulic conductivity due to horizontal flow prior to reclamation and after ground improvement. Tests were carried out in a Vertical Drain Area as well as in an adjacent untreated Control Area, 23 months after preloading for comparison purposes. The purpose of this research is to determine the consolidation parameters of soft soil before reclamation and after 23 months following preloading with and without vertical drains by means of *in situ* dissipation tests. This should indicate the change in these consolidation parameters associated with void ratio changes caused by the consolidation process under the same magnitude of load at different degrees of consolidation.

## 1 INTRODUCTION

The future expansion of Changi International Airport in Singapore, involves land reclamation next to the existing airport. The offshore land reclamation is being carried out by the hydraulic filling of sand which is followed by the installation of vertical drains and subsequently surcharge placement as a preload. As vertical drains are used to accelerate the consolidation of the marine clays, the permeability and consolidation properties of the soil particularly in the horizontal flow are important design parameters. The determination of these design parameters is traditionally based on the multiplier of coefficients of consolidation due to vertical flow,  $c_v$  value obtained from the laboratory conventional consolidation tests. Results of these laboratory tests however are usually subject to uncertainties primarily due to inevitable sample disturbances and uncertain multiplier values. Laboratory testing also does not yield appropriate properties of soil due to different loading and drainage conditions as compared to the actual *in situ* condition.

*In situ* dissipation tests are an alternative to traditional laboratory testing methods and furthermore the effect of disturbance to marine clays is minimal. These dissipation tests can be conducted at various levels in the marine clay and hence variations of the coefficient of consolidation and hydraulic conductivity due to horizontal flow with depth can be studied. The last two decades have seen an emergence of *in situ* testing methods as an alternative to laboratory testing methods. The *in situ* dissipation test has emerged as a useful method to obtain the required consolidation due to horizontal flow and permeability parameters for the design of vertical drain projects.

Several types of *in situ* dissipation tests were adopted for the investigation of the Singapore marine Clay at Changi. The dissipation tests were carried out with piezocone (CPTU), dilatometer (DMT), self-boring pressuremeter (SBPT) and BAT permeameter (BAT) at an *In Situ* Test Site. The tests were carried out prior to reclamation and 23 months after preloading. Tests were carried out in an area treated with vertical drains known as the "Vertical Drain Area" as well as in an adjacent untreated "Control Area". The tests were carried out to compare the change in consolidation and hydraulic conductivity parameters at different degree of consolidation stages under the same magnitude of load.

The objective of this paper is to investigate the comparison of *in situ* dissipation tests prior to and after surcharge loading as well as between the various test methods. Dissipation tests carried out prior to land reclamation in the same reclamation project have been reported previously by Arulrajah *et al.* (2004), Chu *et al.* (2002) and Bo *et al.* (2003). However, analysis and comparisons of the dissipation test results prior to and after ground improvement with and without vertical drains have only been carried out very briefly. The in-depth evaluation of this particular research of dissipation tests should make these tests methods valuable for regional application particularly for ground improvement projects in marine clays.

## 2 SITE DESCRIPTION

The site for this research is located in the Changi East Reclamation site in the Republic of Singapore. The area is submerged underwater with seabed elevation varying from 2 metres below Admiralty Chart Datum ( $-2$  mCD) to 8 metre below Admiralty Chart Datum ( $-8$  mCD). The northern part of the project area is underlain by marine clay up to 40 metres thickness in certain areas and it is this portion of the project area that is relevant to this research. Arulrajah *et al.* (2006) and Bo *et al.* (2000, 2003) have previously described the location of the project site and the *In Situ* Test Site. Field tests carried out prior to reclamation were denoted as FT-2. Field tests carried out in the Vertical Drain Area after improvement and 23 months of preloading, were denoted as FT-8. Tests carried out in the untreated Control Area after 23 months of preloading were denoted as FT-9. A pre-reclamation borehole and various *in situ* tests were carried out prior to the commencement of land reclamation works to characterize the marine clay properties.

The *In Situ* Test Site is located in an area where the thickest compressible layers existed and a portion of where the future airport runway would be located. The original seabed level in the *In Situ* Test Site was 3.29 metres below Admiralty Chart Datum ( $-3.29$  mCD). The *In Situ* Testing Site comprises of two distinct layers of marine clay, which are the "Upper Marine Clay layer" and the "Lower Marine Clay layer". The "Intermediate Stiff Clay layer" separates these two distinct marine clay layers. A pre-reclamation borehole and various *in situ* tests were carried out prior to the commencement of land reclamation works to characterize the marine clay properties. Following the completion of the pre-reclamation *in situ* tests, land reclamation was carried out by hydraulic placement of sand to the platform level of 4 metres above Admiralty Chart Datum ( $+4$  mCD) which is suitable for vertical drain installation. Vertical drains were next installed at this elevation at 1.5 metre square spacing, to depths of up to 35 metres in the Vertical Drain Area. Surcharge was next placed to the design elevation of 10 metres above Admiralty Chart Datum ( $+10$  mCD) for both areas. Another series of *in situ* tests for comparison purposes were carried out after a preloading period of about 23 months in the Vertical Drain Area and adjacent untreated Control Area.

Singapore marine clay at Changi is a Quaternary deposit that lies within valleys cut in the Old Alluvium. It is locally known as Kallang formation. Figure 1 indicates the soil profile of the *In Situ* Test Site prior to reclamation. Details on the characteristics of Singapore marine clay at Changi have been discussed by Bo *et al.* (2003) and Bo & Choa (2004).

