CHAPTER 8. SUMMARY AND CONCLUSIONS

Soil-bentonite cutoff walls are frequently used for containing contaminants in the subsurface. The hydraulic conductivity of a cutoff wall is a key factor in its effectiveness as a barrier to contaminant migration. There are important difficulties and uncertainties regarding the accuracy of commonly used methods of measuring the hydraulic conductivity of cutoff walls.

The influence of hydraulic conductivity on contaminant transport is well established. In addition, it is known that diffusion of contaminants through barriers must also be considered. A factor that has not been discussed in the literature with respect to contaminant transport is the variability in hydraulic conductivity from point to point in a barrier. It is a hypothesis of this dissertation that variability in hydraulic conductivity should be considered in cutoff wall design and contaminant transport studies.

A pilot-scale facility was envisioned where subsurface barrier issues such as those described above could be studied. Building this facility was the first activity in this research. The facility is called the Subsurface Barrier Test Facility (SBTF). One of the goals of this research was to establish a procedure for constructing soil-bentonite cutoff walls at the facility.

Another goal of this research was to use the pilot-scale soil-bentonite cutoff walls constructed at the SBTF to evaluate the effectiveness of various currently used methods for measuring the hydraulic conductivity of cutoff walls. The studied methods included laboratory and in situ tests. The SBTF enables measurement of the global average hydraulic conductivity of a pilot-scale cutoff wall. The results of the various hydraulic conductivity tests were compared to each other and to this global average hydraulic conductivity.

The other goal of this research was to investigate the influence of variability in hydraulic conductivity on contaminant transport through cutoff walls. Three tasks were accomplished to meet this goal. One task was performing a laboratory experiment to show the effect that variability in hydraulic conductivity can have on contaminant transport. Another task was using the advection-diffusion equation to predict the influence of variability in hydraulic conductivity on the contaminant flux through a cutoff wall. The third task was to summarize information on hydraulic conductivity variability from case histories.

This chapter is divided into seven sections. There is one section for each chapter from Chapter 2 to Chapter 7 (Sections 8.1 to 8.6). Each section summarizes the important activities and conclusions from the chapter it covers. Section 8.7 discusses recommendations for future work.

8.1 Literature Review (Chapter 2)

Currently used methods for measuring the hydraulic conductivity of cutoff walls were reviewed. The methods were divided into lab tests and in situ tests. Below is a summary of issues related to the reviewed tests:

<u>Lab tests</u>

A) *Lab tests on grab samples*. This is the industry standard for evaluating hydraulic conductivity. Flexible-wall, consolidometer permeameter, or API filter press equipment may be used to perform the tests. While straight-forward to perform, the extra mixing that goes into preparing the samples has been found to significantly lower the hydraulic conductivity of the samples (e.g., Barvenik and Ayres, 1987).

B) *Lab tests on undisturbed samples*. It is difficult to obtain undisturbed samples of relatively soft soil-bentonite from cutoff walls. The sampling procedure is not well established. From a few reported cases where undisturbed sampling was performed (presented in Daniel and Choi, 1999), the hydraulic conductivity of the undisturbed samples was higher than the hydraulic conductivity of remolded samples of the backfill material, presumably due to the extra mixing in the remolded samples.

<u>In situ tests</u>

A) *Single-well tests*. Single-well tests (or slug tests) have been performed in cutoff walls, but there are uncertainties related to performing and interpreting the tests. The three main issues are: 1) the compressibility of the soil-bentonite, 2) the close proximity of the trench walls, and 3) hydraulic fracturing. Soil compressibility has been addressed in the literature (e.g., Cooper et al., 1967; Butler, 1996; and Daniel and Choi, 1999). Methods to account for the nearby trench walls have been presented by Teeter and Clemence (1986), Yang et al. (1993), and Daniel and Choi (1999). Several authors (e.g., Bjerrum et al., 1972) have discussed hydraulic fracturing. Hydraulic fracture is especially important in cutoff walls, where vertical stresses are less than geostatic due to arching. The literature review revealed that further work is needed in the areas of items 2 and 3: accounting for the nearby trench walls and avoiding hydraulic fracture. For item 2, a particular problem is knowing where the well is with respect to the centerline of the wall so that the influence of the trench walls can be accounted for properly.

B) *Large-scale pumping/injection tests*. In this common test, the idea is to apply a hydraulic gradient to a part or all of a cutoff wall and evaluate the hydraulic conductivity of the area of the wall being tested from the flow rate induced by the gradient. Two difficulties in performing these tests are: 1) accounting for the heterogeneity in the subsurface in which the cutoff wall has been constructed (Evans, 1994) and 2) accounting for flow through the underlying aquitard (Filz and Mitchell, 1995). Despite these difficulties, it may still be possible to infer valuable information from a large-scale test, such as the existence of high-hydraulic-conductivity defects in a wall.

