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In situ permeability measurement of a contaminant containment wall

Mesure de la perméabilité in situ d'une paroi en ciment-bentonite

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ABSTRACT
In order to assess the performance of contaminant containment systems, such as slurry cut-off walls, it is essential to quantify their engineering properties, in particular the permeability of the materials used for their construction. In-situ testing is a preferable alternative to laboratory testing as it allows for testing a substantial volume of material in as undisturbed a state as possible as well as the evolution of its properties over time. A series of in situ permeability tests were conducted in an eight year old cement-bentonite wall using a piezocone, a straddle packer system and a self-boring pressuremeter. The results suggest that not all of these methods are always suitable. The data also show that the permeability of the wall is often larger than the value typically obtained with laboratory scale samples. This difference is likely to be due to the heterogeneous nature of the wall at the field scale.

RÉSUMÉ
Pour contrôler la performance des systèmes de confinement de contaminants tels que les barrières de type «slurry wall» il est essentiel de quantifier les propriétés physiques, en particulier la perméabilité, des matériaux utilisés pour leur construction. C'est pourquoi les essais in situ sont préférables puisqu'ils permettent de tester un volume substantiel de matériel avec une perturbation minimal ainsi que l'évolution des propriétés au cours du temps. De ce fait une série d'essais ont été réalisés in situ sur une paroi en ciment-bentonite de sept ans pour comparer les méthodes de pénétration au cône, de packer et de pressiomètre autoforeur. Les résultats suggèrent que toutes ces méthodes ne sont pas toujours appropriées. Les données montrent aussi que la perméabilité in situ de la paroi est souvent plus élevée que les valeurs typiquement obtenues sur échantillons en laboratoire. Cette différence peut être attribuée à la nature hétérogène de la paroi à l'échelle du terrain.

1 INTRODUCTION

The use of slurry trench cut-off walls for the containment of contaminants has become more prevalent in the last decade, with cement-bentonite walls commonly used in Europe and the United Kingdom. Cement-bentonite walls are constructed using the single phase method where the trench supporting slurry is allowed to set in place to form the hardened wall material.

Although past studies have focused on the effects of the constituent materials on the permeability, strength, and chemical compatibility through laboratory testing, there is little understanding of the behaviour in situ. Nevertheless, proper geotechnical characterisation of the in situ permeability and deformation characteristics is required in order to improve the state of the art of design of these systems. Currently these parameters are only reliably obtained through laboratory testing of samples which are either cast in the laboratory or taken from the field. However filed samples can only be taken from testing walls where entire blocks have to be excavated in order to obtain samples at depth. Rotary coring has been attempted in past research, but showed poor results. Hence operational walls can not be tested.

Furthermore, it has become evident that cement-bentonite walls are not homogeneous due to the presence of fissures and inclusions in the material, which depend largely on the type of host soil where the slurry wall is constructed. Also, typical confining pressures used in permeability testing are much higher than those which exist in the field and are thus not representative. Hence, there is a need for an appropriate in situ assessment technique for slurry trench systems. Once established, this method could be used to verify that the guidelines for construction of slurry trench cut-off walls (ICE. 1999) are met, as part of a quality assurance program after construction, as well as for the assessment of long-term behaviour.

At present there exists no approved method for the determination of all the required parameters, particularly the permeability of cement-bentonite walls (Tedd et al., 1995). Several studies have been completed in the past (Manassero, 1994; Tedd et al., 1997; Ratnam, 2002) using different devices. They have met with varying degrees of success, possibly due to differences in technique but also because of the change in material behaviour that occurs in cement-bentonite walls after construction. Tests conducted in wall material near the end of construction, or even 90 days after construction can be successfully completed since the wall stiffness has not achieved its maximum value. This allows proper seals between an in situ measurement device and the wall to be achieved for test methods that measure pore pressure response. At later stages in the design life, the wall stiffness can be very high, and so obtaining a proper seal is difficult unless an inflatable membrane can be used as part of the method (i.e. packer test and self-boring pressuremeter).

2 IN SITU PERMEABITLY MEASUREMENT METHODS

There are three candidates for measuring the in situ permeability of a cement-bentonite wall; (a) Piezocone, (b) Straddle Packer system and (c) Self-boring permeameter. Appling a hydraulic gradient across the wall is another possibility. However, the time frame required to obtain a permeability value is so large that it is not suitable for rapid assessment.