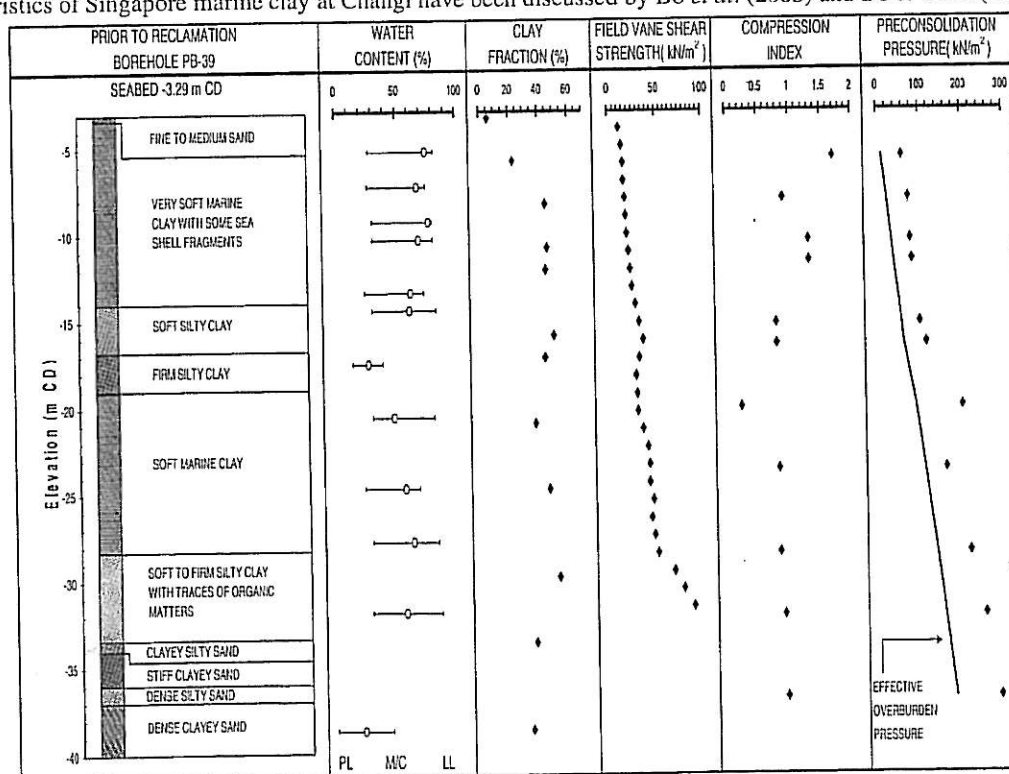


Figure 1: Typical soil profile and engineering parameters at *In Situ* Testing Site prior to reclamation (Arulrajah *et al.*, 2004).

### 3 IN SITU DISSIPATION TEST METHODS AND INTERPRETATION

The  $c_h$  values of natural soils can be affected considerably by the stratification or the fabric of the soils which are too costly to be characterized by laboratory tests. As an alternative, *in situ* dissipation tests using the CPTU, DMT, SBPT and BAT permeameter were carried out to determine the coefficient of consolidation and hydraulic conductivity due to horizontal flow of the marine clay prior to reclamation and after ground improvement. Coefficients of consolidation due to horizontal flow,  $c_h$  can be determined from the CPTU, DMT and SBPT. Hydraulic conductivity due to horizontal flow,  $k_h$  can be obtained directly from the BAT permeameter tests and indirectly from the  $c_h$  results of the other *in situ* tests. Arulrajah (2005) and Bo *et al.* (2000, 2003) have described the geometry and method of analysis of the *in situ* dissipation test equipment used for the testing of Singapore marine clay at Changi.

#### 3.1 PIEZOCONE DISSIPATION TEST (CPTU)

The coefficient of consolidation due to horizontal flow was worked out by applying the Baligh and Levadoux (1980, 1986) method. In order to obtain the hydraulic conductivity in the normally consolidated condition, a correction taking the recompression ratio into account was applied (Bo *et al.*, 1998).

#### 3.2 FLAT DILATOMETER DISSIPATION TEST (DMT)

The  $c_h$  of the soil can be estimated from a DMT dissipation test using either the A reading (DMTA) or the C reading (DMTC) proposed by Marchetti & Totani (1989) and Schmertmann (1988) respectively.

#### 3.3 SELF-BORING PRESSUREMETER DISSIPATION TEST (SBPT)

The Cambridge-type self-boring pressuremeter (Windle & Wroth, 1997) with 6 strain measuring arms located at the mid-level was used for the testing purposes. The testing procedure followed that described by Bo *et al.* (2003).

#### 3.4 BAT PERMEAMETER (BAT)

The BAT permeameter developed by Torstensson (1983) and Torstensson & Petsonk (1986) was used in this research for the *in situ* testing of horizontal hydraulic conductivity. The BAT permeameter results are used as the baseline data for hydraulic conductivity due to horizontal flow since the system measures hydraulic conductivity due to horizontal flow directly compared to other *in situ* testing methods in which the  $k_h$  values are indirectly evaluated from  $c_h$  values.

### 4 PRE-RECLAMATION IN SITU DISSIPATION TESTS

$c_h$  values as obtained from the various *in situ* tests prior to reclamation at the *In Situ* Test Site have been discussed previously by Arulrajah (2005). All the *in situ* tests indicate large  $c_h$  values in the intermediate stiff clay layer. Among the *in situ* tests the  $c_h$  values in the marine clay layers from SBPT are the highest overall while that from the CPTU test indicate the least variations with depth. The DMT result seems high up to depths of 20 metres and this could be due to the variation in the profile of the intermediate layer in the lower depths. However, the DMT results are reasonable in the lower marine clay layer. It is observed that all the methods indicate large  $c_h$  values in the intermediate stiff clay layer. It can be said that the *in situ* tests results vary from one test method to another and the results are relatively higher overall when compared with the laboratory testing results.

The pre-reclamation CPTU dissipation test indicate that the  $c_h$  values of the upper and lower marine clay varies between 2 to 6 m<sup>2</sup>/yr.  $c_h$  values of 4 to 7 m<sup>2</sup>/yr were obtained in the intermediate stiff clay, separating the upper and lower marine clay layers. The CPTU results are found to be the closest to the laboratory testing results. The  $c_h$  values for the laboratory tests were obtained from radial flow Rowe cell of 75 mm diameter and 30 mm thickness and also from horizontally cut 63.5 mm oedometer test samples.

