Hydraulic Conductivity Assessment of Slurry Wall Using Piezocone Test

By M. Manassero[1]

Abstract: Cone-penetration tests (CPTs) with pore pressure (u) measurement or piezocone tests (CPTUs) are carried out inside a cutoff wall for polluted-groundwater containment. The backfilling material for the cutoff wall is a typical cement-bentonite (CB) self-hardening slurry whose composition is 76.8% water, 19.2% blast furnace cement, and 4% sodium bentonite. A tentative framework for interpretation of CPTUs in terms of hydraulic conductivity (k) is developed. In particular, a continuous assessment of hydraulic conductivity along a vertical profile is attempted by combining the piezocone penetration parameters [i.e. total point resistance (q_t), pore-pressure increment (Δu), and sleeve friction (f_s)]. The obtained k results are comparable with results from CPTU dissipation tests, in-situ borehole infiltration tests, and laboratory tests performed on the same CB mixture. The test results indicate that the CPTUs are a promising tool for in-situ quality control of cutoff walls in terms of evaluating the actual hydraulic conductivity of the completed cutoff wall and, to some extent, of detecting and locating hydraulic defects that, in many cases, are the main causes of poor in-situ performance.

INTRODUCTION

The use of cutoff slurry walls as containment systems for polluted subsoils has increased considerably (Paul et al. 1992). The main backfill materials for this kind of containment barrier in Western European countries are cement-bentonite (CB) mixtures. In addition, many types of construction equipment (e.g., Hydrofraise) and procedures (e.g., single-phase and double-phase) together with special additives for the cement-bentonite mixtures have been used and patented by specialized contractors in order to obtain the best sealing, deformability, and durability performance for cutoff slurry walls used as containment barriers against pollutant migration (Ryan 1987; Meseck and Hollstegge 1989; De Paoli et al. 1991; Muller-Kirchenbauer et al. 1991; Esnault 1992; Manassero and Pasqualini 1992).

The main concern of containment barriers for polluted areas is the check of the actual in-situ effectiveness in terms of hydraulic conductivity, pollutants diffusion and sorption, deformability, and durability. Among the features to be checked, hydraulic conductivity or permeability plays a fundamental role for the following reasons.

- Advective transport, as a result of seepage, is usually the main pollutant migration mechanism in terms of mass flux
- Diffusive transport is influenced strongly by the structure of the porous media via the tortuosity factor (τ) and the effective porosity (θ), which are linked closely to hydraulic conductivity (Shackelford and Daniel 1991)
- Low hydraulic conductivity generally improves the durability and

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resistance to chemical attack on cement-bentonite mixtures (Jefferis 1990)

The assessment of the small-scale hydraulic conductivity of CB mixtures is straightforward via laboratory tests on samples taken in situ during casting operations or molded and cured directly in the laboratory. Unfortunately, these samples are not always representative of the actual in-situ permeability of the whole barrier. Localized defects such as random variations of the mixture composition during preparation in the field, sand lens inclusions, cracks and fissures following slurry consolidation, or the displacement of the surrounding soil can result in a poor correlation between laboratory and field assessed values of the permeability of CB slurries.

Field permeability tests (e.g. borehole permeameter, preinserted porous probes, self-boring permeameters, etc.) seem to produce more-reliable results than do laboratory tests in terms of assessing the actual in-situ performance of containment barriers (Leps 1989). There is also the possibility of carrying out large-scale in-situ tests (Ryan 1987; De Paoli et al. 1991) by confining a small area in the field and performing a pumping test. Although this is the best test for checking construction procedures, only a localized and relatively small portion of the final barrier is tested. However, field tests are expensive and time-consuming and, therefore, it is not always possible to perform the number of tests required for statistically significant results.

The use of cone-penetration tests (CPTs) with pore pressure (u) measurements, or piezocone tests (CPTUs), is proposed in this paper for in-situ quality control in terms of the hydraulic conductivity of CB cutoff slurry walls. The proposed methodology, taking into account the previous observations, tries to comply with the requirement for a fully reliable, feasible, and inexpensive assessment of the in-situ performance of CB cutoff slurry walls. The aim of the proposed procedure is to offer a framework for the hydraulic behavior assessment of an in situ CB mixture and, to some extent, to detect localized defects in slurry walls. In addition, a case history of the use of the CPTU to provide quality control of a CB cutoff slurry wall is presented to demonstrate the proposed procedure and to illustrate its utility and potential.

HYDRAULIC CONDUCTIVITY OF CEMENT-BENTONITE SLURRY WALLS

The main factors influencing the hydraulic conductivity of CB slurry walls are listed and briefly discussed in this section.

Mixture Composition

An increase in solids content (cement and/or bentonite and/or filler) in lieu of water decreases the hydraulic conductivity. Sodium bentonite and furnace slag cement are better than calcium bentonite and portland cement, respectively, for getting low hydraulic conductivity. The hydraulic conductivity of a basic CB mixture can be decreased by more than one order of magnitude by using special dispersive additives as the sodium metacrilates (De Paoli et al. 1991).

Setting Time

Setting time is one of the main factors that influences the hydraulic conductivity of CB mixtures (Jefferis 1981; Schweitzer 1989; Meseck and Holl-

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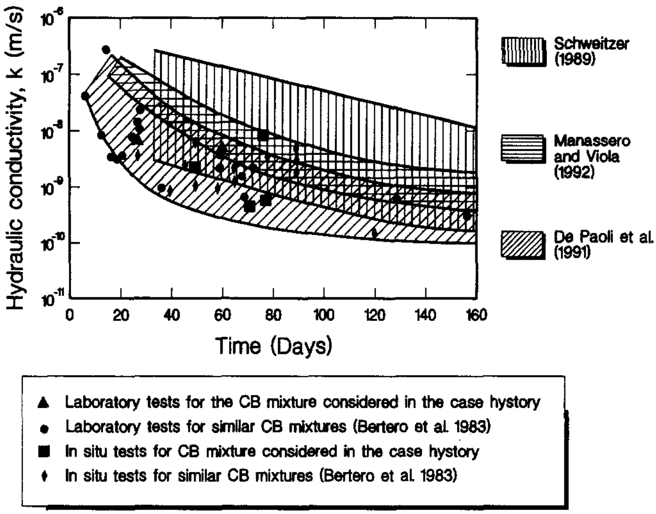

FIG. 1. Hydraulic Conductivity versus Curing Time

stegge 1989; De Paoli et al. 1991; and Manassero and Viola 1992). The hydraulic conductivity versus time trends of some typical CB mixtures, including the one in this study, are shown in Fig. 1. The major decrease in permeability occurs in the first two months of aging; nonetheless, a continued decrease of hydraulic conductivity can still be expected even after this period.

