Stress-dependent flow through fractured clay till: a laboratory study

John E. Sims, Derek Elsworth, and John A. Cherry

Abstract: Stress-dependent hydraulic conductivities of weathered fractured clay till were measured in a flexible-wall permeameter. Measured conductivities were in the range 10^{-7} to 10^{-8} cm/s, of the same order as the clay matrix (10^{-8} cm/s), and representing equivalent hydraulic apertures in the range 0–5 μm. In general, the isolated fractures exhibited strongly nonlinear closure characteristics and hysteretic behaviour under stress reversal. Some fracture samples exhibited only weak stress dependency, representing observable features of only nominal conductivity. Results of the investigations suggest fractures are closed to residual aperture for an overburden load of the order of 12 m, this defining an effective closure depth and the degree of maximum useful compactive effort that might be applied to "seal" fractures and reduce fluid migration.

Key words: fracture permeability, till, stress permeability, landfills.

Résumé : Les conductivités hydrauliques d'un till argileux altéré et fracturé ont été mesurées en fonction du niveau de contrainte à l'intérieur d'un perméamètre à paroi flexible. Les conductivités mesurées étaient comprises entre 10^{-7} et 10^{-8} cm/s, du même ordre de grandeur que celle de la matrice argileuse (10^{-8} cm/s) et représentaient des ouvertures hydrauliques équivalentes de 0 à 5 μm. Les fractures isolées présentaient en général des caractéristiques de fermeture fortement non linéaires et un comportement avec hystérésis sous inversion de contrainte. Quelques échantillons fracturés n'ont indiqué qu'une faible dépendance vis-à-vis des contraintes et n'ont montré que les caractères d'une conductivité nominale. Les résultats des recherches suggèrent que les fractures se réduisent à leur ouverture résiduelle pour une charge verticale d'environ 12 m, ce qui définit la profondeur effective de fermeture et le degré d'effort de compactage utile maximum pouvant être appliqué pour « sceller » les fractures et réduire la migration des fluides.

Mots clés : perméabilité des fractures, till, contrainte-perméabilité, décharge.

[Traduit par la rédaction]

Introduction

Clay-rich deposits are commonly favoured as locations for the siting of landfills for the containment of municipal or hazardous wastes. Such deposits are ubiquitous in glaciated areas (Flint 1971; Cherry 1989) and, if their properties are favourable, the deposits can form the primary means of containment for waste. In many surficial weathered clay till deposits, fractures are found from surface to depths ranging from 5 to 10 m (e.g., Keller et al. 1986; Ruland et al. 1991). There is also evidence for fracturing in certain unweathered subsurface till units located in the Interior Plains region of North America (Grisak and Cherry 1975; D. Thompson, personal communication, 1990).

The presence of fractures within clay-rich deposits can greatly increase bulk hydraulic conductivities over that of the intact clay. Vertical and horizontal bulk hydraulic conductivity values 2–3 orders of magnitude higher than values for bulk unfractured till have been measured for certain surficial fractured clay till units (e.g., Keller et al. 1988; McKay et al. 1993). Fracturing, where present, can influence the nature and rate of transport of contaminants in the event of a release of contaminants from a waste zone. Therefore, an important consideration related to the integrity of landfills, and other hazardous waste disposal facilities located in or on fractured clay-rich deposits, is the influence of in situ stresses at depth on the closure, and corresponding hydraulic conductivity characteristics, of fractures.

Investigations on the influence of stress on flow and transport through individual rock fractures are well documented (e.g., Witherspoon et al. 1980; Pyrak-Nolte et al. 1987). Studies of similar behaviour in isolated clay till fractures are not reported in the literature. Investigations by Harding (1986) and others (A. Ylinen, personal communication, 1991) have been directed toward an assessment of the influence of stress on till fracture closure; however, this work has concentrated on testing at the field scale and therefore has focused mainly on bulk clay response. Results of other studies (e.g., McKay 1991) have shown that bulk hydraulic conductivities in surficial clay till units generally decrease with depth. However, this decrease is often attributed to the decrease in fracture frequency with depth and the influence, if any, of stress on fracture closure

Received March 17, 1995. Accepted February 8, 1996.

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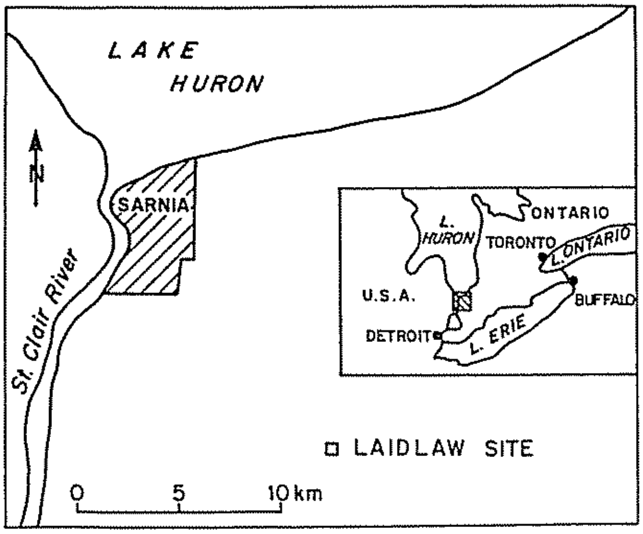
Fig. 1. Location of Laidlaw field site (after Ruland et al. 1991).



has not been established. This relationship is examined in this work. Using laboratory tests, the experimental conditions applied to a single fracture can be more easily controlled when compared with the difficulty in isolating a single fracture and controlling test conditions in the field. The main disadvantage of the laboratory tests over field tests is the unknown influence of disturbance during sampling and the uncertainty associated with applying the results from small-scale samples used in the laboratory to field conditions.