The  $k_h$  values as obtained from the various *in situ* dissipation tests have been discussed previously by Arulrajah *et al.* (2004). Based on the results obtained, the BAT was found to give the lowest values whereas the dilatometer and CPTU gave the highest values. The same observation has been reported by Bo *et al.* (1998) and Chu *et al.* (2002) in the reclamation site for tests carried out prior to land reclamation. The laboratory results are also close to that of the BAT results.  $k_h$  of *in situ* tests was found to range between 10<sup>-7</sup> to 10<sup>-10</sup> m/s for the marine clay.  $k_h$  prior to reclamation is in the order of 10<sup>-9</sup> to 10<sup>-10</sup> m/s based on the BAT results. Dilatometer and CPTU values range around 10<sup>-8</sup> to 10<sup>-9</sup> m/s while the SBPT are in the 10<sup>-7</sup> to 10<sup>-9</sup> m/s range. The results from the BAT tests can be used as the baseline data since the system measures horizontal hydraulic conductivity directly whereas the other *in situ* tests require the introduction of

additional parameters to interpret  $k_h$  from  $c_h$  values. It can be observed that  $k_h$  values decrease with depth. The *in situ* test results also show high  $k_h$  values in the intermediate desiccated zone.

## 5 POST-IMPROVEMENT IN SITU DISSIPATION TESTS

### 5.1 PIEZOCONE DISSIPATION TEST

The comparison of the  $c_h$  values for the Vertical Drain Area and the Control Area is presented in Figure 2, while Figure 3 shows the  $k_h$ . The  $c_h$  value seems to be higher in the Vertical Drain Area at some elevations as compared to the Control Area. This is due to the greater reduction in the coefficient of volume compressibility,  $m_v$ , after consolidation or it was simply affected by the correction factors used. The post-improvement CPTU results in the upper and lower marine clay layers indicate  $c_h$  varies between 3 and 6 m<sup>2</sup>/yr in the Vertical Drain Area and between 3 and 5 m<sup>2</sup>/yr in the Control Area, after 23 months of surcharge loading. Higher  $c_h$  values are obtained in the intermediate desiccated zone separating the upper and lower marine clay layers which have been ignored in the assessment.

It can be observed that the pre-reclamation,  $k_h$ , values are decreasing with depth. The piezocone test results also show higher  $k_h$  values in the intermediate desiccated zone. It is apparent that the prior to reclamation  $k_h$  is higher than that of the Vertical Drain Area and Control Area 23 months after preloading. This is expected due to reduction in the void ratio after preloading. It is also apparent that the  $k_h$  in the Vertical Drain Area is lower than that in the Control Area which is expected due to greater void ratio changes.  $k_h$  varies between  $10^{-9}$  and  $10^{-10}$  m/s in the Vertical Drain Area and Control Area, 23 months after preloading.

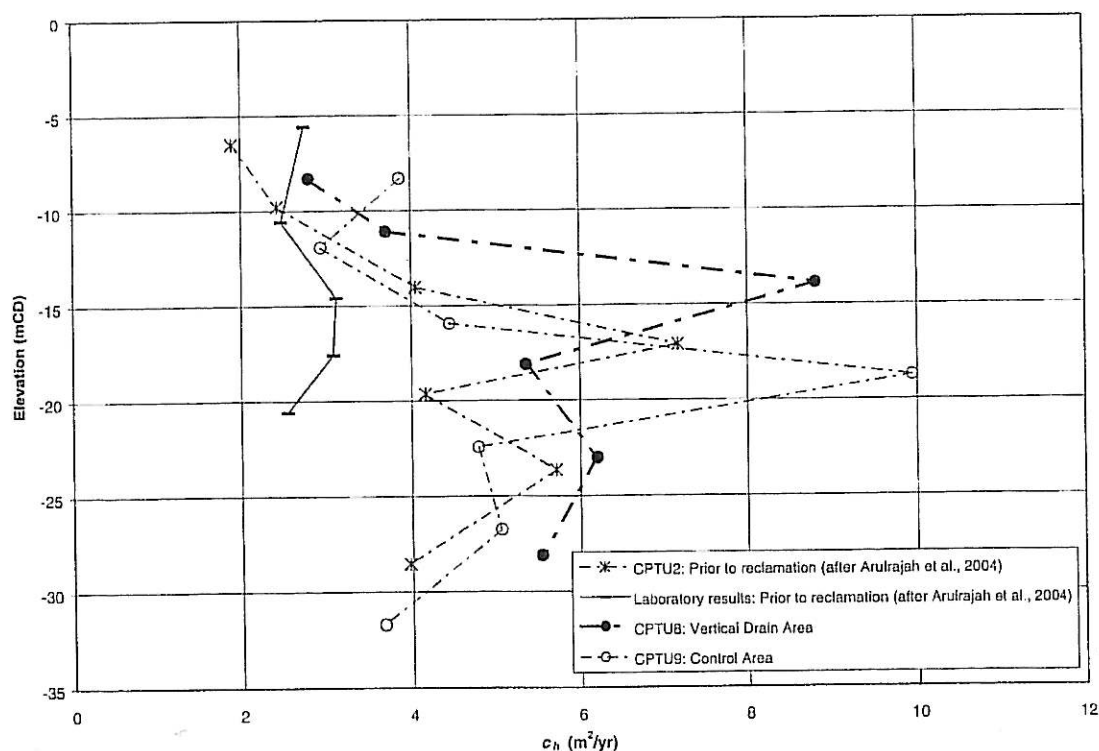


Figure 2: Comparison of coefficient of horizontal consolidation from CPTU dissipation test between Vertical Drain Area and Control Area 23 months after preloading.