Confinement Stresses

The hydraulic conductivity of CB mixtures is typically insensitive to variation in the confining pressures below the isotropic effective threshold stress in compression σ'_y, which causes the failure of cementation bonds and the consequent significant volumetric strain due to the collapse of the solid skeleton. On the other hand an appreciable hydraulic conductivity decrease can be observed when effective confining pressures during the setting time of the specimens are greater than the current threshold stress σ'_y of the mixture (Jefferis 1981). Further research is needed to fully clarify and quantify this particular aspect of mechanical and hydraulic behavior of CB mixtures.

Hydraulic Gradient

Jefferis (1981) reports an example of a common CB mixture that was not damaged by an hydraulic gradient of 2,000 applied for 40 days. Therefore, it appears that CB mixtures are able to withstand a very high hydraulic gradient. However, care must be taken when high gradients act together with aggressive permeants (Jefferis 1990).

Permeant Type

The effects of permeant containing aggressive chemical compounds are not within the scope of this paper. However, it is important to outline that the cement in these mixtures is much more sensitive to chemical attack than bentonite due to the support function that the cement develops after hardening of the mixture (Jefferis 1990). Both low hydraulic conductivity and

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high confining stresses tend to reduce the sensitivity of the mixture to chemical attack, at least in the short term.

Preparation of Specimens

In general, CB mixture qualification and suitability tests are performed on specimens hardened directly in the test mold or prepared with the correct dimensions for flexible wall permeameters (molded samples) so that no trimming operations are needed. "Undisturbed samples" obtained by drilling and sampling operations commonly used for soil are often required to check cutoff wall performance after hardening of the mixture. Due to the rather brittle behavior of CB mixtures in undrained conditions and to the sensitivity to both mechanical and hydraulic fracturing and thermal shock during drilling operations, it is difficult to obtain a large percentage of representative samples of the cutoff wall regardless of the sampling procedure. As a result, one cannot be sure if poor test results are due to sample disturbance or low quality of the in-situ mixture.

Scale Effect

The scale effect on hydraulic conductivity is a very well known aspect as far as compacted clay liners are concerned (Daniel 1984; Day and Daniel 1985; Trautwein and Williams 1990; Shackelford and Javed 1991). Similar phenomena involve vertical barriers for pollution control. Laboratory tests on small specimens may not be representative of the actual performance of the cutoff walls. These discrepancies arise because of the presence of defects due to construction problems (i.e. joints between panels, localized lenses of coarse soil, supported slurry filled windows or ineffective bottom key), cracks for large deformations of surrounding soil, and/or chemical degradation. An appreciation of the influence of defects on actual cutoff wall performance can be gained from the plots in Fig. 2, which shows a dramatic

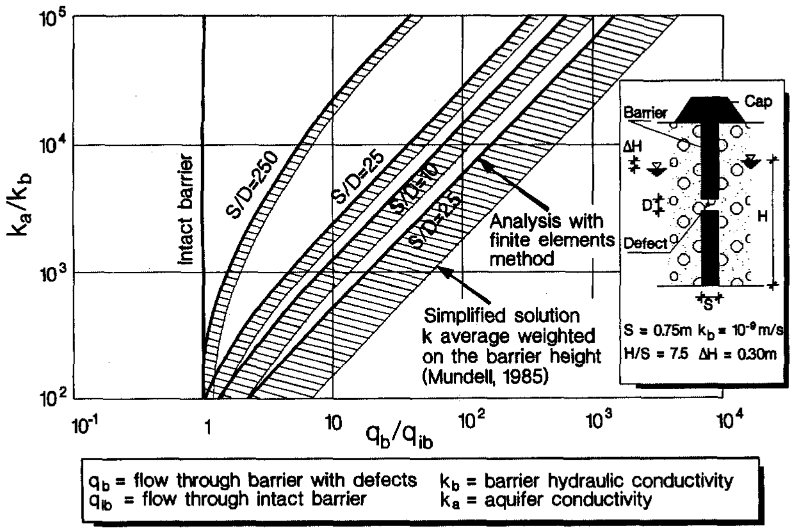

FIG. 2. Hydraulic Flow Increments due to Defect in Vertical Barrier [adapted from Mutch (1990)]

increase in flow rate due to a thin layer of permeable material (e.g. sand or gravel) in a vertical barrier.

Typical frequency distribution of permeability values measured after 28 days of setting time from 172 laboratory tests for the CB mixture evaluated in this study are plotted in Fig. 3. Flexible-wall permeability tests were performed with effective confining stresses at the middle height of the specimens equal to 100 kPa and applied gradients (i) across the sample equal to 30. Specimen dimensions were 50 mm in diameter and 200 mm in height.

In-situ infiltration tests were set up on the slurry wall of the case history using preinserted pipes before CB hardening. Falling-head tests were performed paying special attention to avoid hydraulic fracturing (Leps 1989). The interpretation procedures of *Control* (1986), Boutwell and Derick (1986), and Teeter and Clemence (1986) were used to get the permeability test results shown in Table 1. In this particular case history the few in-situ infiltration tests seem to be, on average, in good agreement with laboratory tests also considering the different curing time and even though the scatter of in-situ tests is much higher than that of laboratory tests (see Figs. 1 and 3).

PIEZOCONE TESTS (CPTUS)

A vertical barrier made up of a CB cutoff slurry wall was built to contain subsoil pollution underneath a chemical plant located in the northern part

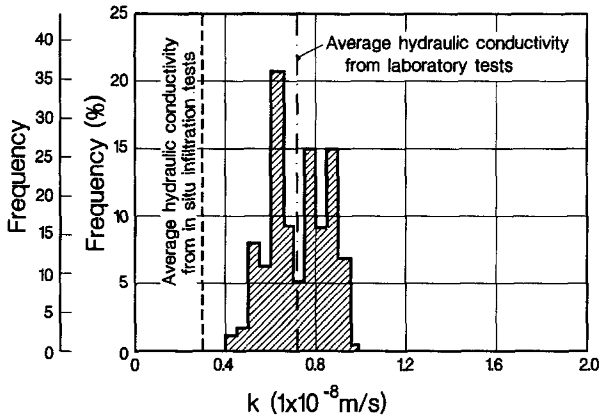

FIG. 3. Frequency Distribution of Hydraulic Conductivity Test Results on 172 Laboratory Specimens of CB Backfill Mixture of Case History