This paper describes the results of a laboratory research program examining the closure of isolated clay till fractures under applied stress. The stress – closure – hydraulic conductivity relationships are investigated to determine both the anticipated profile of hydraulic conductivity with depth and expected residual aperture magnitudes for discrete till fractures.

Site description

Naturally occurring clay till fracture samples, collected from the field for the laboratory investigations, were obtained from the Laidlaw Environmental Services hazardous waste disposal site (formerly TRICIL Ltd.) located approximately 20 km southeast of Sarnia, Ontario (Fig. 1). The site is located in the physiographic region known as the St. Clair clay plain (Chapman and Putnam 1984), an areally extensive sequence of Quaternary glacial till and glacial lacustrine deposits 40 m in thickness overlying Devonian age sedimentary bedrock.

The Laidlaw site has been the focus of much of the fractured clay research in the southwestern Ontario region. Cherry (1989) provides a summary of this and other research pertaining to fractured clay till deposits. McKay (1991) gives a detailed description of the field site and surficial clay till zone from which fractures were obtained for the investigations described herein. The origin of the fractures at the field site is generally attributed to desiccation (Hannah 1966; Harding 1986; Mase et al. 1990).

Experimental method

Fracture sampling method

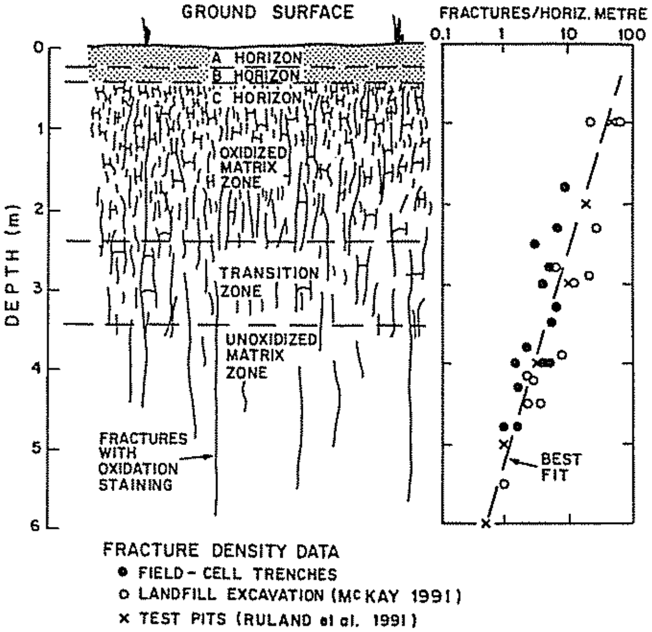
Fractured clay till samples were collected at the field site from benches and pits excavated to approximately 4 m depth below ground surface. The sampling method consisted of locating vertical fractures in the exposed till sections. Fractures were often identified by associated "fracture haloes" of oxidized matrix material. In plan, the fracture haloes appeared similar. However, during excavation of the benches and pits two types of fractures were observed, those with heavy black coloration (staining), with lesser amounts of brown staining, and those with predominantly grey-green coloration and minor brown staining. The black and brown coloration was interpreted as manganese and iron oxidation staining, suggestive of active flow of oxygenated groundwater through fractures. The grey-green coloration was interpreted as reduced iron, suggestive of a lesser amount of recent oxygenated groundwater flow through this type of fracture.

Observation of the distribution and appearance of fracture planes suggested that the black and brown stained fractures were more widely spaced and continuous in the shallow till zone (above 3–4 m depth). The grey-green fracture planes, although not exclusively limited to below 3–4 m depth, were typical of the deeper till (below 4 m) and characteristic of smaller scale fractures, which often formed "dead end" offshoots from larger scale fractures. The larger scale fractures included black-brown and grey-green types. Only the second type of fracture (i.e., grey-green) were recovered and subsequently tested in the laboratory. These fractures were observed to be the most pervasive at the depth of sampling and were selected for the hydraulic study. The frequency and distribution of fracture plane staining at the field site is described in detail by McKay (1991).

Fractures were sampled by centering a 70 mm diameter Shelby tube over isolated fracture haloes and driving the Shelby tube approximately 40 cm into the till. One of two types of devices was used to drive the Shelby tubes: a "Torpedo", a pneumatically driven hammer manufactured by Footage Tools Ltd. of Mississauga, Ontario, or a "Cobra", a mechanically driven hammer manufactured by Atlas Copco Co. of Sweden. After reaching the desired depth of penetration, the Shelby tube and driving tool were rotated 360° using a pipe wrench in order to shear the sample from the in situ clay. The till sample was extracted from the ground and detached from the Shelby tube head.