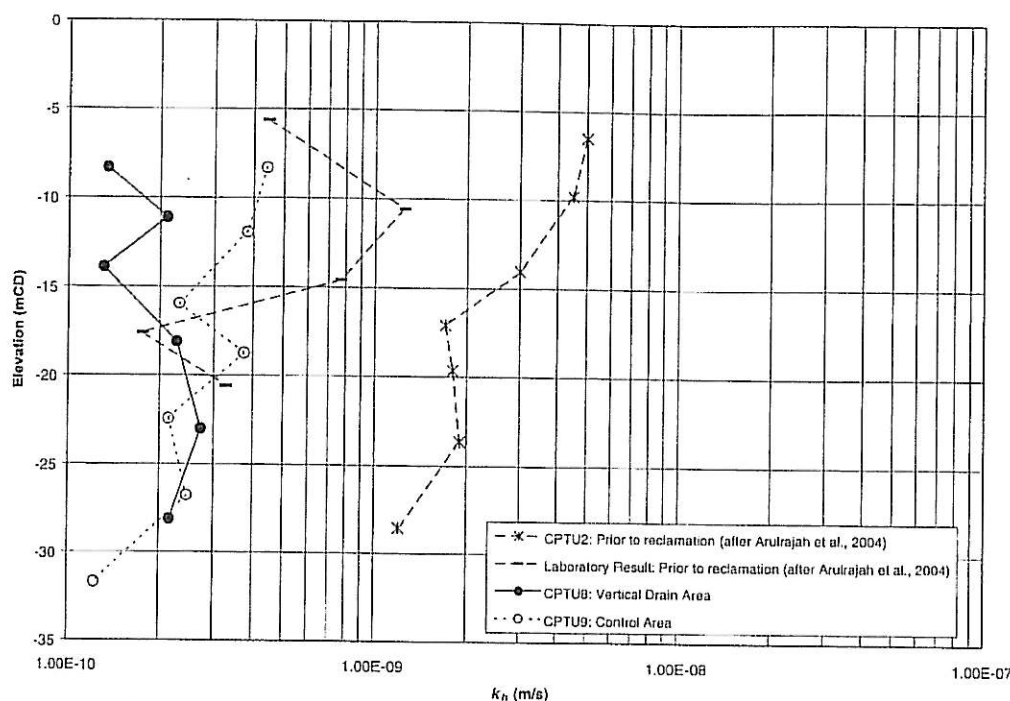


Figure 3: Comparison of horizontal hydraulic conductivity from CPTU dissipation test between Vertical Drain Area and Control Area after 23 months of surcharge loading (Arulrajah, 2005).

## 5.2 FLAT DILATOMETER DISSIPATION TEST

The comparison of the  $c_h$  results for the Vertical Drain Area and the Control Area is presented in Figure 4 while Figure 5 shows that of  $k_h$  results.  $c_h$  value is seen to be generally higher in the Vertical Drain Area as compared to the Control Area. Despite the  $k_h$  being lower in the Vertical Drain Area, the  $c_h$  could be higher due to greater ratio of reduction in the coefficient of volume change,  $m_v$ . It is evident that the prior to reclamation DMT dissipation test (which is a combination of DMTA and DMTC readings) has encountered the intermediate stiff layer strata at the lower elevations and hence the high initial  $c_h$  values. The DMT dissipation tests in the Vertical Drain Area and the Control Area also indicate higher  $c_h$  values in the intermediate stiff layer. Only the DMTA readings method was carried out after ground improvement in both the Vertical Drain Area and the Control Area. The *in situ* results in the upper and lower marine clay layers indicate  $c_h$  values of 4-6 m<sup>2</sup>/yr in the Vertical Drain Area and values of 4-6 m<sup>2</sup>/yr in the Control Area.

The  $k_h$  values in the Vertical Drain Area are found to be lower than that in the Control Area. It is noted however that  $k_h$  values are indirectly obtained from  $c_h$  values.  $k_h$  values ranging from 10<sup>-9</sup> to 10<sup>-10</sup> m/s were obtained in the Vertical Drain Area with vertical drains while values of 10<sup>-9</sup> m/s were obtained in the Control Area.

## 5.3 SELF-BORING PRESSUREMETER DISSIPATION TEST

The comparison of the  $c_h$  results for the Vertical Drain Area and the Control Area are presented in Figure 6 while Figure 7 shows the  $k_h$  results.  $c_h$  value is seen to be higher in the Vertical Drain Area as compared to the Control Area. Despite the  $k_h$  being lower in the Vertical Drain Area, the  $c_h$  could be higher due to greater ratio of reduction in the coefficient of volume compressibility,  $m_v$ . The SBPT dissipation tests in the Vertical Drain Area and Control Area also indicate higher  $c_h$  values in the intermediate stiff layer which is as expected. The *in situ* results in the upper and lower marine clay layers indicate  $c_h$  values of 3-12 m<sup>2</sup>/yr in the Vertical Drain Area with vertical drains and values of 4-7 m<sup>2</sup>/yr in the Control Area. It also seems that  $k_h$  values in the Vertical Drain Area are higher than in the Control Area which should not be the case and could be attributable to the indirect method of computing  $k_h$  from  $c_h$  values.  $k_h$  values ranging from 10<sup>-9</sup> to 10<sup>-10</sup> m/s were obtained in the area with vertical drains while values of 10<sup>-9</sup> to 10<sup>-10</sup> m/s were obtained in the Control Area.



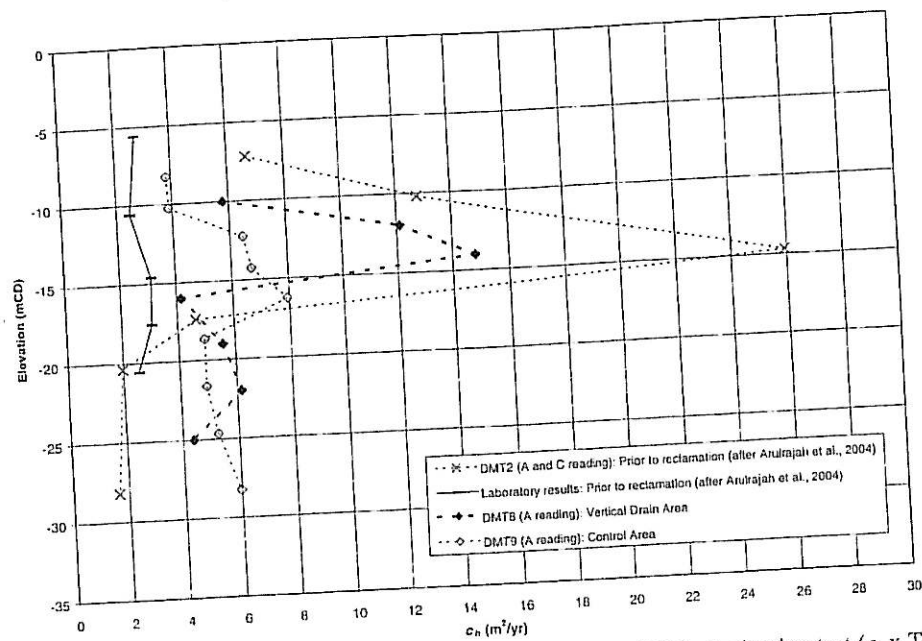


Figure 4: Comparison of coefficient of horizontal consolidation from DMTA dissipation test ( $c_h \times T_{flex} = 5 \text{ cm}^2$ ) between Vertical Drain Area and Control Area after 23 months of surcharge loading (Arulrajah, 2005).

