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Evaluating the in-situ hydraulic conductivity of soft soil under land reclamation fills with the BAT permeameter

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Abstract

In-situ tests were undertaken with a BAT permeameter as part of a hydrogeological study to determine the horizontal hydraulic conductivity of Singapore marine clay at Changi. BAT permeameter tests were undertaken in marine conditions prior to land reclamation at a Test Site. An additional series of tests were undertaken after land reclamation and subsequent ground improvement works with prefabricated vertical drains after 23 months of surcharge loading. The BAT permeameter results were compared to laboratory test results carried out using a Rowe consolidation cell as well as hydraulic conductivity tests interpreted from other in-situ dissipation tests including Piezocone Penetration Test (CPTU), Dilatometer Test (DMT) and Self Boring Pressuremeter Test (SBPMT). The BAT permeameter was found to be suitable for horizontal hydraulic conductivity measurements. The BAT permeameter has the advantage that it measures horizontal hydraulic conductivity directly whereas other in-situ test methods require the introduction of additional parameters to evaluate the hydraulic conductivity indirectly. The horizontal hydraulic conductivity measured using the BAT permeameter was however lower than that expected which is attributed to smear effect. The horizontal hydraulic conductivity was found to decrease in the vertical drain treated area as compared to the prior to reclamation results which is attributed to the significant void ratio reduction at the vertical drain treated area.

Keywords: in-situ testing; hydraulic conductivity; BAT permeameter; soft soil; land reclamation.

1. Introduction

The hydraulic conductivity in the horizontal flow direction is an important parameter for the engineering geology interpretation of land reclamation projects on soft marine clay deposits. Laboratory tests are commonly used for determination of the hydraulic properties of soft soils and rocks (Heister et al. 2005; Ponziani et al. 2011). In-situ tests are commonly used for determination of the hydraulic conductivity of rocks and sands (Mollah and Sayed 1995; Meijas et al. 2009; Chapuis 2012) but are not commonly used for soft soils.

The determination of hydraulic conductivity parameters of soft soils are traditionally based on laboratory consolidation tests or falling head tests (Nayak et al. 2007). Prototype cells have also been developed in recent years for monitoring the hydraulic conductivity of soft soils such as peat (Ponziani et al. 2011). The Rowe consolidation cell (Rowe and Barden, 1966) has provisions for horizontal drainage, which enables the determination of the horizontal hydraulic conductivity indirectly from coefficient of horizontal consolidation values. The usage of the Rowe consolidation cell for the determination of the horizontal consolidation and hydraulic conductivity properties of Singapore marine clay has been discussed previously by Bo et al. (2003) and Chu et.al (2002). The standard test methods for undertaking the Rowe consolidation test is specified by ASTM D-2435 (2004) and BS1377-6 (1990). These laboratory tests for soft soils are however subject to uncertainties due primarily to sample disturbances. In recent years, in-situ testing methods have become increasingly popular for the determination of hydraulic conductivity of soft soils. In the determination of hydraulic conductivity by laboratory testing methods, with an increase in sample disturbance the void ratio and yield stress subsequently reduces and the compression curve tends towards the remolded line (Shogaki and Kaneko, 1994;

Nagaraj et al., 1990; and Horpibulsuk et al., 2007). Sample disturbance therefore causes a significant difference in hydraulic conductivity between the in-situ and laboratory test methods.

There has been an increasing emergence of in-situ testing methods as an alternative to laboratory testing and field instrumentation methods for assessing the hydraulic characteristic of soft marine clays in land reclamation projects. Ground improvement with Prefabricated Vertical Drains (PVDs) is a widely used technique for the treatment of soft soil deposits in land reclamation projects (Holtz et al. 1991; Bergado et al. 1996; Choa et.al 2001; Arulrajah el al. 2004a; Arulrajah et al. 2009a; Bo et al. 2003; Bo et al. 2012; Chu et al. 2004a, Chu et al. 2006; Chu et al. 2009a). Field instrumentation with the usage of settlement gauges and piezometers is frequently used to assess the degree of consolidation of soft soils in these land reclamation projects after ground improvement with prefabricated vertical drains (Bergado et al. 1996; Arulrajah et al 2004b, Arulrajah et al. 2009b; Arulrajah et al. 2013; Bo et.al 2007, Chu et al. 2009a).

In-situ testing equipment such as the piezocone penetration test with pore pressure measurements (CPTU) (Baligh and Levadoux 1986; Bo et al. 2003; Bo et al. 2012; Arulrajah et al. 2009a; Arulrajah et al. 2011; Cai et al. 2010; Cai et al. 2012), Dilatometer Test (DMT) (Marchetti 1980; Bo et al. 2003; Arulrajah et al. 2006a; Bo et al. 2012) and Self-Boring Pressuremeter Test (SBPMT) (Mair and Wood 1987; Arulrajah et al. 2011) have been previously used as alternative methods to field instrumentation in the determination of the hydraulic characteristics of soft soils.

In-situ dissipation tests are particularly useful in the determination of the in-situ hydraulic conductivity of soft soils at various depths (Bo et.al 2012, Chu et al. 2002). In-situ dissipation tests have been undertaken previously in ground improvement projects in soft soils with equipment such as the SBPMT (Bo et.al 2012; Arulrajah et al. 2011), DMT (Marchetti and Totani 1989; Arulrajah et al. 2006b; Bo et.al 2012) and CPTU (Arulrajah et al. 2007; Cai et al. 2010; Cai et al. 2012). However, hydraulic conductivity is only measured indirectly by these in-situ tests methods.

The BAT permeameter system has the advantage over these other in-situ testing equipments because it can directly measure the in-situ hydraulic conductivity (Torstensson, 1984). The key objective of this paper is to compare the results of the horizontal hydraulic conductivity (k_h) from the BAT permeameter tests to laboratory testing results undertaken with a Rowe consolidation cell as well as to in-situ testing results with the SBPMT, CPTU and DMT.

2. BAT permeameter testing method

The BAT permeameter developed by Torstensson (1984) was used in this study for in-situ measurements of horizontal hydraulic conductivity of the soft marine clay at Changi, Singapore. The BAT permeameter results can be considered as the baseline measurements of horizontal hydraulic conductivity as this is directly measured. This contrasts with dissipation testing by other in-situ testing methods such as CPTU, DMT or SBPMT where the horizontal hydraulic conductivity is indirectly evaluated from the coefficient of horizontal consolidation. The BAT permeameter measures the pore pressure locally in the soil, with little water movement, resulting in a quick reaction time in soft soils (Torstenson 1999). The BAT permeameter also has the ability to sample ground water, measure pore water pressure and determine in-situ hydraulic conductivity of soft soils. The BAT permeameter in this research was used to determine the in-situ hydraulic conductivity of the soft marine clay prior to land reclamation and after ground improvement.