Postsampling desiccation of the sample was minimized by sealing the open ends of the Shelby tube with plastic bags sealed with tape. After all samples were taken (4–5 h), the bags were removed and the ends of the Shelby tubes were sealed using beeswax. Upon returning to the laboratory, the samples were stored in a cold room at 4°C. A profile of the surficial fractured clay till zone from which the samples were obtained is shown in Fig. 2. Till samples were recovered from approximately 4 to 5 m depth, as this seemed the optimum depth for obtaining samples of isolated fractures. Samples were taken by driving the Shelby tube vertically into the horizontal bench section, as illustrated in Fig. 3.

Fig. 2. Weather zone profile (after McKay 1991).



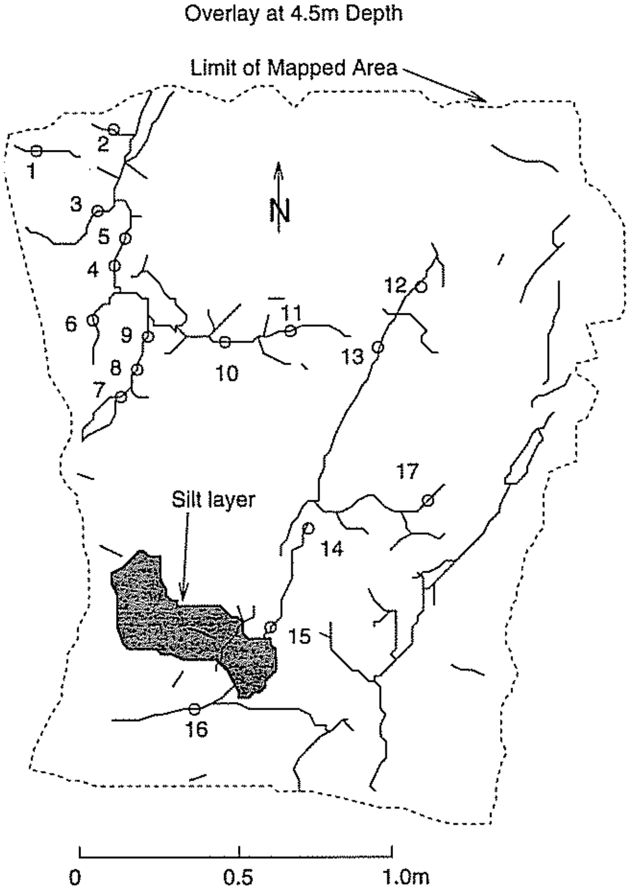
Laboratory method

Till samples collected from the field were extruded in the laboratory and prepared for flexible-wall permeameter flow tests. The extruded sample was examined for the presence and location of a fracture, and an appropriate section of 8–10 cm in length with a fracture trace located along a diametral axial plane was cut and trimmed from the sample. The sample was trimmed at either end using a putty knife. The ends were chipped lightly with a razor blade to remove any smearing caused by the trimming process. The fracture aperture trace, identified by a thin grey line roughly centered in the fracture halo, was chipped to a depth of a few millimetres.

At either end of the sample, a saturated filter paper disk (Whatman No. 1, 11 μm) and a porous stone or sintered metal plate, both of much greater permeability than the sample being tested, were interfaced between the soil sample and a flow cap. The porous stones, immersed in boiling water prior to installation to ensure saturation, ensured a uniform hydraulic connection across the sample. Each flow cap had two ports, an inflow–outflow port to facilitate flow in or out during testing, and a vent port to facilitate removal of air bubbles or the introduction of a constant source tracer across the entire flow cap for the tracer tests, which are described by Sims (1993). Two flexible latex membranes (0.051 in. thick) were placed over the sample. The membranes were sealed around the flow caps using silicon grease and four O-rings. A dye tracer indicated negligible leakage between the sample and membrane.

Following preparation, the sample was installed in a flexible-wall permeameter apparatus manufactured by Brainard-Kilman of Stony Mountain, Georgia. The device is shown schematically in Fig. 4. Middleton (1990) provides a detailed description of operation and capabilities of the permeameter. The sample was saturated with permeant under a vacuum applied sparingly to the top so as to minimize any compression of the fracture. Native groundwater collected from the field site or tap water that had been previously equilibrated with the native till served as the permeant. The permeant was vacuum filtered through a 0.45 μm filter to separate out any larger colloidal material that might clog the fracture. The permeant was deaired prior to testing.

Fig. 3. Representative fracture pattern at 4.5 m depth. Numbered circles indicate location of Shelby tube samples (adapted from McKay 1991).



Flow tests were conducted to determine the influence of stress on fractured till sample hydraulic conductivity. Of particular interest was whether there was a finite stress level at which a fracture would close, such that fracture till sample flow rates would equal bulk clay till sample flow rates. The flow tests were accomplished by subjecting the sample to incremental effective stress levels estimated to be representative of those in the field. The stress values, identified in Table 1, were calculated according to Terzaghi's principle of effective stress (Craig 1983). For these calculations an average saturated unit weight for the clay till of 19.8 kN/m^3 was assumed. This value was based on results of geotechnical tests given by McKay (1991) for samples collected from the field site. For calculation of effective horizontal stress, a coefficient of lateral earth pressure at rest, K_0, of 1.0 was assumed. This value is within the range of 0.7 to 1.5 reported by Harding (1986) who measured K_0 at the Lambton site. The Lambton site is characteristic of the weathered clay tills in the region

Fig. 4. Schematic diagram of a flexible-wall permeameter apparatus used for flow and transport experiments (after Middleton 1990). (*a*) Control and cell. (*b*) Permeameter cell.