2.1 *Piezocone*

In order to indirectly estimate the hydraulic conductivity of a material, dissipation tests can be carried out with a recording of the response of the pore pressure while penetration is ceased. For such tests, the time for 50% reduction of the excess pore pressure that was generated during expansion has been linked with the coefficient of consolidation of the tested material (e.g. Lunne et al., 1997).

Alternatively, Manassero (1994) developed a scheme that combines the pore pressure increments, Δu, with the measured cone resistance, q_t, and the sleeve friction, f_s. The parameter, B_k, is defined as the following.

$$B_k = q_t^2 / \left(100 f_s \Delta u\right) \tag{1}$$

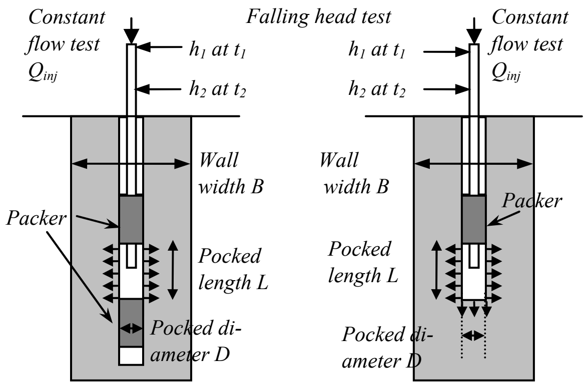
Using B_k, it has been empirically found that the hydraulic conductivity can be estimated using the following

$$\log k = A\sqrt{B_k} + B \tag{2}$$

where A and B are curve fitting parameters given by Manassero (1994).

2.2 *Straddle Packer system*

A packer device consists of upper and lower membranes that are inflated using air pressure in order to seal off a water filled cavity between them. Packer tests are usually performed in holes that have been previously bored, allowing for the lowering of the instrument into the hole. Once the device is situated at the proper depth, the membrane or membranes are expanded. In low permeability materials either falling head tests or constant flow tests can be carried out.



(a) Double packer system (Mark I geometry) *(b) Single packer system (Mark II geometry)*

Fig. 1 Packer test configurations

2.2.1 *Falling Head Tests*

Packer tests with single or double arrangements (see Fig. 1) can be used to perform falling head tests, with the head loss measured as a function of time. In such tests, the rods above the sealed off section of the borehole are filled with water, along with a measuring tube which is fixed onto the top of the system. For a wall with width B (see Fig. 1), permeability can be evaluated from the following equation.

$$k_r = \frac{\pi r_t^2}{F(t_1 - t_2)} \ln\left(\frac{h_1 - n\bar{h}}{h_2 - n\bar{h}}\right) \tag{3}$$

where r_t is the radius of the tube in which the head measurement is made, and h_1 and h_2 are the head at time t_1 and t_2, respectively (see Fig. 1). n is the fraction of the average active head $\bar{h} \approx (h_1+h_2)/2$ at the wall-soil interface. n is equal to zero when the soil is infinitely permeable compared to the wall. This can be used as a sensitivity analysis or, if a head measurement can be taken near the wall interface during a test, the actual value could be used.

The shape factor F depends on the geometry of the injection cavity (length L and diameter D), the width of the wall (B) and the hydraulic boundary condition of the cavity (i.e. double or single packer). Three dimensional finite element steady state seepage analysis can be performed to evaluate F. Ratnam et al. (2001) derived a formula that can be used for tests in materials of infinite domain using either double packer arrangements (Mark I) or single packer arrangements (Mark II). In this study, the analysis has been extended further to take into account the finite boundary. Such a case exists for typical slurry trench cut-off walls, where the material adjacent to the wall has a much higher permeability. Fig. 2 shows the FE-derived shape function for two different normalized widths of the wall (B/D) compared to the infinite case.