The key element in the BAT system is the filter tip, which consists of a thermoplastic body and a porous plastic filter tip (Torstensson 1984). The diameter of the BAT filter was 30 mm and the length is 40 mm. The different test adapters make a tight temporary connection to the filter tip with the aid of a hypodermic needle. The pore pressure adaptor contains a hypodermic needle and an electronic pressure transducer, connected to a battery-operated digital readout unit. The pore pressure adaptor is threaded to an extension pipe, lowered into a prebored borehole and placed at the desired elevation. When the pore pressure adaptor is lowered down the borehole, it is coupled to the nozzle in the filter tip and gravity draws the hypodermic needle downward, penetrating the rubber disc mounted in the filter tip. The needle provides a hydraulic connection between the interior of the filter tip and the test adapter (Torstensson 1984). In the BAT permeameter test, the penetrometer has to be pushed into the soft clay and this results in smearing around the BAT permeameter. Smearing affects the k_h measurement, similar to the insertion of a mandrel (Bo et al. 2003). Fig. 1 shows the geometry and dimensions of the BAT permeameter.

The in-situ measurement of hydraulic conductivity can be carried out either as an inflow test or as an outflow test. In the former case, the gas/water container is completely gas-filled at the start of the test. An inflow test can be conducted simultaneously with extraction of pore water sample. In an outflow test, the container is partially filled with compressed gas. The air in the chamber is evacuated (or pressurized) to any desired pressure. As water flows into (or out of) the probe, this results in a change in air pressure in the chamber. A pressure transducer monitors the pressure change. The test is based on measurement of flow into and out of a sample container. This rate is computed by the pressure change measured in the container using Boyles’s law, which can be translated into a volume change and analysis of the time-pressure record yields the horizontal hydraulic conductivity. The quantity of flow and heads are computed from the change in the gas pressure measured in the chamber using Boyle's Law (Torstensson 1984).

$$k_h = \frac{P_0\,V_0}{Ft}\left[\frac{1}{P_0\,U_0} - \frac{1}{P_t\,U_0} - \frac{1}{U_0^2}\ln\left(\frac{P_0 - U_0}{P_0} \times \frac{P_t}{P_t - U_0}\right)\right] \qquad (1)$$

$$F = \frac{2\pi L}{\ln\left[\frac{L}{d} + \sqrt{1 + \left(\frac{L}{d}\right)^2}\right]} \qquad (2)$$

where k_h is the horizontal hydraulic conductivity in m/s; P_0 is absolute initial system pressure; V_0 is initial gas volume in ml; F is shape factor and is calculated as 228.76 mm for the current test; U_0 is static pore water pressure; P_t is absolute pressure at time t; L is length of filter in mm and d is diameter of filter in mm. All pressures are measured in meter.

3. Results and Discussions

The Test Site comprises of two distinct layers of marine clay, which are the upper marine clay layer and the lower marine clay layer (Arulrajah and Bo, 2008). These two layers are separated by an intermediate stiff clay layer, which in reality is the desiccated crust of the lower marine clay (Arulrajah and Bo, 2008). The original seabed elevation at the site was -3.29 mCD (CD refers to Admiralty Chart Datum). Prefabricated vertical drains were installed in the Vertical Drain Area at 1.5 m by 1.5 m square spacing at the installation platform level of +4 mCD to an elevation of -25 mCD (29 m length of vertical drains). The test site was subsequently surcharged, with the placement of additional reclamation sandfill to an elevation of +10 mCD and surcharge left in place for a period of 23 months. The purpose for the surcharge was for preemptive settlement to take place during this temporary surcharging period under the load greater than future loads so as to minimise post-construction settlement. An adjacent Control Area (where no vertical drains were installed) was constructed similarly for BAT permeameter result comparison purposes. The implementation of land reclamation and ground improvement with prefabricated vertical drains in the Test Site has been discussed by Bo et al. (2003, 2004 and 2007) and Chu et al. (2009b).

Fig. 2 presents the geotechnical borelog of the Test Site. The upper marine clay is very soft clay with some sea shell fragments. This upper clay layer is from the seabed to 11 m depth. Its water contents are close to the liquid limits and the clay fractions increase with depth while the compression indices tend to decreases with depth. The undrained shear strengths are 18-20 kN/m^2. The lower marine clay, from 16 m to 25.2 m in depth, comprises of soft clay with water contents lower than the liquid limits. The compression indices are almost constant with depth. An intermediate stiff clay layer, with undrained shear strength larger than 75 kN/m^2, is present between the upper and lower marine clay layers. Field vane shear tests could not be undertaken below this intermediate stiff clay layer due to its relative stiffness and was terminated in this layer. The BAT permeameter tests were undertaken prior to reclamation and after ground improvement. Fig. 3 shows the typical horizontal hydraulic conductivity versus elapsed time plot from the BAT permeameter test at a specific elevation undertaken prior to reclamation.

The pre-reclamation horizontal hydraulic conductivity (k_h) values obtained from three BAT permeameter tests are shown in Fig. 4. The horizontal hydraulic conductivity of Singapore marine clay prior to reclamation is in the order of 10^{-9} to 10^{-10} m/s, generally reducing with depth based on the BAT readings. It is interesting to note that hydraulic conductivities obtained from Rowe consolidation cell is nearly one order of magnitude higher than that measured with the BAT permeameter in the upper and lower marine clay layers.

The BAT permeameter results are observed to be lower than those of the laboratory testing results undertaken using a Rowe consolidation cell in the intermediate stiff clay. This could be due to the smear effect in BAT test which leads to a reduction of the measured k_h value (Bo et al. 2003). Smearing effect exists in all measurements by any form of push-in, in-situ tests including with the BAT permeameter. The effect of smearing will be different between upper and lower marine clay as well as the stiff intermediate clay. The stiff intermediate clay, though considered as the dessicated upper layer of the lower marine clay, is very different from the upper and lower marine clay layers in terms of water content, compression index, pre-consolidation pressure, and sensitivity as shown in Fig 2 (at a depth of 15 meters).