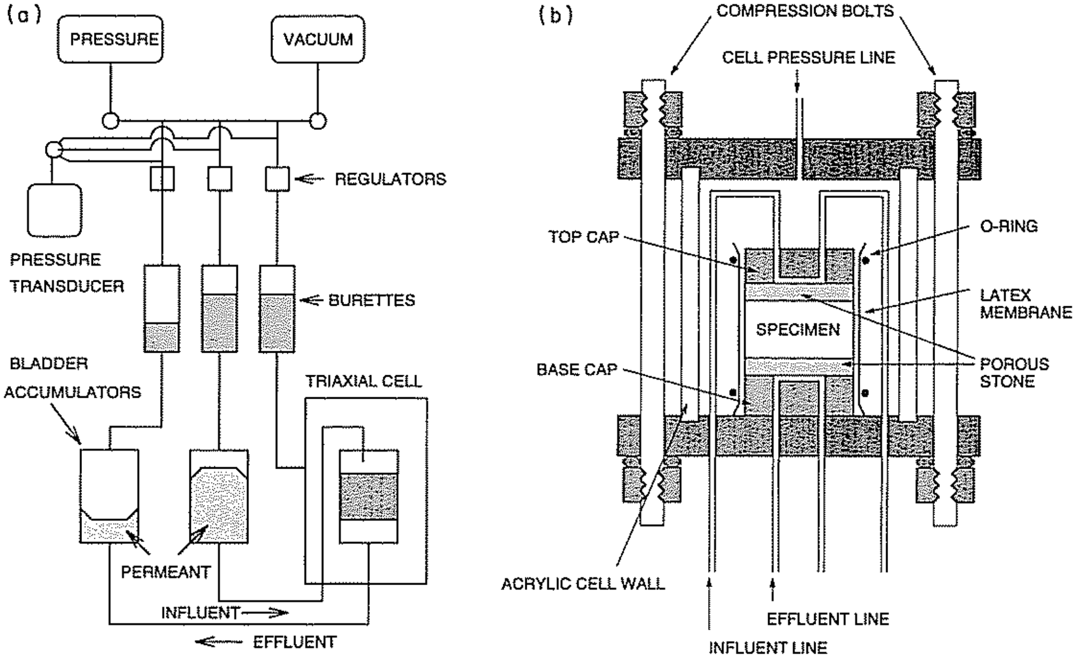


Table 1. Values of stress assumed representative of in situ stress conditions at the field site (assuming $K_o = 1.0$, $\gamma_{sat} = 19.8$ kN/m^3).

Depth below ground surface (m)	Total vertical and horizontal stress (kPa)	Pore-water pressure, u (kPa)	Effective horizontal and vertical stress (kPa)
2	39.6	19.6	20.0
4	79.2	39.2	40.0
6	118.8	58.8	60.0
8	158.4	78.4	80.0
12	237.6	117.6	120.0
16	316.8	156.8	160.0

(D'Astous et al. 1989; Ruland et al. 1991), and data from this area are assumed applicable to the clay tills at the Laidlaw field site.

An all-around total stress was applied to the sealed sample through a uniform confining pressure, with equilibrated pore-fluid pressure applied via the end-caps. Effective stress levels applied in the tests included equivalent overburden loads of 0.5, 2, 4, 6, 8, 12, and 16 m. Table 2 is a summary of tests completed. The suite of samples tested included a "bulk" till sample with no visible fracture present. In the fractured till samples, flow in excess of that expected through a bulk sample of similar size was assumed to be through the fracture.

During testing, flow was induced from the bottom to the top of the sample so as to enhance the removal of any entrapped air within the sample. Flow was induced with a head drop of 26.5 cm of water set across the sample. Samples tested measured 5.5–10 cm in length. The hydraulic gradient for samples therefore was within a range of 4.82–2.65. Vertical gradients across aquitards are typically in a range of 0.05–0.50. It is assumed the higher laboratory gradient, used to minimize error due to leakage rates through the membrane seals and other losses (see Results and Discussion section) on the test results, would not significantly affect hydraulic conductivity (K) measurements. This is particularly important for the low conductivity samples used in these tests. A consideration of laminar versus turbulent flow indicated that laminar flow could be assumed for the range of aperture sizes (assuming parallel plate apertures) anticipated to be present in the laboratory samples.

At each stress level a series of inflow and outflow measurements were made. The hydraulic conductivity, K, for the sample was calculated from the average of the measured inflow and outflow for each set of measurements recorded using both constant and falling head equations (e.g., reported by Middleton 1990). Once a relatively constant value of hydraulic conductivity, K, had been established at that

Table 2. Summary of hydraulic conductivity tests completed.

Sample	Stress conditions (as metres below ground surface) 0.5	2	4	6	8	12	16
C1		+					
C6	+	+	+	+	+	+	+
C5V		+	+	+	+	+	
C12		+	+	+			
C3		+	+	+		+	
C11		+	+				
C5/90		+					
C15		+	+				

Note: + indicates test completed.

stress level, the stress was incremented and the sample was allowed to reequilibrate at the new stress level. The hydraulic conductivity at the new stress level was determined as for the previous stress level. Using results from a permeameter test on a bulk clay sample, the flow volume through the clay matrix was accounted for and subtracted to obtain net or residual flow through the fracture for each flow reading, as described in the following. All stress levels were incremented until conductivity would no longer decrease substantially, hence the different end-point effective overburden levels of 12–16 m.