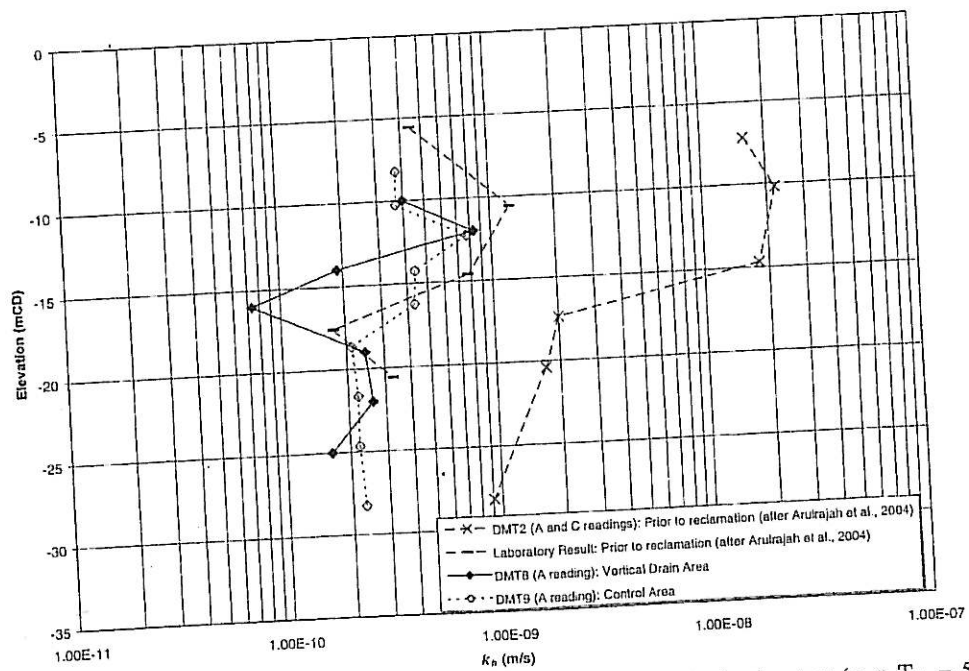


Figure 5 Comparison of horizontal hydraulic conductivity from DMTA dissipation test ( $c_h \times T_{flex} = 5 \text{ cm}^2$ ) between Vertical Drain Area and Control Area after 23 months of surcharge loading (Arulrajah, 2005).

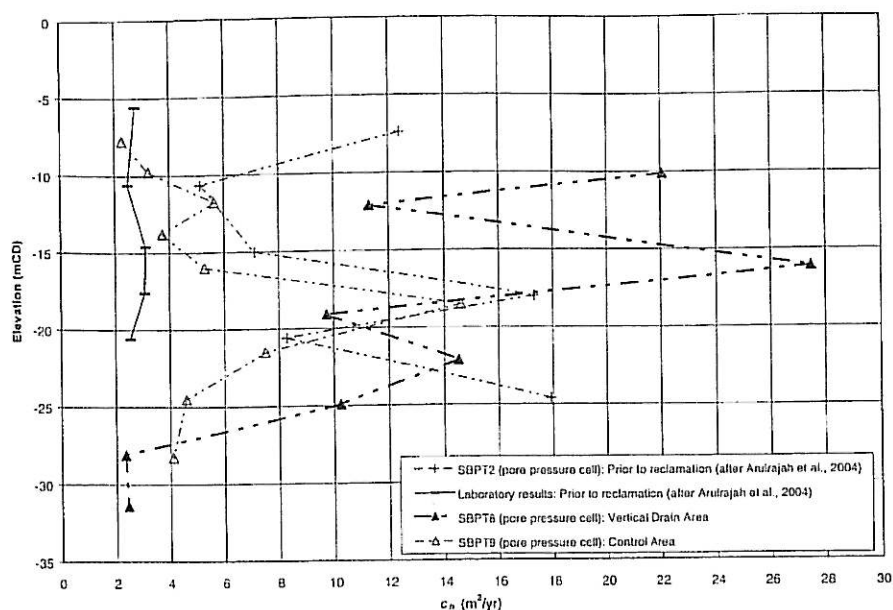


Figure 6 Comparison of coefficient of horizontal consolidation from SBPT dissipation test between Vertical Drain Area and Control Area 23 months after preloading (Arulrajah, 2005).

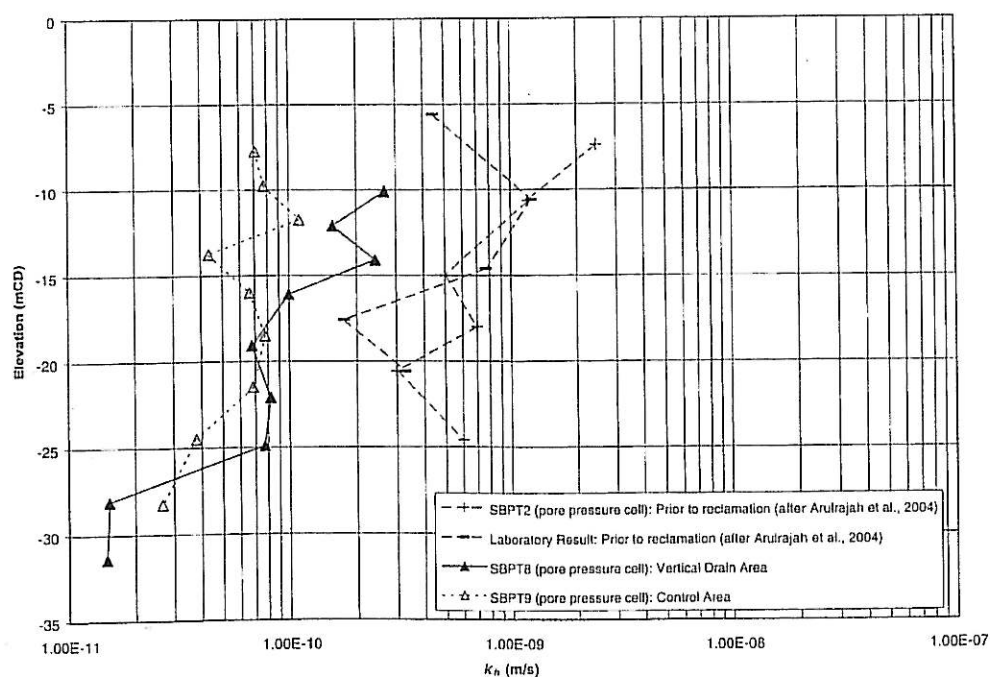


Figure 7: Comparison of horizontal hydraulic conductivity from SBPT dissipation test between Vertical Drain Area and Control Area after 23 months of surcharge loading (Arulrajah, 2005).