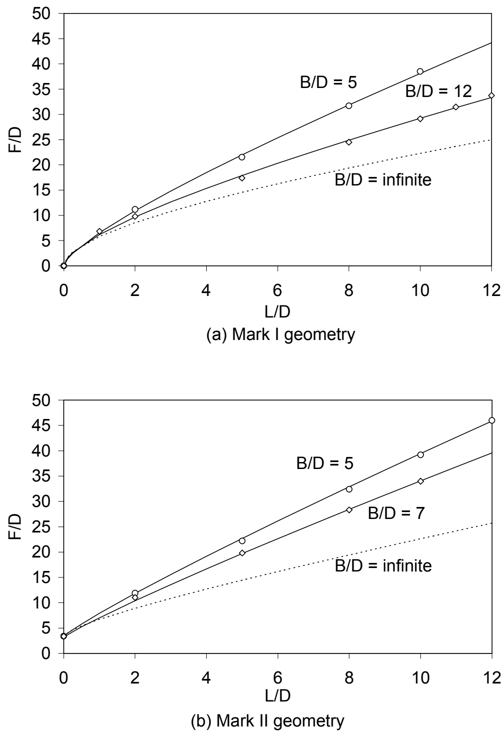


Fig. 2 Normalised shape factor F/D as a function of L/D and B/D

2.2.2 *Constant flow tests*

For constant flow tests the rods above the sealed off cavity are filled with water and fitted with a top cap with an air vent used to de-air the system. A constant flow pump is connected to the top cap and used to inject water at very low flow-rates with the corresponding pressure in the system data-logged. The permeability can be derived from the following equation.

$$k = \frac{Q_{inj}}{F(h_{ss} - nh_{ss})} \tag{4}$$

where Q_{inj} is the injection flow rate, h_{ss} is the steady state head measured at the cavity and nh_{ss} is the head at the wall-soil interface, which is given by the fraction of the measured head. The same shape factor F used in the falling head tests can be adopted.

2.3 *Self-boring permeameter*

Two of the main advantages of using the self-boring method are that a limited amount of disturbance is created in the surrounding soil (when compared to other in situ techniques) and that both deformation and strength parameters can be determined at the same time. Estimates of permeability can also be made directly using a standard self-boring pressuremeter with the constant flow technique (Ratnam, 2002). The geometry of such a cavity is known as the Mark II geometry (see Fig. 1), with the results from such tests interpreted using Eq. 4. At a given test depth, the probe can be pulled back in order to create a water filled cavity with different sizes. If the material is assumed to be isotropic, any differences in measured permeability at different *L/D* will be related to a scale-effect.

3 FIELD TEST SITE

The site used in the current research project is that of a disused gasworks where approximately 120m of cement-bentonite cut-off wall were constructed. The walls are in the form of two boxes, square in plan, plus three isolated lengths of wall. The test walls and boxes were constructed in 1996 as part of past research projects conducted to investigate the behaviour of slurry walls in chemically aggressive ground (Tedd et al., 1995&1997). The walls and the boxes are 0.6m in width, 5m deep and were constructed using the single-phase method using the following mix design: (a) 40 kg of sodium activated bentonite, (b) 30 kg of ordinary Portland cement, (c) 120kg of ground granulated blast furnace slag and (d) 1000kg of water.

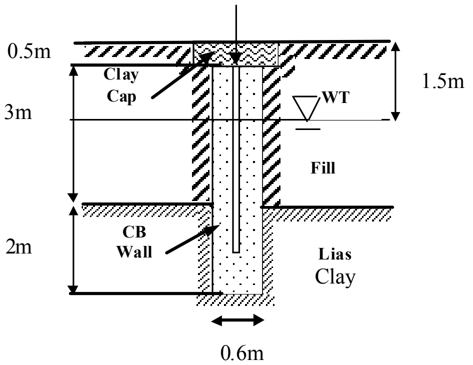


Fig. 3 Typical cross section

The site is contaminated, but to varying degrees. The walls are located in low contamination areas whereas the boxes contain the largest amount of contamination. The main contaminants consist of sulphates, spent oxide, coal residue, carbon black, and foul lime. The 3 metres of made ground overlie a deposit of stiff Lower Lias Clay, with the groundwater typically 1.5 to 1.6 metres below the top of the wall. The top of the wall is capped with compacted clay. The general geotechnical profile of a typical wall section is illustrated in Fig. 3. The tests were performed at various depths at seven locations of the walls and in some cases different test procedures were conducted in the same hole.