Fracture apertures were back-calculated from the residual flow volumes using the cubic law relationship (Witherspoon et al. 1980). The cubic law is based on the assumption that fracture walls are smooth parallel plates separated by a constant distance, 2*b*. For a parallel plate fracture aperture (2*b*) of width *W* and length ΔL, the flow rate of a fluid through the fracture, Q_F, may be determined from the cubic law as

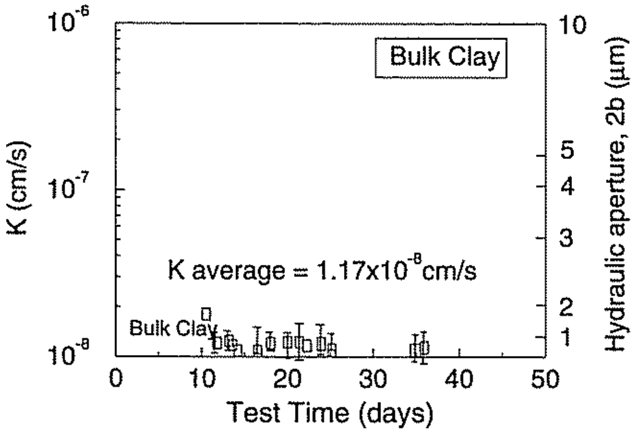
$$[1] \quad Q_F = \frac{\rho g}{12\mu}(2b)^3 W \frac{\Delta H}{\Delta L}$$

where ρ is the fluid density, *g* is gravitational acceleration, μ is the dynamic viscosity of the fluid, and ΔH is the head drop across the length of the fracture. The cubic law relationship is found to be adequate for characterizing flow where an "equivalent hydraulic aperture," <2b>, is used that may be different from the physical aperture, 2*b*. The relationship is derived by applying the Navier-Stokes equations for fluid flow between two parallel plates. The interested reader is referred to the treatment by, for example, Streeter and Wylie (1975). In field and laboratory experiments of flow through fractures, the volumetric flux, Q_F, is usually measured and the magnitude of the aperture, 2*b*, is back-calculated from the cubic law. Such aperture values are generally referred to as "equivalent parallel plate" or "equivalent hydraulic" apertures (Silliman 1989).

Where flow in the matrix is also incorporated, the bulk conductivity, K_{bulk}, may be readily evaluated (Elsworth and Mase 1993) as

$$[2] \quad K_{\mathrm{bulk}} = \frac{\rho g (2b)^3}{12\mu s} + K_{\mathrm{matrix}}\left(1 - \frac{2b}{s}\right)$$

Fig. 5. Hydraulic conductivity measurements for bulk (no visible fractures) clay sample C1 (*K* corrected to 20°C). Test run at equivalent loading of 2 m in situ stress conditions.



where K_{matrix} is the conductivity of the matrix, and the fracture spacing is defined as *s*. Correspondingly, the net influence of porous media flow in augmenting the fracture flow may be determined and subtracted from the overall response.

Results and discussion

Hydraulic conductivity values calculated from measured flow rates (as a function of test time) for a sample of unfractured (bulk) clay till are plotted in Fig. 5. The average hydraulic conductivity, corrected to 20°C, was calculated as 1.17×10^{-8} cm/s, with a low value of 9.94×10^{-9} cm/s and high value of 1.7×10^{-8} cm/s based on outflow and inflow measurements, respectively. These results show essentially no sensitivity to stress level and are plotted on a common scale with later results to enable direct comparison. The data points on the graph correspond to the hydraulic conductivity calculated from the average of the inflow and outflow volume measurements. Often these values did not coincide. This was attributed to leakage and (or) diffusion of permeant through pipettes (on the order of 0.05 mL/day loss); regulator pressure fluctuation (maximum 7% of the minimum effective stress at 2 m conditions); lab temperature fluctuations (±2°C); and error in meniscus readings between the inflow and outflow pipettes (estimated at ±0.05 mL). The discrepancy between the inflow and outflow measurements was most acute at low flow volumes (approximately 0.1 to 0.2 mL/day for bulk clay flow rates). In Fig. 5 error bars reflect the uncertainty in the value of the true hydraulic conductivity values due to the differences in inflow and outflow volumes.

The hydraulic conductivity of four fractured till samples, determined as a function of effective stress, are presented in Figs. 6–9 (samples C6, C5V, C12, and C3, respectively). These plots are representative of the type of stress-conductivity behaviour observed for the suite of samples tested in the laboratory. Plotted in these figures is the equivalent hydraulic conductivity (left-hand *y*-axis) and the equivalent hydraulic aperture (right-hand *y*-axis) versus

Fig. 6. Hydraulic conductivity and equivalent hydraulic aperture versus time for fracture sample C6 (*K* corrected to 20°C). Equivalent in situ loading is noted for each stress level applied (0.5–16 m).