#### 5.4 BAT PERMEAMETER

The comparison of the  $k_h$  results from BAT for the Vertical Drain Area and the Control Area is presented in Figure 8. It is evident that the horizontal hydraulic conductivity decreases in the Vertical Drain Area as compared to the prior to reclamation and the Control Area within the marine clay layer. As the BAT permeameter method of measurement is a direct method, the  $k_h$  values obtained here can be used as the benchmark values for this research. The coefficient of permeability is in the order of  $10^{-9}$  to  $10^{-10}$  m/s in the Vertical Drain Area with vertical drains while values of  $10^{-9}$  m/s were obtained in the Control Area.

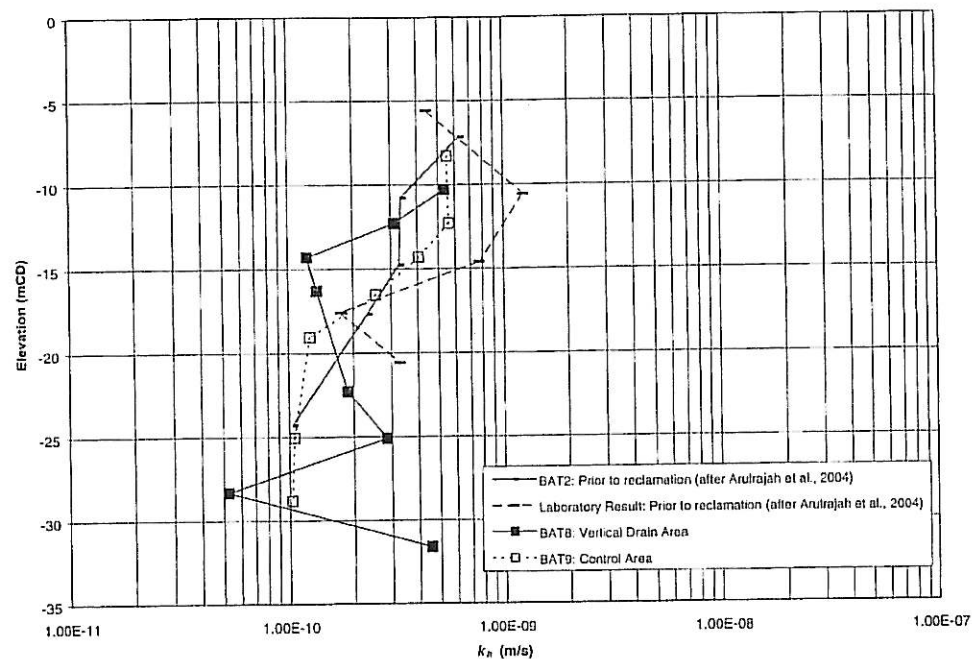


Figure 8: Comparison of horizontal hydraulic conductivity from BAT permeameter between Vertical Drain Area and Control Area 23 months after preloading (Arulrajah, 2005).

### 6 COMPARISON OF POST-IMPROVEMENT IN SITU DISSIPATION TESTS

The comparison between coefficient of horizontal consolidation at the Vertical Drain Area and Control Area from *in situ* dissipation tests is presented in Figure 9. Greater  $c_h$  values are obtained in the intermediate marine clay layer in both areas due to the comparatively higher permeability of the intermediate stiff clay layer. The  $c_h$  value seems to be higher in the Vertical Drain Area at some elevations as compared to the Control Area. This is due to the greater reduction in the coefficient of volume compressibility,  $m_v$ , after consolidation and it can also be affected by the correction factors used. Due to the lower magnitude of consolidation that has taken place in the Control Area, the Control Area  $c_h$  results are not much different with the prior to reclamation results.

The comparison between horizontal hydraulic conductivity at the Vertical Drain Area and Control Area *in situ* dissipation tests is presented in Figure 10. The horizontal hydraulic conductivity decreases in the Vertical Drain Area as compared to the Control Area within the marine clay layer as evident in the BAT readings. This confirms the phenomenon that there is a reduction of vertical permeability from time to time during consolidation. The other *in situ* testing methods however do not all accurately reflect this and it could be due to their indirect measurement of  $k_h$  readings from  $c_h$  values. As the Control Area has undergone only a small degree of consolidation, there is not much variation in the permeability of this area as compared to the prior to reclamation results.