For both the in-situ and laboratory tests, k_h values in all the three clay layers is found to decrease with depth, which is attributed to the reduction in void ratio caused by the increase in overburden stress. In the intermediate desiccated zone (-11 mCD to -16 mCD), the k_h values obtained from the BAT permeameter and Rowe consolidation tests indicate relatively higher k_h values as compared to the upper and lower marine clay layers. It is implied from the test results that the smear effect is significant for the intermediate stiff clay layer, which possesses higher k_h values, though this effect can be ignored in the soft marine clay i.e., the in-situ k_h values obtained from the BAT permeameter test is essentially the same as those from Rowe consolidation test on undisturbed samples. Smearing and remoulding of the surrounding soils is furthermore dependent upon the dimensions of push-in equipment, their roughness and penetration rate and initial condition of soil (Bo et.al 1998). Among the three in-situ tests which involved penetration by static pushing, the BAT has slightly larger dimensions and the roughest surface. The hydraulic conductivity measured with Rowe cell might have furthermore been over-estimated to some extent, due to the indirect interpretation from the coefficient of consolidation, which involves using an average coefficient of volume compressibility from two stress ranges from consolidation test.

The comparison of the k_h results from BAT permeameter for the Vertical Drain Area and the Control Area (where no vertical drains were installed) after 23 months of surcharge loading is presented in Fig. 5. 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 upper marine clay and intermediate stiff clay layers. This is as expected due to the significant reduction of void ratio due to consolidation of soil at the vertical drain treated area and confirms that there is a reduction of horizontal hydraulic conductivity from time to time during consolidation. Degree of consolidation as well as reduction in void ratio is much more significant in the area with PVD. Differences in void ratio change are more pronounced in the upper marine clay, therefore reduction in hydraulic conductivity is evident in Figure 5. Differences in the change in void ratios for these three different layers and relationship between void ratio change and hydraulic conductivity were discussed by Bo et.al (1997 and 1998). It is to be noted that care should be made in these comparisons as areas treated with PVD has settled much more than the Control Area, in which case, the same soil element will be at a deeper elevation in the area with PVD. In the lower marine clay, the k_h values from BAT permeameter test for both control and vertical drain areas are almost in the same order of magnitude as the effect of surcharge on consolidation decreases with depth.

Fig. 6 compares the BAT permeameter results to that of other in-situ test methods, namely CPTU, DMT and SBPMT. The relationships between k_h versus depth are in similar patterns as k_h decreases with depth. The k_h values from the DMT are the highest while those from the BAT permeameter test are the lowest. The difference in measured k_h values from these methods is large at shallow depth. For the lower marine clay layer, the results from the CPTU, DMT and SBPMT are comparable. The BAT permeameter test is therefore suggested as a suitable test method for measurements of in-situ hydraulic conductivity. The field and laboratory test results for upper and lower marine clay layers are also noted to be in good agreement. The smear effect on the measurement of hydraulic conductivity in the intermediate stiff clay is evident when comparing the results of the BAT and Rowe consolidation tests. Among the in-situ test results, the BAT permeameter test is recommended for the k_h measurement.

The determination of hydraulic conductivity from other in-situ test methods requires the indirect interpretation from coefficient of consolidation measured under recompression conditions. Therefore assumptions on recompression ratio as well as average coefficient of volume compressibility from relevant stress range are required. The magnitude of the recompression ratio is largely dependent upon the degree of disturbance on the laboratory tested samples for consolidation. The BAT is however a direct measurement device, which does not require any assumption or indirect interpretations from laboratory data in the determination of hydraulic conductivity. Therefore, due to its nature of direct measurements of hydraulic conductivities, the BAT is the recommended in-situ testing equipment for soft marine clays.

4. Conclusions

This research study indicates that the BAT permeameter is suitable for measurements of horizontal hydraulic conductivity. The BAT permeameter has the advantage that it measures horizontal hydraulic conductivity directly whereas other in-situ test methods require the introduction of additional parameters to evaluate the hydraulic conductivity indirectly.

The horizontal hydraulic conductivity measured using the BAT permeameter is however noted to be lower than expected which can be attributed to smearing when the permeameter is pushed into the soil. This effect is negligible for upper and lower marine Singapore clay layers but was found to be significant for the intermediate stiff clay layer. The hydraulic conductivity of the marine clay was found to decrease with depth, as the soil becomes more consolidated even under self-weight.

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. This can be attributed to the significant void ratio reduction at the vertical drain treated area and confirms that there is a reduction of horizontal hydraulic conductivity from time to time during consolidation.

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References

Arulrajah, A., Nikraz, H., Bo, M.W., 2004a. Factors affecting field instrumentation assessment of marine clay treated with prefabricated vertical drains. Geotextiles and Geomembranes, Elsevier, 22 (5), 415-437.

Arulrajah, A., Nikraz, H., Bo, M.W., 2004b. Observational methods of assessing improvement of marine clay. Ground Improvement, Proceedings of the Institution of Civil Engineers (UK), 8 (4), 151-169.

Arulrajah, A., Nikraz, H., Bo, M.W., 2006a. Assessment of marine clay improvement under reclamation fills by in-situ testing methods. Geotechnical and Geological Engineering, 24 (2), 219-226.

Arulrajah, A., Nikraz, H. and Bo, M.W., 2006b. In situ pore water pressure dissipation testing of marine clay under reclamation fills. Geotechnical and Geological Engineering, 24 (1), 29-43.

Arulrajah, A., Bo, M.W., Nikraz, H., Balasubramaniam, A.S., 2007. Dissipation testing of Singapore marine clay by piezocone tests. Journal of Geotechnical and Geological Engineering, 25 (1), 647-656.

Arulrajah, A., Abdullah, A., Bo, M.W., Bouazza, A., 2009a. Ground improvement techniques for railway embankments. Ground Improvement, Proceedings of the Institution of Civil Engineers (UK), 162 (1), 3-14.

Arulrajah, A., Bo, M.W., 2008. Characteristics of Singapore marine clay at Changi. Geotechnical and Geological Engineering, 26(4), 431-441.

Arulrajah, A., Bo, M.W., Chu, J., Nikraz, H., 2009b. Instrumentation at the Changi Land Reclamation Project, Singapore. Geotechnical Engineering. Proceedings of the Institution of Civil Engineers (UK), 162 (1), 33-40.

Arulrajah, A., Bo, M.W., Piratheepan, J., Disfani, M., 2011. In-situ testing of soft soil at a case study site with the self-boring pressuremeter. ASTM Geotechnical Testing Journal, 34 (4), 355-363.