TABLE 1. Results of In-Situ Permeability Tests on Cutoff Wall of Case History

Panel number (1)	Casting date (2)	Infiltration test date (3)	Curing time (days) (4)	Hydraulic conductivity (m/s) (5)	Average hydraulic conductivity (m/s) (6)
1B	03/04/92	04/24/92	51	1.9×10^{-9}	2.9×10^{-9}
2B	01/30/92	04/16/92	77	8.5×10^{-9}	
3B	02/04/92	04/14/92	70	5.2×10^{-10}	
4B	01/29/92	04/15/92	77	5.6×10^{-10}	

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of Italy. The total length of the barrier is 2.5 km with depths ranging from 3 to 15 m. The wall passes first through an alluvial formation of very pervious sand and gravel and is embedded from 1.5 to 2 m into bedrock more than 150 m thick and consisting of a marl with very low hydraulic conductivity ($<10^{-9}$ m/s). The thickness of the CB wall is 1.2 m.

It was decided to test the vertical barrier with a piezocone probe during the quality control activity at the end of the CB wall construction on the basis of the following considerations.

- A procedure that allows a sufficient number of tests to be performed to obtain statistical significance in a short time is required.
- The location of tests should be random and not localized before construction, as in the case of preinstalled wells, and the test procedure should be easy and repeatable and not influenced by the operators.
- The useful information should concern not only hydraulic conductivity but also strength and deformation characteristics which are essential for the assessment of the global performance.
- The results should be easy to evaluate and interpret yet be based on a well-established theoretical framework.

The piezocone test is able to satisfy these requirements.

The piezocone probe used for the tests inside the CB barrier (see Fig. 4) is characterized by a water-pressure transducer activated by a grease fluid (like the wheel-bearing lubricants) that fills a slot located just behind the cone shoulder (*Technical* 1991). The CPTUs were carried out in the panels where the infiltration tests were also performed. One reading was recorded every second for each parameter (i.e. point resistance, q_c; water pressure, u; and sleeve friction, f_s) at a penetration rate of 2 cm/s. Typical results of the CPTUs are given in Fig. 4 pointing out in particular CPTU 32 taken as an example in the following section of the paper. Unfortunately, the limit

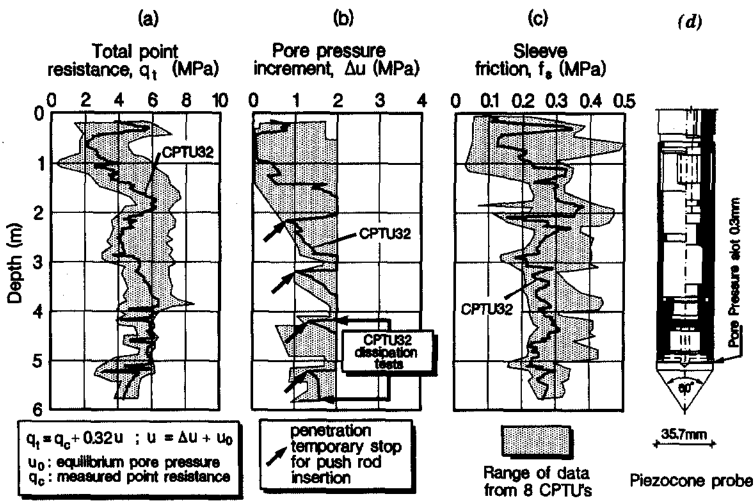


FIG. 4. Piezocone Probe and Typical Results of Piezocone Tests Carried Out in CB Mixture of Case History

of the Δu transducer was restricted to 2 MPa, thus preventing the measurement of higher pore-pressure values [see Fig. 4(*b*)]. No significant cone-probe penetration problems occurred since the undrained strength (s_u) of the CB mixture at testing time varied from 0.4 to 0.6 MPa and the penetration resistance ranged from 4 to 6 MPa showing a q_c/s_u ratio of about 10.

Overall Response to Cone Penetration and Comparison with Natural Soils Behavior

The results of a typical CPTU carried out in the CB mixture (CPTU 32) have been plotted on the Robertson et al. (1986) classification charts (Fig. 5) to compare the overall response to cone penetration of a CB mixture with that of natural soils and to provide qualitative indications about the mechanical and hydraulic behavior of this man-made porous medium. Based on the B_q-q_t classification system [see Fig. 5(*a*) also for symbols explanation], the following observations are made.

Because of the limit (2 MPa) on Δu transducer the actual values of B_q may be slightly larger. Therefore the points in Fig. 5(*a*) that could be moved to the right have been displayed. However, in the following considerations such possible shiftings have been neglected since it is impossible to quantify them.

Most of the CPTU results lie in the range of natural soils such as clay, clayey silt, and silty clay (zone 5), which are characterized by a fully undrained behavior during penetration and, therefore, a rather low hydraulic conductivity is expected for the CB mixture.

Some of the CPTU results fall into the range of values for silt and sandy silt in which case a lower efficiency in terms of hydraulic conductivity should be expected for the CB mixture in comparison with results falling inside zones 4 and 5.

Parameters, such as overconsolidation ratio (OCR), lose their significance in the case of CB mixture because in situ the mixture is essentially normally consolidated but cemented.

Based on the R_f-q_t (classification system) [Fig. 5(*b*)], the following observations are made.