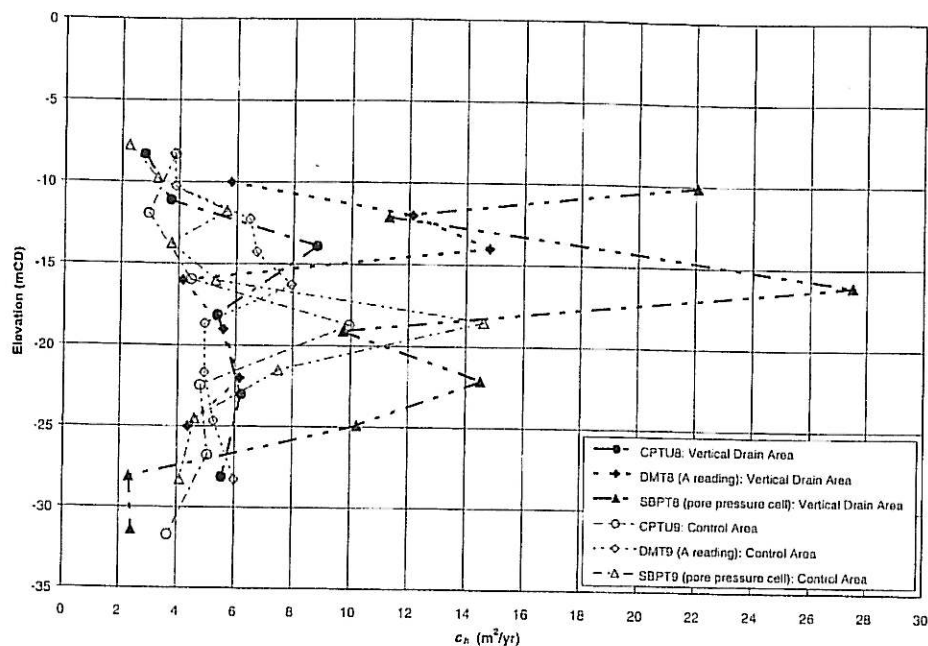


Figure 9: Comparison of coefficient of horizontal consolidation from dissipation tests between Vertical Drain Area and Control Area, 23 months after preloading.

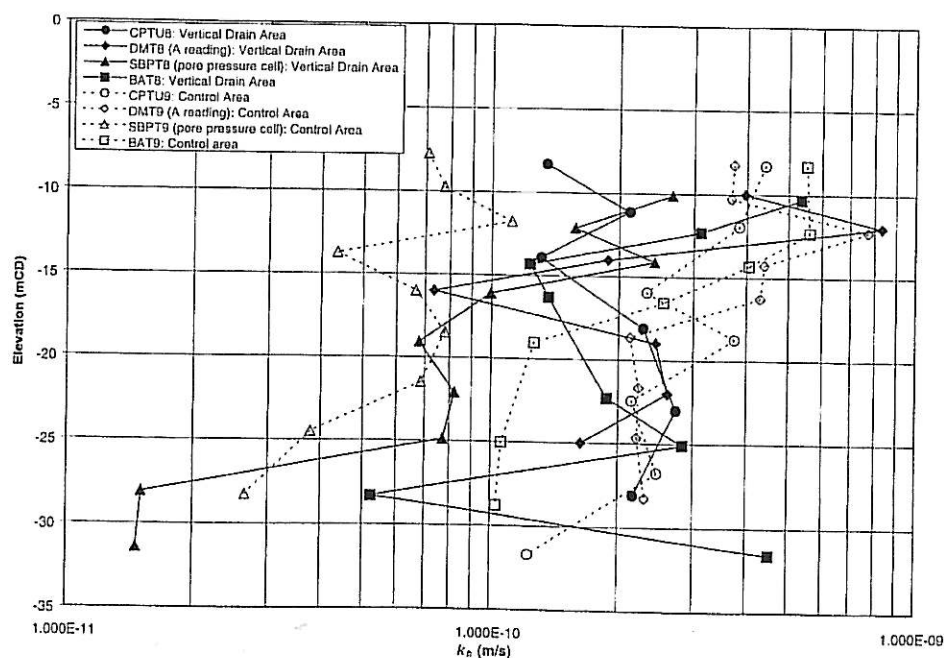


Figure 10: Comparison of horizontal hydraulic conductivity from dissipation tests between Vertical Drain Area and Control Area, 23 months after preloading.

## 7 OBSERVATIONS AND DISCUSSION

It is apparent that the *in situ* dissipation test results vary between one test method and another due to differing assumptions in cavity radius and the method of analysis of the various test methods. The varying  $c_h$  values will subsequently lead to differing  $k_h$  in the CPTU, DMT and SBPT results as  $k_h$  computations are worked out indirectly from  $c_h$  values. Scatter in measured values is observed in the intermediate stiff clay layer which is attributable to the higher  $c_h$  and  $k_h$  of the intermediate stiff layers. Furthermore the presence of laminations and sand lenses in the marine clay layers could also result in the scatter in measured values at various depths. Other factors could be slight differences in the seabed elevations at the test locations.

The  $c_h$  values derived from the CPTU dissipation test are generally lower than those obtained from the other *in situ* dissipation tests. The  $c_h$  value obtained from the SBPT exhibits a larger variation in comparison with that of other tests. In general, the  $c_h$  value measured by the SBPT is much larger than those obtained from the other *in situ* dissipation tests. This finding is in agreement with that of Chu *et al.* (2002). The  $c_h$  value obtained from the DMT dissipation tests is usually larger than that from the CPTU dissipation test but smaller than that from the SBPT holding test.

The smear effect could also affect the CPTU, DMT and the BAT permeameter measurements for  $k_h$  and  $c_h$ . In the CPTU, DMT and BAT tests, a penetrometer has to be pushed into the clay and a smear effect similar to the insertion of a mandrel could have been introduced prior to the measurements. The smear effect for the BAT permeameter could be greater than that for the CPTU, as the BAT permeameter has a filter with a larger surface area. This may explain why  $k_h$  measured by the BAT permeameter is normally lower than that by the CPTU, although the working mechanisms of the two tests are very similar. The SBPT should not be affected by the smear effect due to its self-boring mechanism. This may be part of the reason why the  $c_h$  or  $k_h$  value measured by the SBPT dissipation test is generally higher than that by the BAT permeameter or the CPTU tests. This finding also indicates that when vertical drains are used in soft clay, the smear effect on the consolidation properties of soil has to be taken into consideration in the design (Chu *et al.*, 2002).

## 8 CONCLUSIONS

*In situ* dissipation tests by means of piezocone, dilatometer, self-boring pressuremeter and BAT permeameter have been used in the characterization of the coefficient of consolidation and hydraulic conductivity due to horizontal flow of Singapore marine clay in a land reclamation project.

The *In Situ* Test with the CPTU is a suitable method for the determination of the  $c_h$  in soil improvement schemes involving vertical drains. The CPTU holding test can also be done relatively quickly over the whole soil profile. The pre-reclamation CPTU holding tests indicate that the  $c_h$  values vary between 2-6 m<sup>2</sup>/yr. The post-improvement results in the upper and lower marine clay layers indicate  $c_h$  of 3-6 m<sup>2</sup>/yr in the Vertical Drain Area and 3-5 m<sup>2</sup>/yr in the Control Area.  $c_h$  value is seen to be higher in the Vertical Drain Area compared to the Control Area. Despite the  $k_h$  being lower in the Vertical Drain Area, the  $c_h$  could be higher due to greater ratio of reduction in the coefficient of volume change,  $m_v$ . The CPTU results are found to be the closest to the laboratory testing results.