Arulrajah, A., Bo, M.W., Leong, M., Disfani, M.M., 2013. Piezometer measurements of prefabricated vertical drains improvement of soft soils under land reclamation fills. Engineering Geology, 162, 33-42.

ASTM, 2004. Standard test methods for one-dimensional consolidation properties of soils using incremental loading", Standard D2435-04. ASTM International. West Conshohocken, PA.

Baligh, M.M., Levadoux J.N., 1986. Consolidation after undrained piezocone penetration.
II: interpretation. Journal of Geotechnical Engineering, ASCE, 112 (7), 727–745.

Bergado, D.T., Alfaro, M.C., Balasubramaniam, A.S., 1996. Improvement of Soft Bangkok Clay using Vertical Drains. Geotextiles and Geomembranes, 12(7), 615-663.

Bo M. W., Chu, J, Low, B. K., Choa, V., 2003. Soil Improvement – Prefabricated Vertical Drain Techniques. Thomson Learning, Singapore.

Bo M. W., Choa, V. 2004. Reclamation and Ground Improvement. Thomson Learning, Singapore.

Bo, M.W., Arulrajah, A, Nikraz, H, 2007. Preloading and prefabricated vertical drains design for foreshore land reclamation projects: a case study. Proceedings of the Institution of Civil Engineers (UK), Ground Improvement, Vol. 11, No. 2, April, pp. 67-76.

Bo, M.W., M-F, Chang, Arulrajah, A., Choa, V., 2012. Ground investigations for Changi East Reclamation Projects. Geotechnical and Geological Engineering, 30 (1), 45-62.

British Standards BS1377-6, 1990. Consolidation and permeability tests in hydraulic cells and with pore pressure measurement.

Cai G.J., Liu S.Y., Tong L.Y., 2010. Field evaluation of deformation characteristics of a lacustrine clay deposit using seismic piezocone tests, Engineering Geology. 116 (3-4), 251-260.

Cai G.J., Liu S.Y., Puppala A.J., 2012. Predictions of coefficient of consolidation from CPTU dissipation tests in Quaternary clays, Bulletin of Engineering Geology and the Environment. 71 (2), 337-350.

Chapuis R. P., 2012. Estimating the in situ porosity of sandy soils samples in boreholes, Engineering Geology, 141-142, 57-64.

Choa, V., Bo, M. W., Chu, J., 2001. Soil Improvement Works for Changi East Reclamation Projects, Ground Improvement 2001, 5 (4), 141-153.

Chu J., Bo M. W., Chang M. F., Choa V., 2002. Consolidation and permeability properties of Singapore marine clay. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 128 (9), 724-732.

Chu. J., M.W, Bo, Choa, V., 2004a. Practical consideration for using vertical drains in soil improvement projects. Geotexile and Geomembranes, Special issue for Prefabricated Vertical Drain, 22 (1), 101-117.

Chu. J., Bo, M.W., Choa, V., 2006. Improvement of ultra-soft Soil using prefabricated vertical drains, Geotexiles and Geomembrances, 24 (6), 339-348.

Chu, J., Bo, M.W., Arulrajah, A., 2009a. Soil Improvement Works for an Offshore Land Reclamation. Geotechnical Engineering, Proceedings of the Institution of Civil Engineers (UK), 162 (1), 21-32.

Chu, J., Bo, M.W., Arulrajah, A., 2009b. Reclamation of a Slurry Pond in Singapore. Geotechnical Engineering, Proceedings of the Institution of Civil Engineers (UK), 162(1), 13-20.

Heister, K., Kleingeld, P.J., Keijzer, T.J.S., Loch, J.P.G., 2005. A new laboratory set-up for measurements of electrical, hydraulic and osmotic fluxes in clays. Engineering Geology, 77, 295-303.

Holtz, R.D., Jamiolkowski, M.B., Lancellotta, R., Pedroni, R., 1991. Prefabricated Vertical Drains–Design and Performance, CIRIA.

Horpibulsuk, S., Shibuya, S., Fuenkajorn, K., Katkan, W., 2007. Assessment of engineering properties of Bangkok clay. Canadian Geotechnical Journal, 44 (2), 173-187.

Marchetti, S., 1980. In-situ Tests by Flat Dilatometer. Journal of the Geotechnical Engineering, Division, ASCE, 106 (GT3), Proc Paper 15290, 299–321.

Marchetti, S., Totani, G., 1989. Ch Evaluation from DMTA Dissipation Curves. Proceedings of the 12th International Conference on Soil Mechanics and Testing Engineering,
1, 281–286.

Mair, R.V., Wood, D.M., 1987. Pressuremeter testing methods and interpretation. CIRIA Ground Engineering Report: Insitu Testing.

Meijas, M., Renard, P., Glenz, D., 2009. Hydraulic testing of low permeability formations: A case study in the granite of Cadalso de los Vidrios, Spain. Engineering Geology, 107, 88-97

Mollah, M.A., Sayed, S.A.S., 1995. Assessment of in situ permeability with emphasis on packer testing in Kuwait. Engineering Geology, 39, 217-231.

Nagaraj, T.S., Srinivasa Murthy, B.R., Vatsala, A., Joshi, R.C., 1990. Analysis of compressibility of sensitive clays. Journal of Geotechnical Engineering, ASCE, 116 (GT1), 105-118.

Nayak, S., Sunil, B.M., Shrihari, S. 2007. Hydraulic and compaction characteristics of leachate-contaminated lateritic soil. Engineering Geology, Volume 94, (3–4), pp. 2137-144.

Ponziani, M., Ngan-Tillard, D.J.M, Slob, E.C. 2011. A new prototype cell to study electrical and geo-mechanical properties of peaty soils. Engineering Geology, 119, 74-81.

Rowe, R.W., Barder, L., 1966. A new consolidation cell. Geotechnique, 26 (2), 162-170.

Shogaki, T., Kaneko, M., 1994. Effects of sample disturbance on strength and consolidation parameters of soft clay. Soils and Foundations, 34 (3), 1-10.

Torstensson, B.A., 1984. A new system for ground water monitoring. Ground Water Monitoring Review, 4 (4), 131-138.

Torstensson, B.A., Schellingerhout, A.J.G., 1999. Ground water monitoring with the BAT-system. Geoteckniek, October, 1-13, The Netherlands.

FIGURE CAPTIONS

Figure 1. Geometry and dimensions of the BAT permeameter (Data from Torstensson, 1984).