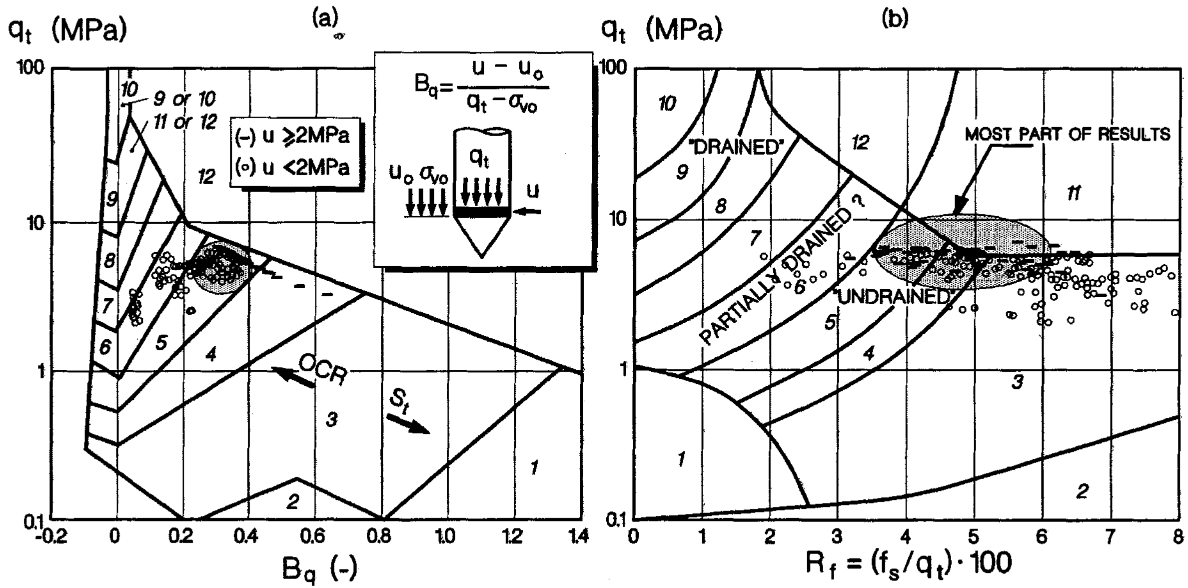
On average, the equivalent natural soil types are finer (lower hydraulic conductivity) than when using the B_q-q_t classification chart with most of the results being in areas 3, 4, and 5 (clay to clayey silt).

Few results fall in area 6 (clayey and sandy silt).

The majority of the results are very close to area 11 (i.e. very stiff, possibly cemented fine grained soil) indicating the cemented structure, high strength, and stiffness of the CB mixture.

Unconsolidated undrained tests carried out on the CB mixture indicate a marked strain softening behavior as a consequence of the contractive behavior due to an initial void ratio (e), which is usually on the order of 200–300%. The specific strain-softening or sensitivity characteristics observed in the unconsolidated undrained tests for the CB mixture are not recognized in the CPTU classification charts.

The attempt to use the more recent soil classification charts of Robertson (1990), which normalize the total resistance q_t with respect to the effective overburden pressure σ'_{vo}, gives poor results since the reduced values of σ'_{vo}, due to the very low total unit weight of the considered mixture ($\gamma \cong$ 1.2 kN/m^3), lead most of the experimental points close to the charts bound-



ZONE	SOIL BEHAVIOUR TYPE	ZONE	SOIL BEHAVIOUR TYPE	ZONE	SOIL BEHAVIOUR TYPE
1	Sensitive fine grained	5	Clayey silt to silty clay	9	Sand
2	Organic material	6	Sandy silt to clayey silt	10	Gravelly sand to sand
3	Clay	7	Silty sand to sandy silt	11	Very stiff fine grained (•)
4	Silty clay to clay	8	Sand to silty sand	12	Sand to clayed sand (•)

(•) Overconsolidated or cemented

FIG. 5. Results of CPTU on CB Mixture in Terms of Soil Classification Charts by Robertson et al. (1986) (Data from CPTU 32)

aries and out of the zones defining the soils of interest. This is particularly true referring to the classification approach based on B_q-q_t.

The previous observations outline the peculiar features of the considered material compared with the common soils.

Hydraulic Conductivity from Consolidation Parameters

In one-dimensional strain conditions (i.e., oedometer test) the permeability of saturated porous media is related to their deformability in drained conditions as follows:

$$k = \frac{c\gamma_w}{M} \tag{1}$$

where c = consolidation coefficient that can be assessed directly from CPTU; M = oedometer modulus; and γ_w = unit weight of water.

The assessment of c-values of fine-grained soils from the CPTU dissipation tests has been investigated extensively (Torstensson 1975; Wissa et al. 1975; Baligh and Levadoux 1980; Tumay et al. 1981; Battaglio and Maniscalco 1983; Teh and Houlsby 1991). Many aspects of this problem that arise with natural soils (such as anisotropy, smear of the piezometer filter during penetration, stratification, and macrostructure) do not exist or are negligible with good-quality CB mixtures. However, other aspects, such as hydraulic fracturing during penetration due to a pronounced contractive mechanical behavior, can arise and need to be carefully investigated.

The Teh and Houlsby (1991) procedure was chosen for interpretation of the CPTU dissipation tests because it allows one to take into account, through the rigidity index (I_r), the most appropriate strength and deformability behavior of the CB mixture for the evaluation of initial excess pore-pressure distribution around the penetrating cone. The rigidity index for an elastic perfectly plastic material in undrained conditions is defined as $I_r = E_u/3s_u$, where E_u is the elastic Young's modulus in undrained conditions. Looking at the data from unconfined compression tests and unconsolidated undrained triaxial tests carried out on the mixture in the case history it is possible to observe typical values of $E_{uf}/s_u \cong 160$ [see also Mastrantuono and Tornaghi (1977)], where E_{uf} is the secant modulus at peak strength. Therefore, the best evaluation for the rigidity index of the considered CB mixture is $I_r = 53$. Baligh and Levadoux (1980) have postulated that the consolidation coefficient obtained from the early stages of dissipation ($\leq$50% consolidation) is relevant for reloading conditions, and, therefore, reflects the behavior of overconsolidated (OC) soils even though their CPTU were carried out in normal consolidated (NC) deposits.

Based on the aforementioned concepts an assessment of the consolidation coefficient c has been carried out for the considered CB mixture taking into account the time for 50% of pore-pressure dissipation (t_{50}) as suggested by Robertson et al. (1992), who refer to the Teh and Houlsby (1991) interpretation method. The values of t_{50} from nine dissipation tests range from 10 s to 40 s with an average result of about 20 s, this last value leads to a c result of 2.5×10^{-5} m²/s. The theoretical solution by Teh and Houlsby (1991) for $I_r = 53$ and the range of variation of the experimental data from the considered dissipation tests have been plotted in Fig. 6 using for all the experimental data the average value $c = 2.5 \times 10^{-5}$ m²/s in order to get the normalized time factor T. The experimental curves show the same shape with respect to the theoretical curve up to 80–90% of excess-pore-pressure

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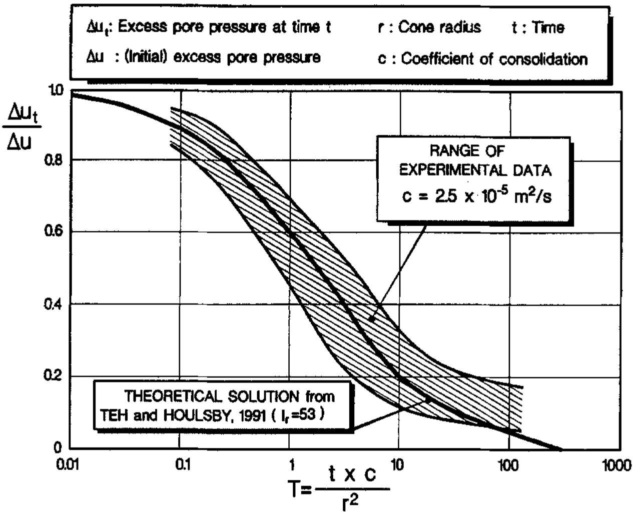

FIG. 6. Interpretation of Dissipation Tests in CB Mixture of Case History

dissipation; thereafter, the experimental consolidation rate decreases as in the case of the consolidation process developing in the NC range.