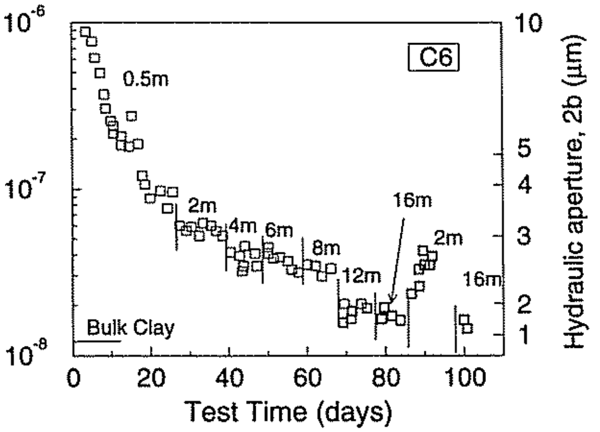
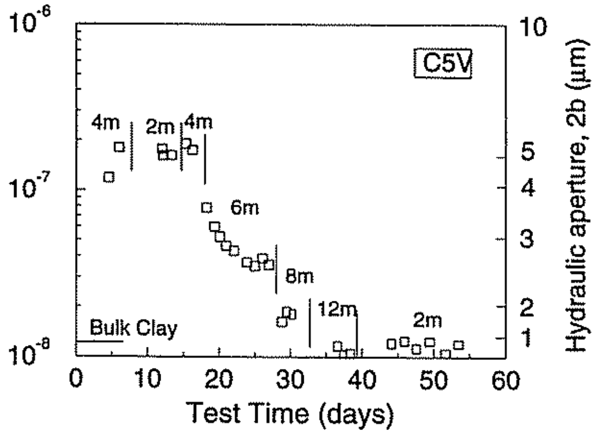


Fig. 7. Hydraulic conductivity and equivalent hydraulic aperture versus time for fracture sample C5V (*K* corrected to 20°C). Equivalent in situ loading is noted for each stress level applied (2–12 m).



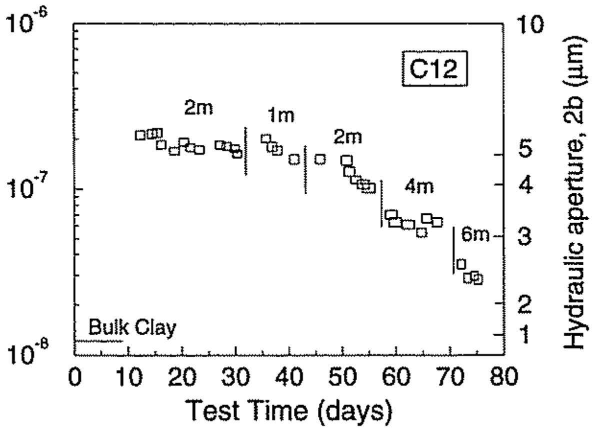
test time. Data points are plotted on the individual graphs for the discrete stress levels that were applied (0.5–16 m). Discrepancies in inflow and outflow measurements for the fractured till samples were similar to those for the bulk clay sample described above. For the suite of samples tested, flow quantities through fractured till samples were in a range of approximately 1–17 times that through the bulk clay till sample.

The results of the stress conductivity experiments (Figs. 5–9) indicate the following behaviour for the fractured till samples tested in the laboratory permeameter apparatus.

Equivalent hydraulic apertures

For the fractured samples tested, equivalent hydraulic apertures that could be maintained during testing were within the range of 0–5 μm. Hydraulic conductivity magnitudes for each sample were relatively constant at each stress level. However, sample C6 (Fig. 6) at 0.5 m stress with an initial hydraulic aperture of 10 μm, and sample C5V (Fig. 7) at 6 m stress, exhibited decreases in hydraulic conductivity values over time. The time-dependent decrease in aperture was attributed to aperture closure or infilling possibly as a result of clay swelling, silting off of the fracture aperture due to fines being deposited in constricted aperture throats, or mineral precipitation. The equivalent hydraulic apertures calculated from laboratory data were much smaller than values obtained from field tests at the Laidlaw site where hydraulic apertures (back-calculated from inflow into seepage collectors emplaced at discrete points at depths ranging from 1.5 to 5.5 m below ground surface) ranged between 1 and 43 μm with slug tests returning values of 33 μm (McKay et al. 1993).

Fig. 8. Hydraulic conductivity and equivalent hydraulic aperture versus time for fracture sample C12 (*K* corrected to 20°C). Equivalent in situ loading is noted for each stress level applied (1–6 m).



Possible explanations for the discrepancy between laboratory and field apertures include the following: (1) that samples tested in the laboratory may not be representative of field apertures; perhaps only fractures with small apertures were collected in the field and subsequently tested in the permeameter; (2) where higher apertures were sampled in the field, the apertures may not have been maintained in the laboratory because of plugging or infilling of the aperture; (3) the small fracture samples used in the laboratory do not provide results representing field-scale processes such as flow channeling; or (4) fracture apertures, initially open in the field, were disturbed and subsequently closed during field sampling and laboratory preparation.

Stress-dependent closure

A plot of hydraulic aperture versus stress for the till samples tested in the laboratory is given in Fig. 10. The hydraulic aperture values plotted for each sample represent the average values of hydraulic aperture corresponding to the respective in situ effective stress levels applied during the test. Figure 10, in conjunction with Figs. 5–9, indicate that fractured till samples tested in the laboratory show two types of behaviour with respect to stress:

(1) *Measurable closure with increasing stress.* Referring to Fig. 10, aperture closure curves for samples C6, C5V, and C12 are interpreted as indicating that in laboratory samples where till fractures are initially open

Fig. 9. Hydraulic conductivity and equivalent hydraulic aperture versus time for fracture sample C3 (K corrected to 20°C). Equivalent in situ loading is noted for each stress level applied (2–12 m).