Figure 2. Borelog of the test site (Data from Arulrajah et al. 2011).

Figure 3 Typical BAT permeameter test measurements for hydraulic conductivity versus elapsed time and pressure, prior to reclamation (elevation –7.19 mCD).

Figure 4. Prior to reclamation horizontal hydraulic conductivity results at various elevations from BAT permeameter tests.

Figure 5 Comparison of horizontal hydraulic conductivity results at various elevations from BAT permeameter tests between Vertical Drain Area and Control Area after 23 months of surcharge loading.

Figure 6 Comparison of horizontal hydraulic conductivity with depth measurements from in-situ tests.

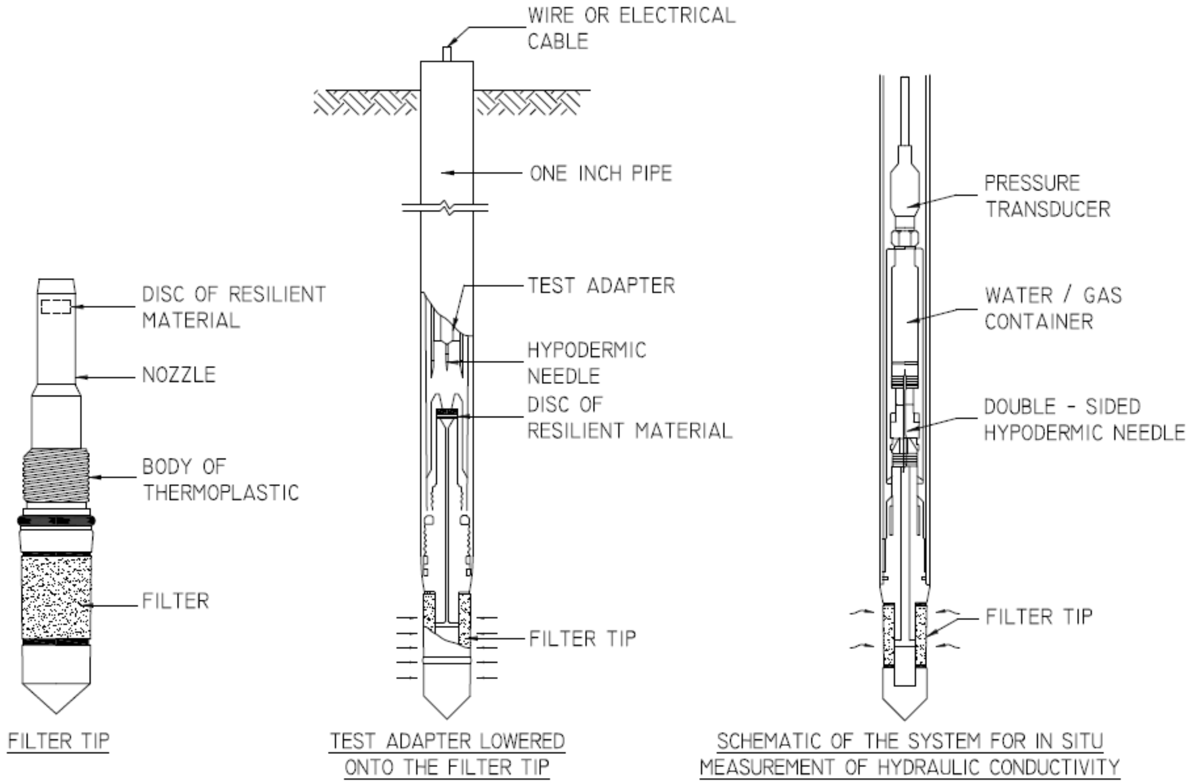

WIRE OR ELECTRICAL CABLE
ONE INCH PIPE
DISC OF RESILIENT MATERIAL
NOZZLE
BODY OF THERMOPLASTIC
FILTER
FILTER TIP
TEST ADAPTER
HYPODERMIC NEEDLE
DISC OF RESILIENT MATERIAL
FILTER TIP
TEST ADAPTER LOWERED ONTO THE FILTER TIP
PRESSURE TRANSDUCER
WATER / GAS CONTAINER
DOUBLE - SIDED HYPODERMIC NEEDLE
FILTER TIP
SCHEMATIC OF THE SYSTEM FOR IN SITU MEASUREMENT OF HYDRAULIC CONDUCTIVITY