The SBPT does not appear to be desirable for the measurement of  $c_h$  of Singapore marine clay at Changi. The  $c_h$  values obtained from SBPT are normally too high to be directly used for the design.

The hydraulic conductivity due to horizontal flow results from the BAT tests can be used as the baseline data since the system measures hydraulic conductivity due to horizontal flow directly whereas the other *in situ* tests require the introduction of additional parameters to evaluate the hydraulic conductivity indirectly from  $c_h$  values. The hydraulic conductivity due to horizontal flow measured by the BAT permeameter is generally lower than that of the other *in situ* tests, possibly due to the smear effect when the permeameter is pushed into the soil. It is clearly evident that the hydraulic conductivity due to horizontal flow decreases in the Vertical Drain Area compared to the prior to reclamation and the Control Area within the marine clay layer. This is expected due to a reduction of hydraulic conductivity from time to time during consolidation.

The hydraulic conductivity due to horizontal flow of Singapore marine clay prior to reclamation at the *In Situ* Test Site is in the order of 10<sup>-9</sup> to 10<sup>-10</sup> m/s based on the BAT readings. The horizontal hydraulic conductivity is in the order of 10<sup>-9</sup> to 10<sup>-10</sup> m/s in the Vertical Drain Area and the Control Area 23 months after preloading.

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## 10 REFERENCES

- Arulrajah, A., Bo, M.W., Nikraz, H. and R. Hashim (2006). Pre-Reclamation In-Situ Testing of Soft Soil, *Australian Geomechanics* (in print).
- Arulrajah, A., Nikraz, H., Bo, M.W. (2004). In-situ testing of Singapore marine clay at Changi, *Geotechnical and Geological Engineering*, **23**, pp. 111-130.
- Arulrajah, A., (2005). *Field Measurements and Back-Analysis of Marine Clay Geotechnical Characteristics under Reclamation Fills*, PhD Thesis, Curtin University of Technology, Perth, Australia.
- Asaoka, A. (1978) Observational procedure of settlement prediction, In: *Soil and Foundations, Journal of the Japanese Society of Soil Mechanics and Foundation Engineering*, **18**(4), 87-101.
- Baligh, M. M., Levadoux J. N. (1980). Pore pressure dissipation after cone penetration, In: *Massachusetts Institute of Technology Research Report*, Cambridge Massachusetts.
- Baligh, M. M., Levadoux J. N. (1986). Consolidation after undrained piezocone penetration. II: interpretation, In: *Journal of Geotechnical Engineering*, ASCE, **112**(7), 727-745.
- Bo Myint Win, Arulrajah, A., Choa, V., (1997a). Assessment of Degree of Consolidation in Soil Improvement Project, *Proceedings of the International Conference on Ground Improvement Techniques*, May, Macau, pp. 71-80.
- Bo Myint Win, Arulrajah A. and Choa V. (1997b). Performance Verification of Soil Improvement Work with Vertical Drains, *Proceedings of the 30<sup>th</sup> Anniversary Symposium of the Southeast Asian Geotechnical Society*, Bangkok, Thailand, pp. 191-203.
- Bo Myint Win, Arulrajah A. and Choa. V. (1998). The hydraulic conductivity of Singapore marine Clay at Changi, *Quarterly Journal of Engineering Geology*, **31**, 291-299.
- Bo Myint Win, Chang M. F, Arulrajah A. and Choa. V. (2000). Undrained shear strength of the Singapore marine clay at Changi from In-Situ Tests, *Geotechnical Engineering, Journal of the Southeast Asian Geotechnical Society*, **31**(2), 91-107.
- Bo M W, Chu, J, Low, B. K. and Choa, V. (2003) *Soil Improvement – Prefabricated Vertical Drain Techniques*, Thomson Learning, Singapore.
- Bo Myint Win and Choa. V. (2004). *Reclamation and Ground Improvement*, Thomson Learning, Singapore.
- Chu J., Bo Myint Win, Chang M. F., and Choa V., (2002). Consolidation and permeability properties of Singapore marine clay, In: *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **128**(9), 724-732.
- Clarke, B.G., Carter, J.P. and Wroth, C.P. (1979). In-situ determination of the consolidation characteristics of saturated clays, In: *Proceedings of the 7<sup>th</sup> European Conference on Soil Mechanics and Foundation Engineering*, Vol. 2, 207-213.
- Hawkins, P. G. Mair, R. J. Mathieson, W. G. and Wood, D. M. (1990). Pressuremeter measurement of total horizontal stress in stiff clay, In: *Proceedings 3<sup>rd</sup> International Symposium on Pressuremeters*, Oxford University, U. K., 321-330.
- Mair, R. V. and Wood. D. M. (1987). Pressuremeter testing methods and interpretation, In: *CIRIA Ground Engineering Report : Insitu Testing*.
- Marchetti and Totani G. (1989).  $c_h$  evaluation from DMTA dissipation curves, In: *Proceedings of 12<sup>th</sup> International Conference on Soil Mechanics and Testing Engineering*, Vol. 1, 281-286.
- Schmertmann J. H. (1988). The coefficient of consolidation obtained from  $p_z$  dissipation in the DMT, In: *Proceedings of the Geotechnical Conference, Pennsylvania*. Department of Transportation, Pennsylvania.
- Torstensson B. A. (1983). *BAT Monitoring System*, BAT AB, Stockholm.
- Torstensson B. A., Petsonk A. M. (1986). A device for in-situ measurement of hydraulic conductivity, *Proceedings of the 4<sup>th</sup> International Seminar Field Instrumentation and In-situ Measurements*, Nanyang Technological Institute, Singapore.
- Windle, D and Wroth, C.P. (1997). The use of a Self boring Pressuremeter to determine the Undrained Properties of Clays, In: *Ground Engineering*, **10**(6), 37-46.