4 RESULTS AND DISCUSSION

4.1 *Piezocone Testing*

Pore pressure dissipation tests were carried out in the 8-year old wall. The permeability was estimated from the time at which 50% dissipation of pore pressure occurred. The data were compared to that of previous piezocone tests conducted in the same wall when it was 90 days old (Tedd et al., 1997).

Similarly to the previous tests data, the results indicated large values of permeability, in the range of 10^{-6} m/s. These large computed permeability values are likely to be due to either fracturing of the material or axial leakage. Even when using a penetration rate approximately one tenth that of the standard rate, the pore pressure response during penetration as well as during dissipation tests indicated that either fracturing or axial leakage had occurred since the rate of pore pressure dissipation was very high. Upon excavation of the clay capping on top of the wall, it was evident that vertical radial cracks had formed along the CPT hole, suggesting that fracturing of the material during penetration had occurred.

On the other hand, the packer tests conducted in the CPT hole created during the previous study (Tedd et al., 1997) show permeability values between 10^{-9} and 10^{-8} m/s (see next section). This implies that fracturing did not occur during the previous tests, when the wall was 90 days old, despite larger penetration rates. It is suggested that during those previous CPT tests, axial leakage had occurred along the side of the instrument, causing a higher computed permeability. Axial leakage is due to the high stiffness of the cement-bentonite material, and the low effective stresses that exists in and around the walls.

For comparison purposes, the data were also interpreted using the technique suggested by Manassero (1994). This resulted in more reasonable estimates of permeability of 10^{-9} m/s. However, it was found, similar to previous findings (Tedd et al., 1997), that the method is very insensitive to the input parameters. Furthermore, computed values of permeability for the current testing were found to be much lower despite the fact that fracturing had taken place. Thus, use of this interpretation method should be treated with caution.

4.2 *Packer System Testing*

Permeability tests were conducted using the packer system in three boreholes. Two holes of 50 mm in diameter were hand augured to a depth of 5 metres and a hole created during the previous CPT testing program described above (Tedd et al., 1997) was reamed out to a diameter of 50 mm. The geometry of the double straddle packer, which has 550 mm long cavity, is known as the Mark I geometry with $L/D = 11$ and $B/D = 12$ (see Fig. 1&2(a)). However, the bottom membrane can be dismantled allowing for a Mark II geometry with varying *L/D*. In this study *L/D* values of 11, 22, 31 and 41 were used.

The packer tests conducted in the old Piezocone hole included falling head tests (CU-PFH) as well as constant flow tests (CU-PCH). The tests in the manually augured holes also included falling head and constant flow tests (CU-A1FH, CU-A1CH, CU-A2FH and CU-A2CF). The measured permeability values are shown in Fig. 4. Also shown is the result of a previous falling head packer test (BRE-PFH) conducted in the same wall by Tedd et al. (1995).

The falling head tests gave permeability values ranging from 10^{-9} to 10^{-8} m/sec, which are above that of the specification (ICE, 1999) but within an acceptable range in practice (EPA, 1998). The results appear to show a decrease in permeability with depth. This reduction in permeability with depth is expected since results from laboratory tests indicate that increasing confining stress during setting decreases the hardened permeability of the material (Manassero et al., 1995). However, the permeability values are larger than those found from laboratory testing (Tedd et al., 1995; Ratnam, 2002).

The permeability values from the constant flow tests are larger than those from the falling head tests conducted in the same hole. The constant flow configuration requires a closed system and hence is affected by entrapped air. This tends to give a softer response during the test, and lower pressure values lead to higher permeability measurements. It is also possible that the larger pressures generally involved in the constant flow tests as opposed to the falling head tests lead to some leakage on the sides of the inflated membranes.

For the tests CU-A2FH and CU-A2CF, both Mark I and Mark II geometry were used. As shown by the direction of the arrows in Fig.4, it can be seen that in some cases an increase in pocket length resulted in a non-negligible increase in permeability. This result is attributed to an effect of scale and to the heterogeneous nature of the wall where at some locations inclusions and fissure are likely to form a network of preferential flow paths leading to a higher permeability. Lack of homogeneity has been evident in the laboratory for some field samples and preferential flow path have been observed through inclusions or fissures when injecting dye.