Figure 1

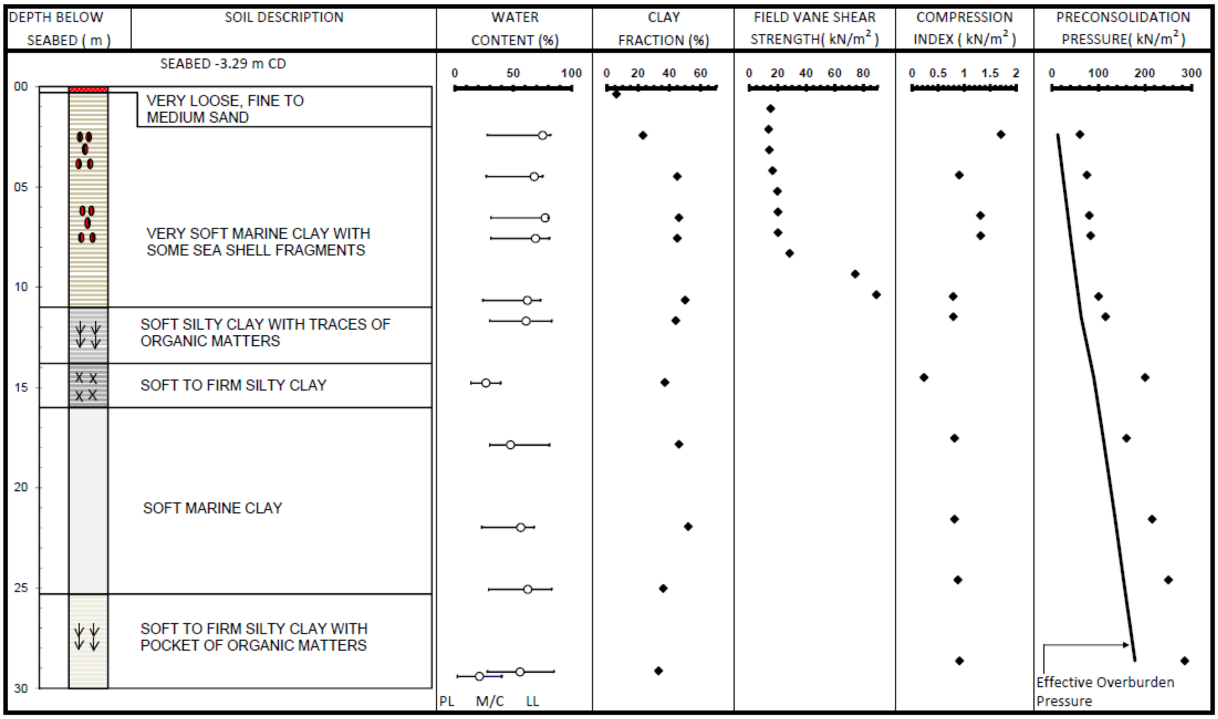

DEPTH BELOW SEABED (m)
SOIL DESCRIPTION
WATER CONTENT (%)
CLAY FRACTION (%)
FIELD VANE SHEAR STRENGTH(kN/m²)
COMPRESSION INDEX (kN/m²)
PRECONSOLIDATION PRESSURE(kN/m²)
SEABED -3.29 m CD
00
05
10
15
20
25
30
VERY LOOSE, FINE TO MEDIUM SAND
VERY SOFT MARINE CLAY WITH SOME SEA SHELL FRAGMENTS
SOFT SILTY CLAY WITH TRACES OF ORGANIC MATTERS
SOFT TO FIRM SILTY CLAY
SOFT MARINE CLAY
SOFT TO FIRM SILTY CLAY WITH POCKET OF ORGANIC MATTERS
0
50
100
0
20
40
60
0
20
40
60
80
0
0.5
1
1.5
2
0
100
200
300
PL
M/C
LL
Effective Overburden Pressure

Figure 2

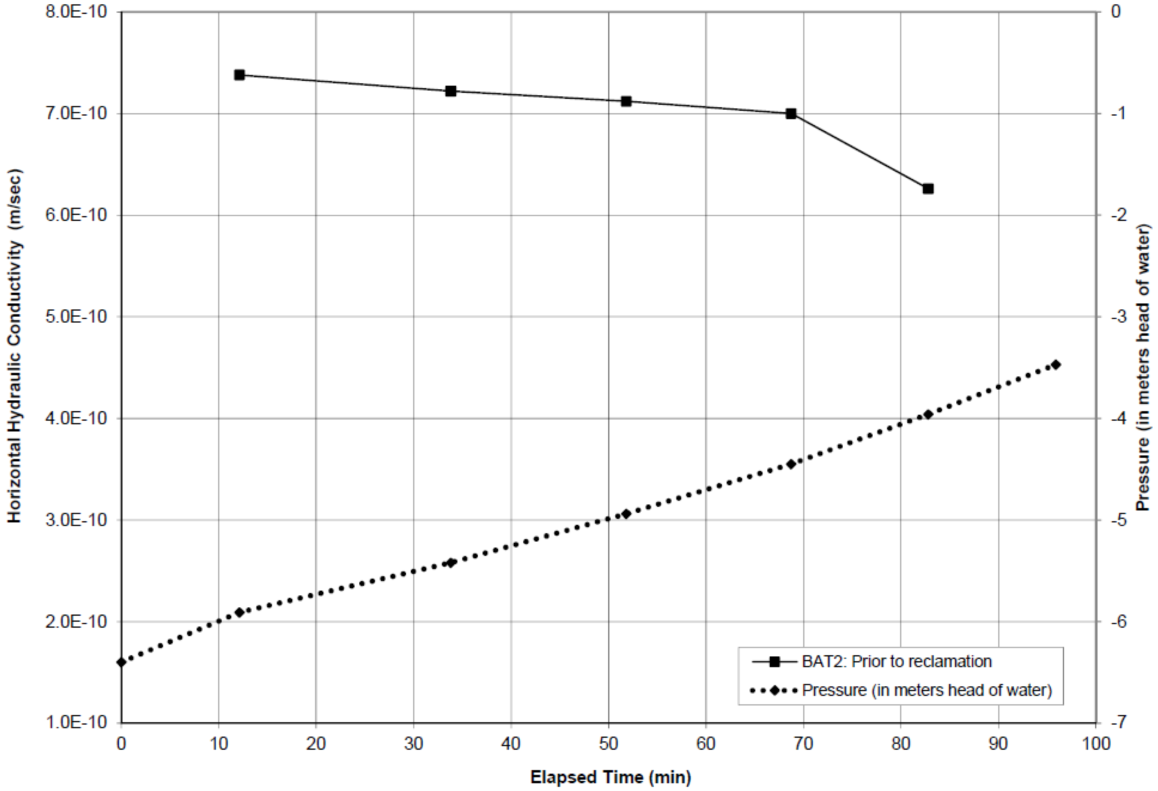

Horizontal Hydraulic Conductivity (m/sec)
8.0E-10
7.0E-10
6.0E-10
5.0E-10
4.0E-10
3.0E-10
2.0E-10
1.0E-10
0
-1
-2
-3
-4
-5
-6
-7
Pressure (in meters head of water)
0
10
20
30
40
50
60
70
80
90
100
Elapsed Time (min)
BAT2: Prior to reclamation
Pressure (in meters head of water)