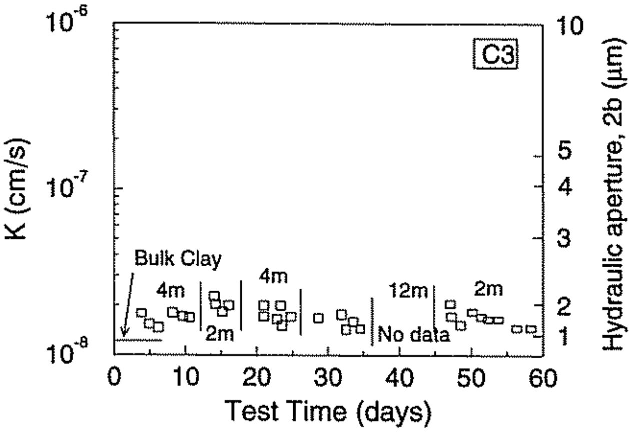
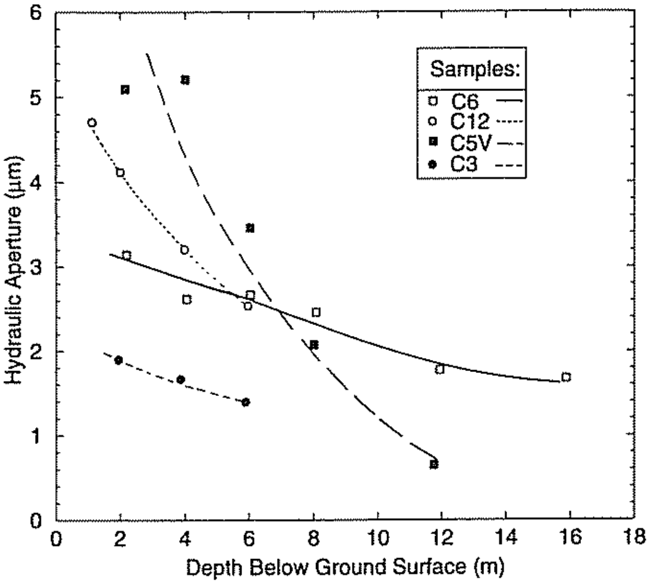


Fig. 10. Aperture closure as a function of stress. Stress is expressed as equivalent depth (m) below ground surface ($K_0 = 1.0$).



with hydraulic apertures on the order of 5 μm, apertures exhibit stress-dependent closure. Hydraulic conductivity magnitudes for samples C6 and C5V (Figs. 6 and 7, respectively) indicate that, for fracture apertures tested in the laboratory, an initial estimate or limiting stress for fracture flow (i.e., where fracture sample flow rates are similar to bulk clay flow rates) is on the order of stress conditions assumed representative of 12 m depth.

(2) *Little or no closure with increasing stress (C3 and C6).* Referring to Figs. 9 and 10, sample C3 shows little change in hydraulic conductivity and consequently hydraulic aperture with increasing stress. For sample C6, the fracture closure (Fig. 10) and hydraulic conductivity behaviour (Fig. 6) indicate that increasing stress above 12 m equivalent depth had little or no effect on fracture aperture. This identifies the changing behavior of the sample under increased load increments as the aperture closure within the fractures is not recoverable.

The behaviour of the till fracture samples that were tested is consistent with a conceptual model of stress-dependent fracture closure and fracture stiffness (Walsh 1981). As effective stress is increased across a fracture, contacting asperities are crushed and (or) plastically deformed and relative contact area between the fracture walls is increased. As fracture closure occurs and the contact area increases, greater increments of stress are required to cause additional closure. Fracture stiffness (the ratio of incremental change in aperture to the incremental change in stress) is nonlinear because more asperities contact as average normal compressive stresses increase across the fracture. For a relatively open parallel plate aperture (i.e., where asperities are small relative to fracture wall separation) that characterizes a fracture at low stress levels, closure under increasing stress would occur rapidly until discrete channels began to form as asperities on the fracture walls came in contact. At some threshold, a residual aperture remains where increases in stress result in only minor closure of the remaining discrete flow channels.

In the context of the foregoing theory, the laboratory results suggest that the more conductive samples (hydraulic apertures of 4–5 μm) are characterized by essentially parallel plates that close rapidly under incremental stress. With fracture closure, the hydraulic conductivity of the fractured clay approaches that of the bulk clay. Discrete channels are expected to form with closure, requiring successively greater incremental stresses to close these channels. The results suggest that residual flow channels remain at equivalent overburden loads of 12–16 m, and these discrete channels are difficult to close because of their small cross-sectional aspect ratio.

Referring to Fig. 10, the laboratory results are generally consistent with this conceptual model. Fracture samples C12, C5V, C3, and particularly C6 exhibit apparent nonlinear fracture closure as effective stresses are increased. A residual aperture effect could explain the less pronounced decrease in hydraulic conductivity (i.e., hydraulic aperture) apparent in samples C3 and C6 as stress is further increased.