A first assessment of hydraulic conductivity k from consolidation coefficient by CPTU dissipations can be made using (1) and referring to the oedometer modulus (M) in the OC range. The use of M is strictly valid only in one-dimensional strain conditions but is adopted here for the preliminary assessment of k-values from CPTU dissipation tests as suggested by Wroth (1984), Baligh and Levadoux (1986), and Battaglio et al. (1986). A reasonable evaluation of oedometer modulus for the OC range for the CB mixture in this case history lies between 50 and 100 MPa with an average value of 75 MPa (Mastrantuono and Tornaghi 1977). Therefore, based on (1) and considering any c-values from interpretation of the available dissipation tests, the permeability can be estimated to be between 2.1×10^{-9} m/s and 8.1×10^{-9} m/s. This range of variation in k from CPTU dissipation tests is in very good agreement with the laboratory permeability tests and in-situ infiltration tests of the CB mixture (see Fig. 1 and Table 1).

Hydraulic Conductivity from Piezocone Penetration Parameters

The main goal of an in-situ quality control of CB cutoff walls is the detection and location of defects that can decrease the containment system performance in terms of overall hydraulic conductivity. The piezocone test can be a useful tool for investigating in-situ, large-scale, CB-cutoff-wall hydraulic conductivity since, under standard procedures, a continuous record of penetration parameters is provided along the vertical axis of the wall. A first indication of the location of possible defects can be obtained easily by observing excess-pore-pressure measurements (Δu) during penetration. A localized reduction of Δu (disappearance or very low value) can be considered as an indication of possible defects. A first attempt at quantifying the hydraulic conductivity and the influence of the defects on the overall performance of the cutoff wall along the vertical axis can be performed using the following procedure.

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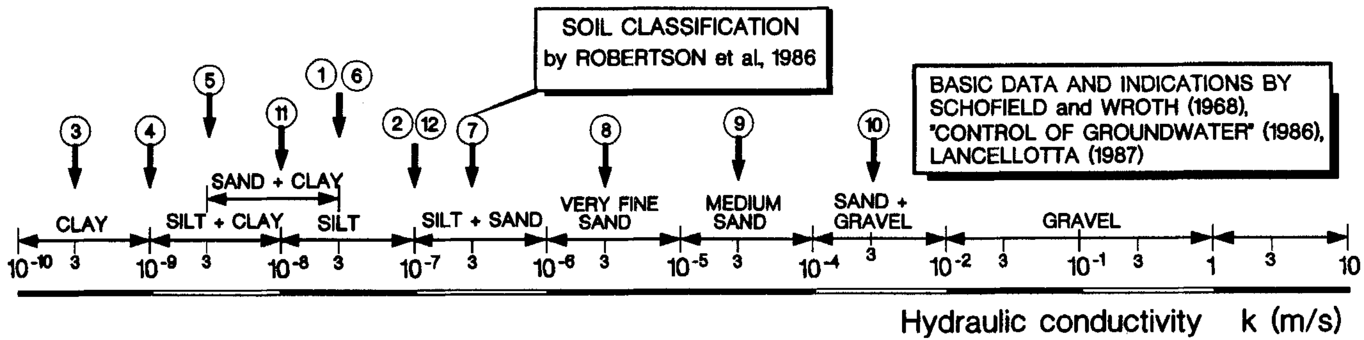

FIG. 7. Tentative Hydraulic Conductivity Assignment to Main Classes of Soil

1. Reference hydraulic conductivity values are assigned to the basic classification categories of natural soils (see Fig. 7).

2. A plot of k-values versus depth can be performed based on both B_q-q_t and R_f-q_t classification models (see Fig. 5).

Fig. 8 shows the results of the proposed procedure using the CPTU 32 data taken as an example. Based, in particular, on the results from the B_q-q_t classification chart, it is possible to observe a high-hydraulic-conductivity zone close to the top of the cutoff wall (depth <1 m), which is probably due to evaporation and drying problems during hardening of the CB mixture above the ground-water table and close to the natural ground level. Some of the other peaks of hydraulic conductivity below 1 m of depth can be attributed to the penetration stops due to operational activities during CPTU (i.e., the addition of push rods or dissipation tests).

Since Δu measurement was limited to 2 MPa the interpretation of soil type and hence k can be influenced at the depths where $\Delta u > 2$ MPa, as

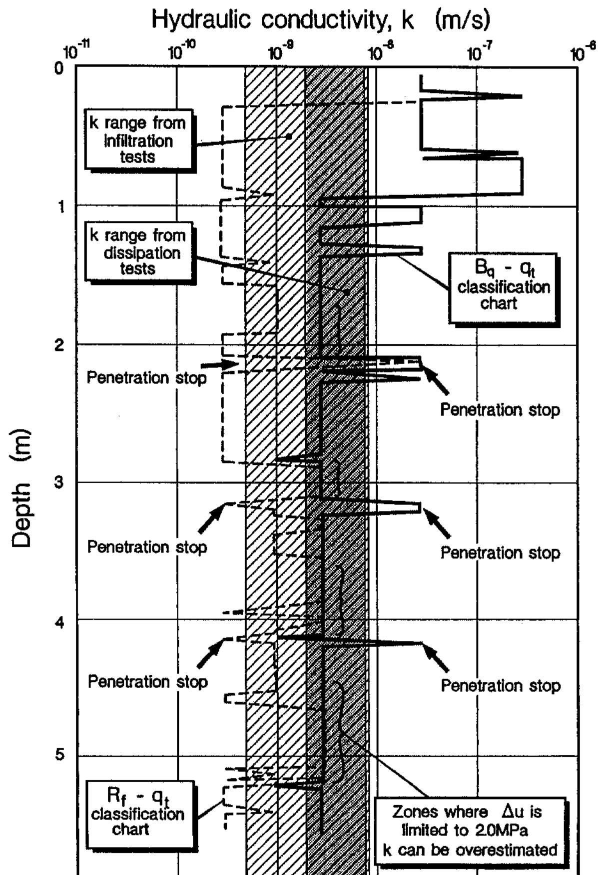

FIG. 8. Hydraulic Conductivity versus Depth Based on Soil Classification (Data from CPTU 32)

pointed out in Fig. 8. However, in the remainder of this paper the value of $\Delta u = 2$ MPa is considered a reliable and operative parameter simply because the actual values cannot be better quantified.