Figure 3

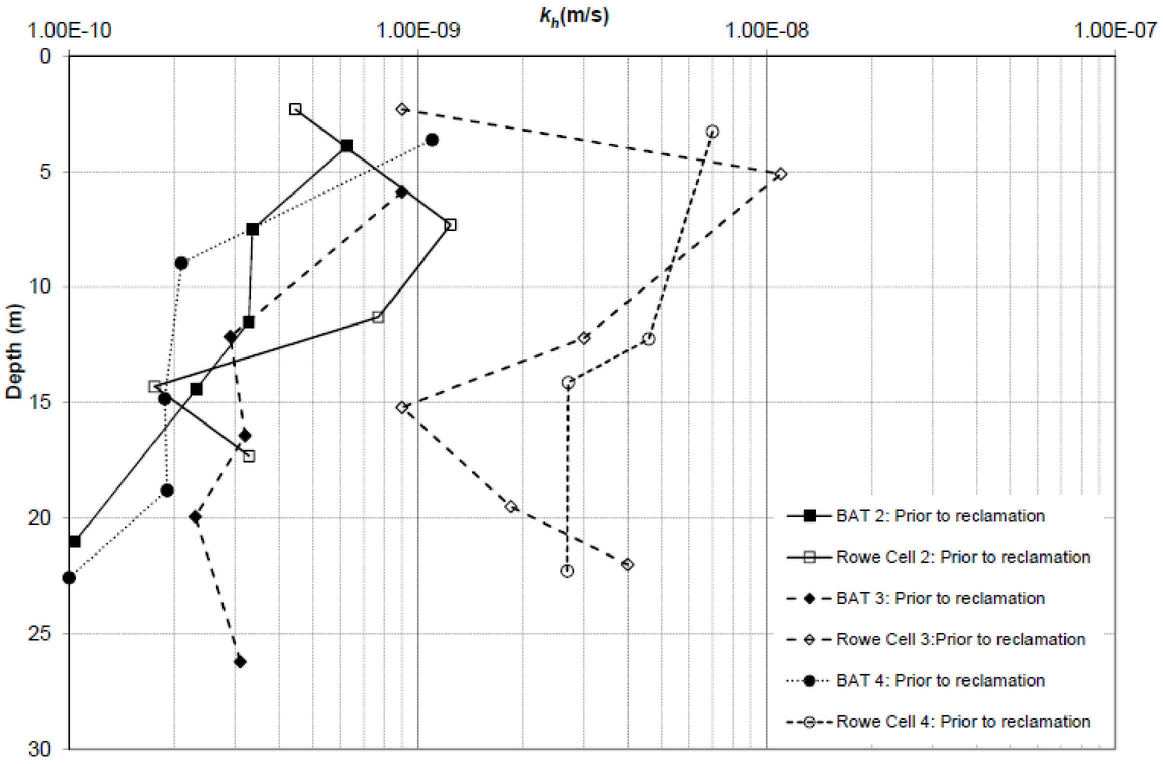
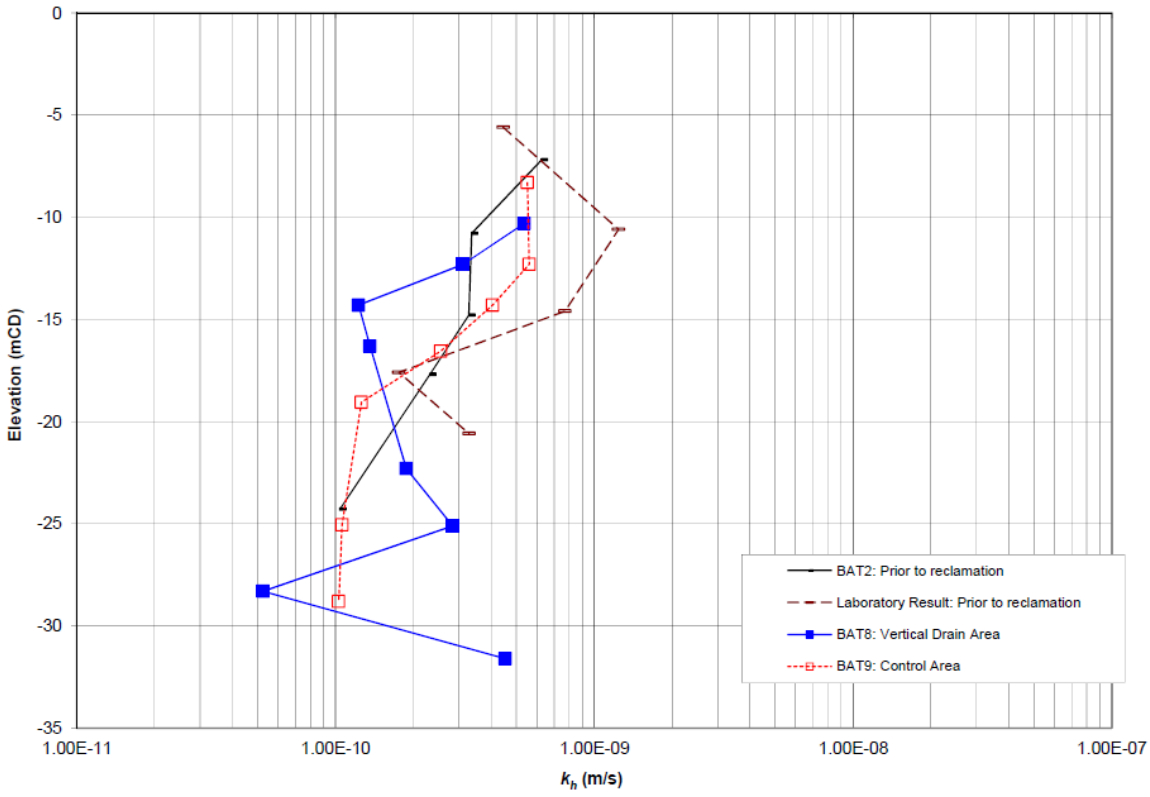

k_h(m/s)
1.00E-10
1.00E-09
1.00E-08
1.00E-07
Depth (m)
0
5
10
15
20
25
30
BAT 2: Prior to reclamation
Rowe Cell 2: Prior to reclamation
BAT 3: Prior to reclamation
Rowe Cell 3:Prior to reclamation
BAT 4: Prior to reclamation
Rowe Cell 4: Prior to reclamation

Figure 4



0
-5
-10
-15
-20
-25
-30
-35
Elevation (mCD)
1.00E-11
1.00E-10
1.00E-09
1.00E-08
1.00E-07
k_h (m/s)
BAT2: Prior to reclamation
Laboratory Result: Prior to reclamation
BAT8: Vertical Drain Area
BAT9: Control Area