Fracture recovery

Some fractured till samples (see Figs. 6 and 7 for samples C6 and C5V) show evidence of partial recovery (reopening of apertures) upon release of stress. This recovery is minimal, as evident within the figures. This has implications regarding excavations in fractured clay till deposits excavated for the purpose of waste disposal. During excavation, as a consequence of stress relief, apertures initially closed could reopen and become conduits for flow and transport. Conversely, application of a load from a berm placed around a disposal pit might induce closure of existing fractures in the near surface zone. Since the apertures of the laboratory samples do not recover completely (e.g., sample C6, Fig. 6), application of a temporary load (such as might be induced by a hammering mechanism) might also enhance aperture closure and therefore be effective in reducing the hydraulic conductivity of existing fractures.

Summary and implications

Hydraulic apertures of four fractured till samples collected in the field from approximately 4 m depth and tested in a laboratory flexible wall permeameter ranged between 0 and 5 μm. In one sample, flow rates representative of a hydraulic aperture approaching 10 μm were observed but could not be maintained. Fractured clay till samples tested in the laboratory exhibited stress-dependent closure consistent with the closure of rough surfaces, in general, and rock fractures, in particular.

Laboratory results from two samples indicate that a fracture closure stress assumed representative of 12 m depth in the field is sufficient to close fracture apertures in laboratory samples to flow rates representative of nonfractured clay. Increasing stress beyond this value results in little if any reduction in sample hydraulic conductivity. This limiting closure stress suggests that fractures are closed but does not preclude the presence of a few discrete flow channels that do not close and, as a result, form a residual aperture. Fractures reopen only partially following stress relief, suggesting hysteretic behaviour.

The range of equivalent hydraulic apertures (0–5 μm) measured in the laboratory samples is uniformly lower than the range (1–43 μm) calculated from in situ flow and transport data (McKay et al. 1993) from the same site. This discrepancy between laboratory and field aperture magnitudes may result from the inability of laboratory sized samples to adequately sample and represent field-scale processes. If only a few fractures or connected channels act as conduits for flow, then intersecting the larger fractures in field sampling is likely a "hit or miss" situation. This is consistent with the conclusion of McKay et al. (1993) that "...hydraulic conductivity values at the field site were strongly influenced by the physical scale of the field measurements which controls how many fractures are sampled by the measurements."

It is possible that the small fracture apertures measured in the laboratory are a consequence of censoring in the sampling process. Fracture surfaces of the laboratory samples were all of a "grey-green" color suggestive of reducing conditions. This coloration may indicate that these fractures are small or closed with little or no preferential flow of oxygenated groundwater through these fractures. Oxygenated recharge water would migrate mainly through larger and more open fracture apertures, which are suggested by the black and brown oxidation staining on other fracture walls. An alternative explanation for the small hydraulic apertures present in laboratory samples is that fracture apertures may have been disturbed (closed) during field collection and laboratory preparation.

The results of the laboratory experiments are in general agreement with the results of field experiments completed at the Laidlaw field site (McKay 1991). McKay found evidence that widely spaced fractures might be present to depths of 12 m. This is identical to the depth inferred for fracture closure from the laboratory flow data. However, McKay found no clear relationship indicating that hydraulic aperture values derived from flow volumes into seepage collectors decreased with increasing depth. This is inconsistent with a stress-dependent closure behaviour model, which predicts closure with increasing stress (i.e., depth). In an experiment involving incremental application of a surface load to McKay's field site, A. Ylinen (personal communication, 1991) found evidence that bulk hydraulic conductivity values decreased as the surface load was increased. The decrease in conductivity was 50% for a 3 m berm height. This supports a stress-dependent fracture closure model and is consistent with the findings of the laboratory experiments.

Assuming that the results of the laboratory samples are representative of processes and conditions that exist in the field, then the observation that fracture apertures in the laboratory samples show stress-dependent closure and partial recovery upon stress relief has important implications to flow and transport through fractured clay till deposits and waste disposal practices in these types of sediments. In the context of closure, where conductive fractures are present, application of a load by placement of a surcharge (e.g., berm or temporary compactive effort) might serve to close or partially close fractures. Partial closure of fractures would result in a reduced bulk hydraulic conductivity beneath the point of load application, thereby reducing the potential for advective migration through the surficial zone. Conversely, fracture recovery upon stress relief could result in the opening of apertures that were previously closed.

For this suite of tests, an effective stress condition assumed representative of 12 m depth was sufficient to reduce the hydraulic conductivity of initially fractured tills to bulk clay magnitudes. Assuming that an overburden load equivalent to 12 m is sufficient to close fractures to residual values, a surcharge load of 120 kN/m^3 would be required. This has important implications with respect to the possible depth penetration of active flow conduits in desiccated clay tills and for the engineering of waste containment barriers in these materials.

Acknowledgements

We would like to thank the staff and graduate students at the University of Waterloo who provided technical assistance and guidance during the course of the research, in particular, Dr. Robert W. Gillham, Dr. Ed Sudicky, Dr. Larry D. McKay, Tammy Middleton, Chris Neville, Stephanie O'Hannessin, Ron Kellerman, Don Helm, and Ed Hinton. We would also like to thank Michael Stone and Dr. Michael English and Wilfred Laurier University for providing additional laboratory equipment and facilities. Financial support for this research was provided through funding and grants from Laidlaw Environmental Services Ltd., the University Research Incentive Fund, the University Consortium for Solvents in Groundwater Research Program, the Natural Sciences and Engineering Research Council of Canada, and the Ontario Graduate Scholarship program.

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