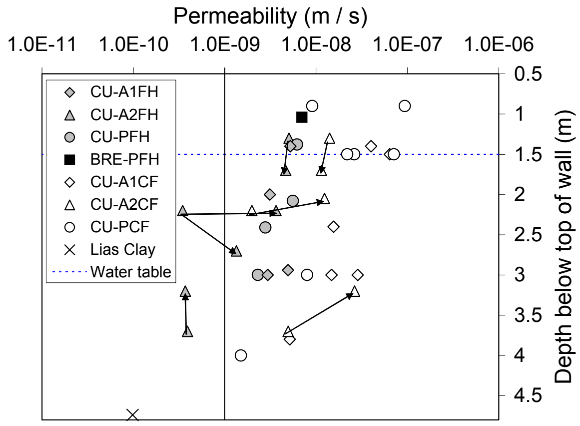


Fig. 4 Permeability values from packer system testing

4.3 *Self-boring Permeameter Testing*

The diameter of the self-boring permeameter used was 0.083 m, giving *B/D* of approximately 7. Various pocket sizes were used (*L/D* = 0, 2.7, 3.1, 11&14.6). The testing followed the procedure described by Sang et al. (2001&2002). The permeability values obtained (Fig.5) are in general slightly smaller than that obtained with the packer system and closer to the ICE specification (10^{-9} m/s after 90 days). This is possibly due to the less disturbing drilling process used by the self-boring method.

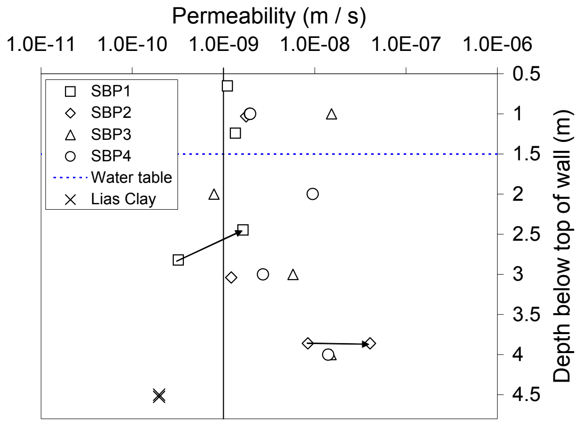


Fig. 5 Permeability values from SBP testing

The data do not show any significant increase in permeability for small increases in pocket size (i.e. when *L/D* varied from 0 to 2.7 or 3.1). However, as shown by the arrows on Fig.5, larger increases in pocket size (*L/D* = 11&14.6) at the same test location led to non-negligible increase in permeability. This is attributed to a scale effect associated with the heterogeneous nature of the wall.

The data obtained for test SBP4, which was conducted in one of the highly contaminated boxes, are similar to the data obtained in the uncontaminated walls (SBP1,2&3). This suggests that the chemicals present at this site had no apparent effect on the permeability of the cement-bentonite over an 8 year period.

5 CONCLUSIONS

The permeability values evaluated from the excess pore pressure dissipation during the piezocone tests were unrealistically high because of either fracturing or axial leakage. These results suggest that standard CPT testing may only be applicable to walls at a very early age (i.e. just after construction), while older walls will require methods that do not cause high shear strains around the device.

The permeability values obtained from the self-boring permeameter were in general smaller than the values obtained with the packer system. Hence, the drilling process appears to have some effect on permeability values. The measurements of permeability from the SBP and the packer tests gave values generally above that required by the specifications. This was not unexpected since the bulk of published laboratory data on permeability testing uses confining pressures much higher than that which exist in such shallow systems. When testing large cavities an apparent scale effect seems to exist. This is likely to be the result of localised heterogeneity occurring in the form of fissures or inclusions. Although chemical diffusion from the contaminated side to uncontaminated side can be more homogeneous, this localised high advection implies that counteracting contaminant diffusion by advection may not be effective.

It should be noted that the in situ mechanical properties may be just as important as the permeability since it is the deformation characteristics which will be required in order to determine the possibility of cracking when various types of strain are induced when conducting in situ tests (e.g. over-pressurisation of membranes). Current work is investigating this in order to help developing guidance that provides references for in situ assessment of slurry trench systems.

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