More-detailed information about hydraulic conductivity versus depth can be obtained by linking the piezocone penetration parameters and the hydraulic conductivity k with a continuous function. The initial step in defining the aforementioned relationship is to combine q_t, Δu, and f_s into a coefficient that maximizes the influence of hydraulic conductivity and minimizes the influences of the other parameters related to the mechanical behavior (e.g., strength, deformability, etc.). The overall response to the piezocone versus the main basic and state material parameters that govern the penetration phenomenon includes the total point resistance (q_t) and pore pressure increment (Δu), which are mainly functions of material peak strength (τ_p) deformability (E), dilatancy (ψ) (positive for expansion and negative for contraction) and permeability (k), and the sleeve friction (f_s), which is mainly a function of remolded strength (τ_r). Therefore, the following qualitative relationships are defined:

$$q_t = f_1(\tau_p, E, \psi, k) \tag{2}$$

$$f_s = f_2(\tau_r) \tag{3}$$

$$\Delta u = f_3(\tau_p, E, \psi, k) \tag{4}$$

For a more or less constant τ_p/E ratio as expected for this kind of CB mixture (Mastrantuono and Tornaghi 1977), (2)–(4) reduce to the following simplified relationships:

$$q_t = f_4(\tau_p, \psi, k) \tag{5}$$

$$f_s = f_5(\tau_r) \tag{6}$$

$$\Delta u = f_6(\tau_p, \psi, k) \tag{7}$$

For a simplified analysis, the three fundamental CPTU measurements can be combined tentatively into a single parameter, B_k, as follows:

$$B_k = \frac{q_t^2}{100 f_s \Delta u} = \frac{q_t}{R_f \Delta u} \tag{8}$$

which, upon substitution of (5)–(7), becomes

$$B_k = \frac{f_4^2(\tau_p, \psi, k)}{f_5(\tau_r) f_6(\tau_p, \psi, k)} \tag{9}$$

A further qualitative and crude simplification of (9) is as follows:

$$B_k = f_7\left(\frac{\tau_p}{\tau_r}, \psi, k\right) \tag{10}$$

An important observation is that the influence of k on q_t (i.e., f_4) is inversely related to the influence of k on Δu (i.e., f_6). Therefore, the influence of k on B_k [(10)] is strongly emphasized. In addition, since τ_p/τ_r represents the sensitivity S_t of the material. When S_t increases, the dilatancy ψ decreases, going toward contractive behavior, and the contributions of the terms S_t and ψ to the function f_7 tend to eliminate each other. As a result, a first approximation for B_k becomes

$$B_k = f_8(k) \tag{11}$$

At present, only empirical relationships can be presented to completely define the function f_8 and related parameters for the considered mixture. On the basis of the k-values defined in Fig. 7 and using the permeability results (Fig. 8) plotted versus B_k-values for the considered CPTU 32, a tentative fitting has been carried out (see Fig. 9). The tentative fitting is based on the following empirical equation:

$$\log k = A\sqrt{B_k} + B \tag{12}$$

The specific values of parameters A and B are

- From B_q-q_t classification [Fig. 9(*a*)]

$$\log k = 1.76\sqrt{B_k} - 9.91 \qquad (k \text{ in m/s}) \tag{13}$$

- From R_f-q_t classification [Fig. 9(*b*)]

$$\log k = 3.45\sqrt{B_k} - 11.95 \qquad (k \text{ in m/s}) \tag{14}$$

- From averaging log k of (13) and (14)

$$\log k = 2.61\sqrt{B_k} - 10.93 \qquad (k \text{ in m/s}) \tag{15}$$

In Fig. 9 are also reported: (1) The k-values from infiltration tests (see Table 1) versus the average B_k parameter at corresponding depths from the nearest CPTUs; and (2) the best estimates of k from dissipation tests versus the B_k parameter averaged on the 50 cm spanning the depth of the dissipation tests. It is possible to observe an encouraging agreement, looking in particular at the data from dissipation tests plotted in Fig. 9(*a*). This kind of data can be useful in calibrating the terms of the function f_8 for any particular CB slurry wall investigated with the proposed procedure.

The resulting hydraulic conductivity profile based on (13)–(15) versus depth is given in Fig. 10 for the CPTU 32 data. The k results are in very good agreement with the best estimate of k ranges from in-situ infiltration tests and CPTU dissipation tests. In particular, the k profile based on B_q-q_t classification charts seems to offer the most reliable results (even though referring to the depths where the Δu was limited to 2 MPa misleading results cannot be excluded with the present limited background). Looking at the localized anomalous values of hydraulic conductivity due to penetration stops (see Fig. 8), it is interesting to observe that in using the B_k interpretation approach a sort of compensation occurs and, at least in the considered CPTUs, such atypical values seem to be smoothed off (see Fig. 10).

On the basis of the procedure proposed by Mundell (1985) for performance assessment of landfill mineral liners with construction defects, the actual efficiency of an hydraulic barrier (e.g., a CB slurry wall) can be related directly to a weighted average of hydraulic conductivities measured at different locations (see also Fig. 2); hence, the average values of hydraulic conductivities assessed using the proposed procedure can be considered a representative value, on the conservative side, of actual performance of the vertical section of the diaphragm wall tested by CPTU. For the example considered herein, the actual in-situ permeability of the wetted zone (below