Figure 5

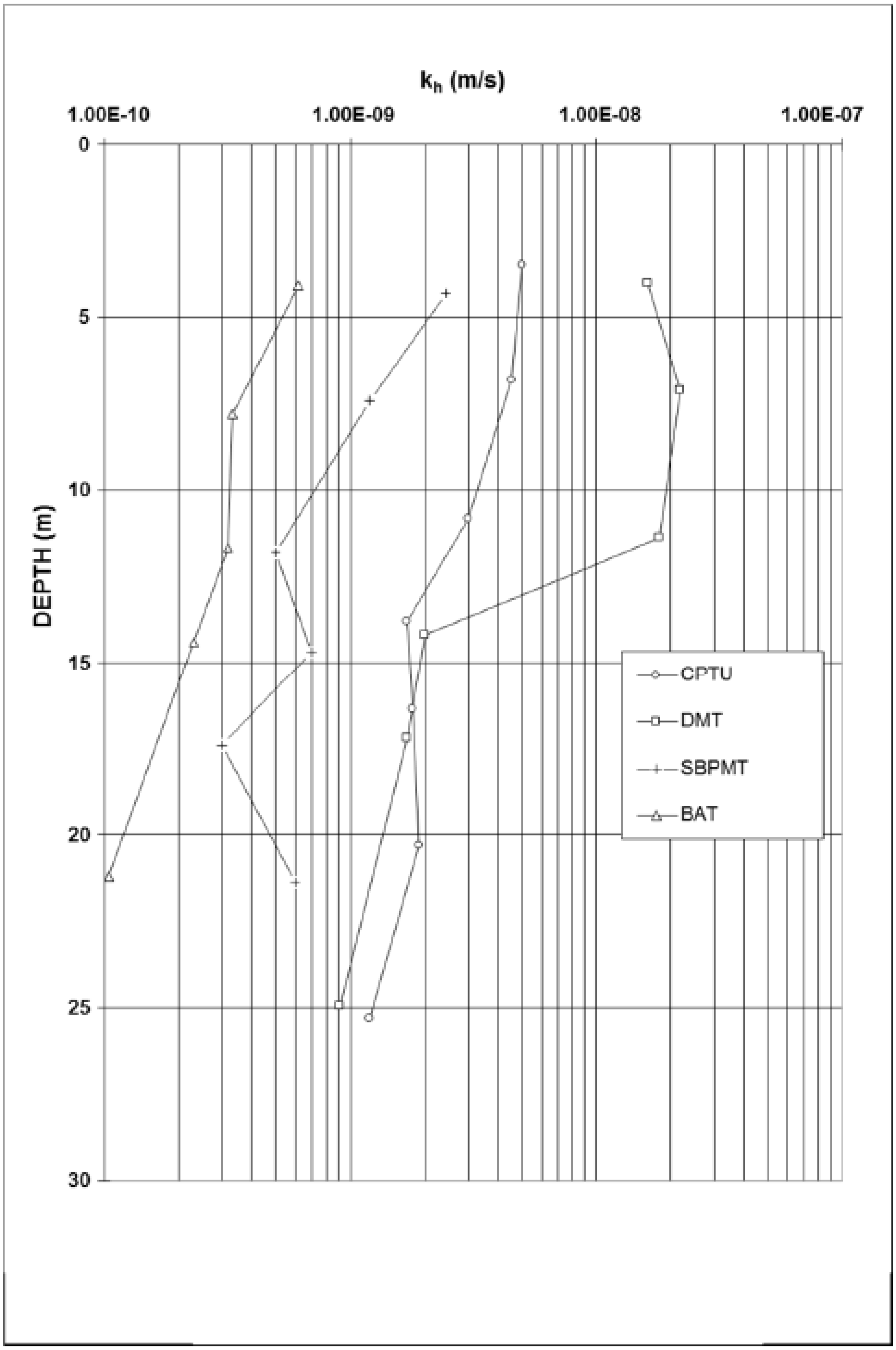
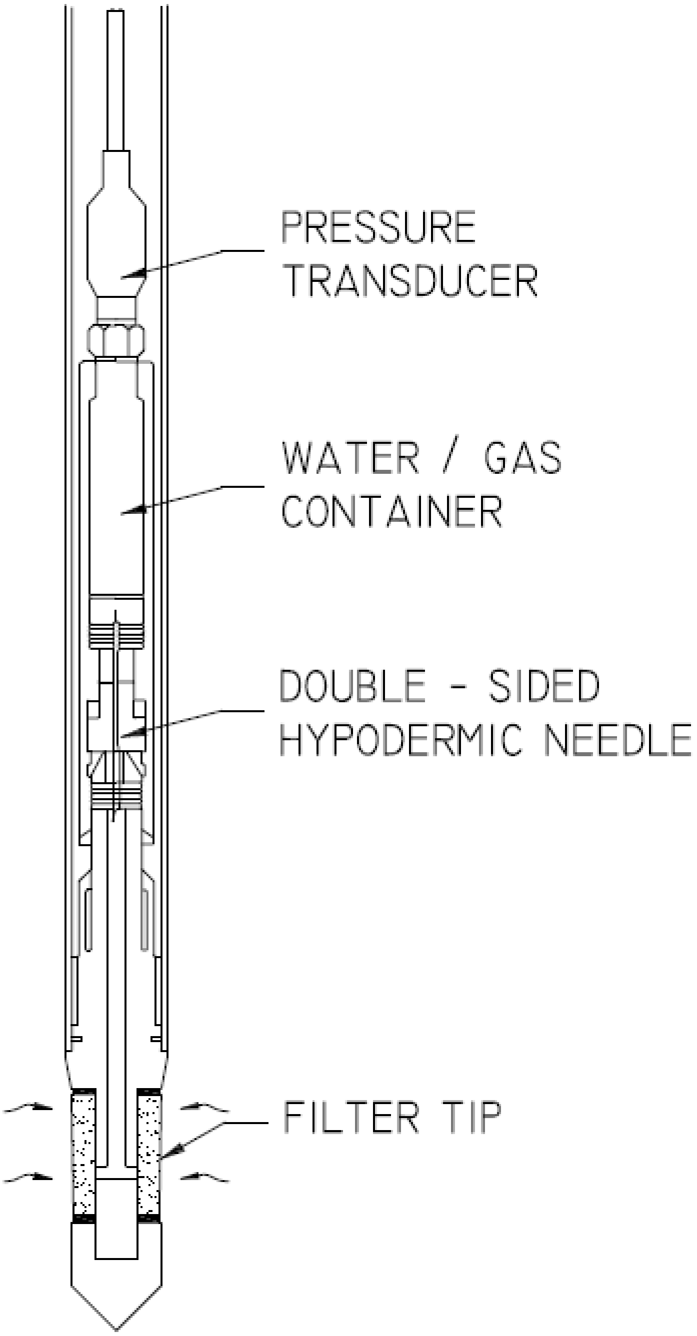

k_h (m/s)
1.00E-10
1.00E-09
1.00E-08
1.00E-07
DEPTH (m)
0
5
10
15
20
25
30
CPTU
DMT
SBPMT
BAT

Figure 6



Graphical abstract

Research Highlights

- In-situ tests with a BAT permeameter
- Determination of hydraulic conductivity of soft marine clay.
- Land reclamation site treated with prefabricated vertical drains.
- BAT results compared to laboratory test and in-situ test results.
- BAT suitable for horizontal hydraulic conductivity measurements of soft soils.