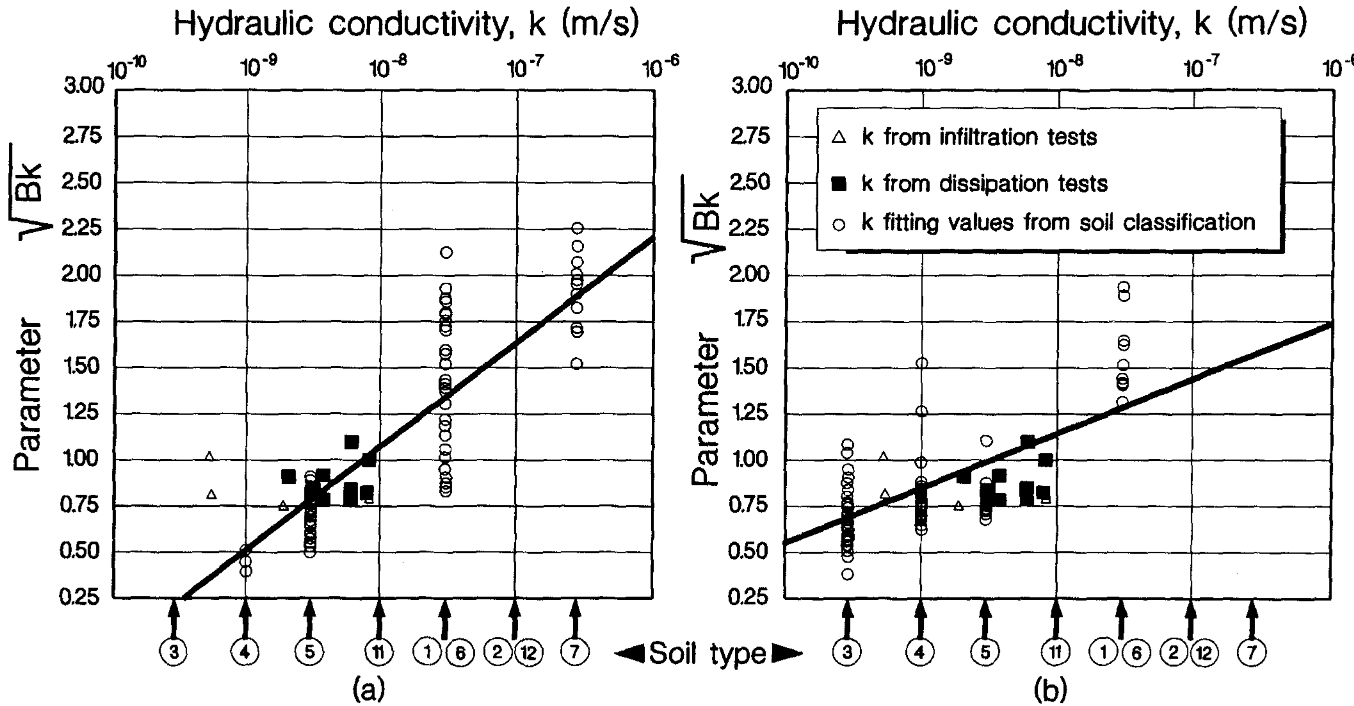

FIG. 9. B_k Parameter versus Hydraulic Conductivity (Data from CPTU 32): (*a*) from B_q-q_t Classification; and (*b*) from R_f-q_t Classification

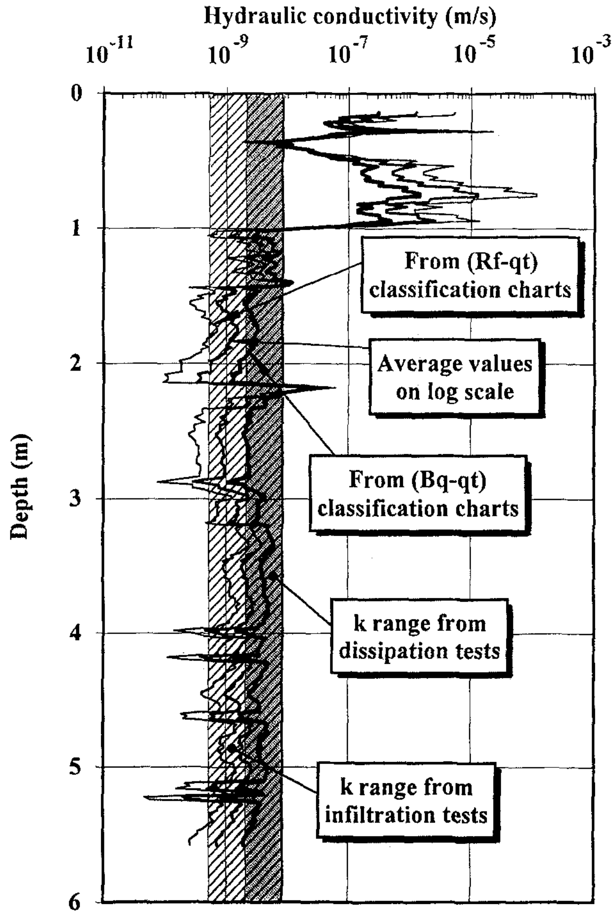

FIG. 10. Hydraulic Conductivity versus Depth based on B_k Parameter (Data from CPTU 32)

1 m of depth) of the panel has been estimated to be in the range of k = 1.0–3.5 × 10^{-9} m/s. If the whole panel height is considered, the k-value reaches 5 × 10^{-8} and 1.5 × 10^{-6} m/s, using (13) and (14), respectively.

Finally, it is interesting to compare the statistical distribution of the laboratory permeability test results performed on good-quality CB mixture samples (see Fig. 3) and k values from the proposed CPTU interpretation example. Plots of cumulative frequency distribution are shown in Fig. 11. The normal distribution fits very well both laboratory test results and the k-values from the CPTU 32 excluding from this last k population the values related to zones where some defects of the mixture have been detected (e.g., the first meter of depth, where evaporation and drying problems are apparent). The standard deviations of in-situ test results (in particular from B_q-q_t classification model) and laboratory test results are very close, providing an indirect validation of the framework proposed for the B_k interpretation approach illustrated in this paper. The difference in average of k-values between in-situ and laboratory tests is probably due to the very

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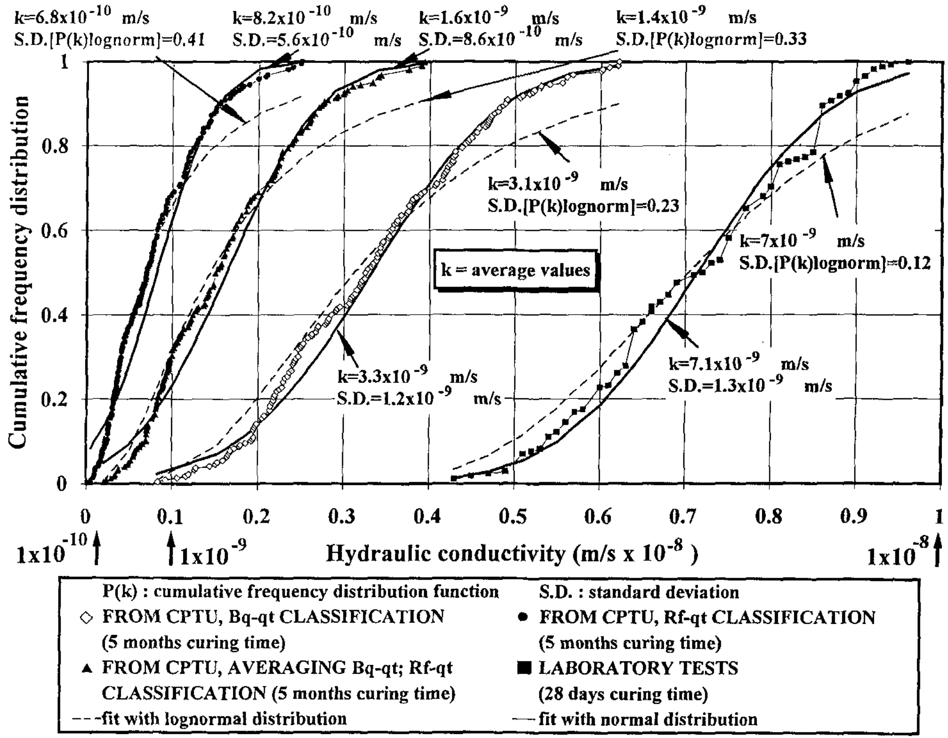

FIG. 11. Cumulative Frequency Distributions of CB Mixture Hydraulic Conductivity from Results of Laboratory Tests and CPTU 32

different curing time: 28 days for laboratory samples and from 100 to 150 days for CPTU tested panels.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A framework for in-situ assessment of an actual CB cutoff wall performance in terms of hydraulic conductivity was proposed using the CPTU. In particular, a continuous function linking an ad-hoc coefficient B_k with hydraulic conductivity (k) was set up and tested. The B_k coefficient is a combination of the three basic penetration parameters by CPTU: (1) Total point resistance; (2) sleeve friction; and (3) excess pore pressure. The proposed methodology is, at present, evaluated only with one kind of CB mixture, tested with eight CPTUs after five months of curing time; nevertheless, the results obtained from interpretation of the CPTUs are promising and give a rather satisfactory picture of slurry-wall behavior in terms of actual in-situ hydraulic properties.

Looking at the whole investigation results, the following final observations can be made.

CPTUs are able to outline zones where hydraulic conductivity defects exist, in particular the Δu parameter is very significant for this reconnaissance [see Fig. 4(*b*)] even though, some problems might arise concerning the response after penetration stops (at least using the equipment of the considered case history).

A first assessment of the range of wall permeability along the tested vertical is possible by simply classifying CB mixtures using charts for natural soils (see Figs. 5, 7, and 8).

Referring to the range of k-values from infiltration and dissipation in-situ tests, the results based on B_q-q_t and R_f-q_t classification charts seem to approach the upper and lower range of the mixture hydraulic conductivity, respectively.

The assessment of k can be improved and refined using an ad-hoc coefficient (B_k), which is based on the combination of the three basic data (q_t, Δu, and f_s) measured during CPTU.

It is important to calibrate the proposed procedure for any particular CB slurry wall, CPTU dissipation tests can be useful tools to calibrate the B_k-k relationship (see Fig. 9).

At present, the proposed interpretation framework of CPTUs in CB slurry walls in terms of hydraulic conductivity is only based on the considered case history, therefore it is important to stress on the limitation of the actual background and on the need to promote experimental and theoretical research in the future. After developing further research based on other case histories aimed at better calibrating and evaluating the proposed procedures, it may be possible to adopt this method to conveniently investigate the actual in-situ hydraulic performance of slurry walls.

Future investigations based on both experimental tests and theoretical modeling should concern the influence of boundary conditions (e.g., slurry wall thickness), the penetration rate (Elsworth 1993) and possibly two or more filters placed on the tip and shaft of the CPTU probe to get more data for a better definition of CB mixture behavior.

For deep diaphragm walls and very hard mixtures, verticality problems of the cone with a consequent extrusion of the cone from the slurry wall can arise. Therefore, it may be important to adopt CPT instrumentation that is able to recognize the exact cone position inside the slurry wall. In some cases, preborings may be necessary to carry out a satisfactory test along the whole barrier depth.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

B_k = parameter for hydraulic conductivity assessment by CPTU, $B_k = q_t/R_f \Delta u$;
B_q = pore pressure parameter ratio from CPTU, $B_q = (u - u_o)/(q_t - \sigma_{vo})$;
c = coefficient of consolidation, $c = Mk/\gamma_w$;
D = thickness of barrier defect;
E = deformability;
E_u = initial elastic modulus in undrained conditions;
E_{uf} = secant modulus at peak strength in undrained conditions;
e = void ratio;
f_s = sleeve friction;
H = aquifer thickness;
I_r = rigidity index, $I_r = E_u/3s_u$;
i = hydraulic gradient;
k = hydraulic conductivity of CB mixture;
k_a = aquifer hydraulic conductivity;
k_b = barrier hydraulic conductivity;
M = oedometer modulus;
$P(k)$ = cumulative frequency distribution function;
q_b = hydraulic flow through barrier with defect;
q_c = measured point resistance from CPTU;
q_{ib} = hydraulic flow through intact barrier;
q_t = total point resistance from CPTU;
R_f = friction ratio, $R_f = 100f_s/q_t$;
r = cone radius of CPTU probe;
S = barrier thickness;
S_t = sensitivity, $S_t = \tau_p/\tau_r$;
s_u = undrained shear strength;
T = consolidation time factor, $T = tc/r^2$;
t = time;
t_{50} = time for 50% of pore pressure dissipation;
u = pore pressure just behind cone shoulder;
u_o = hydrostatic or equilibrium pore pressure;
γ = total unit weight of CB mixture;
γ_w = unit weight of water;
ΔH = hydraulic head;
Δu = excess pore pressure just behind cone shoulder;
Δu_t = excess pore pressure just behind cone shoulder during dissipation tests;
θ = effective porosity;
σ_{vo} = overburden total stress;
σ'_{vo} = overburden effective stress;

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σ'_y = isotropic effective threshold stress in compression;
τ = tortuosity factor;
τ_p = peak shear strength;
τ_r = remolded shear strength; and
ψ = dilatancy.