C) *Piezocone soundings*. Valuable information may be gathered from both continuous pushing of the piezocone and pore pressure dissipation tests at a given depth. During continuous pushing, pore pressure, tip resistance, and sleeve friction measurements are useful for characterizing the cutoff wall's composition and properties, including the location of defects. Manassero (1994) has developed a procedure for correlating hydraulic conductivity to the three typical piezocone measurements listed above. A problem is the possibility of sidewall penetration, which produces responses not representative of the barrier material itself. Finally, the hydraulic conductivity of cutoff walls has been evaluated from pore pressure dissipation tests performed in the walls.

Use of a circumferential cutoff wall with an inward hydraulic gradient is common in remediating contaminated sites. The goal of the inward hydraulic gradient is to create an inward advective contaminant flux to counteract the outward diffusive flux. Because variability in hydraulic conductivity was hypothesized to influence this scheme, the literature was reviewed for information on hydraulic conductivity variability. Information on sources of variability and the distribution of hydraulic conductivity are summarized below:

A) *Sources of hydraulic conductivity variability in cutoff walls*. The sources of variability found in the literature may be grouped into three categories: 1) variations in the soil-bentonite itself (e.g., variations in the composition of the base soil – Evans, 1993), 2) construction defects (e.g., "slurry windows" – Evans, 1993), and 3) variability induced by the environment (e.g., variations due to chemical interactions with the backfill – Evans, 1993).

B) *Distribution of hydraulic conductivity*. The majority of findings in the literature indicate that hydraulic conductivity is log-Normally distributed. The range of values of standard deviation of -log k has been estimated to be 0.2 to 2.0 (Freeze, 1975) based on analyses of a large number of measurements from natural soil deposits, most of which consisted of primarily coarse-grained soils. The range that applies to an engineered, low-permeability soil such as soil-bentonite has not been discussed in the literature. A reasonable assumption is that the 0.2 to 2.0 range may apply to the base soil in a soil-bentonite mix, and the addition of bentonite may reduce this range. Ryan (1987) found that both the average k and the deviation from the average k of soil-bentonite mixtures are reduced at increased dry bentonite contents.

8.2 The Subsurface Barrier Test Facility (Chapter 3)

The Subsurface Barrier Test Facility (SBTF) was constructed in the fall and winter of 1998. The facility is set up for constructing and testing pilot-scale subsurface barriers. The scale and design of the facility is such that barriers can be installed using real construction equipment and tested in a controlled environment.

The main feature of the facility is a below-ground concrete pit, called the "barrier pit," in which vertical barriers can be constructed and tested. The 1.8-m-wide pit is 2.8 m deep for the 3.2-m-long section in the middle, sloping at 3H:1V to the ground surface on each end. The facility also has a below-ground concrete pit for mixing and storing materials, two polyethylene tanks for mixing and storing slurries, and a concrete apron for mixing and stockpiling materials.

8.3 Constructing the Pilot-Scale Cutoff Walls (Chapter 4)

Three pilot-scale cutoff walls (called W1, W2, and W3) were constructed and tested in this research. The following is an outline of steps used to construct and test the walls:

1) A compacted clay liner was placed along the bottom of the barrier pit to simulate a low-permeability layer in the subsurface.

2) Clean sand was placed and compacted all the way to the top of the barrier pit to simulate a high-permeability aquifer in the subsurface.

3) Soil-bentonite backfill was made by mixing bentonite into a silty sand base soil. All bentonite was added to the base soil in slurry form for W1 and W2. For W3, half the bentonite was added in slurry form and half was added dry.

4) Excavation support slurry was mixed.

5) A vertical trench was excavated along the centerline of the barrier pit using a track-mounted excavator. The trench extended all the way through the compacted clay liner to the concrete bottom of the barrier pit.

6) The trench was backfilled with the soil-bentonite, displacing the support slurry and forming the cutoff wall.

7) The cutoff wall was covered and allowed to consolidate.

8) Hydraulic conductivity tests were performed on the wall.

9) All of the soil in the barrier pit was removed. The cutoff wall was sampled and inspected for content, size, uniformity, and continuity.

All of the walls were not constructed exactly the same. Below is a list of key characteristics of the walls:

A) W1 and W2 were excavated using a biodegradable slurry (bioslurry). This was done to eliminate low-permeability filter cakes, which cause difficulties in interpreting in situ hydraulic conductivity tests. Because use of the bioslurry lead to the formation of defects in W1 and W2, as discussed below, W3 was excavated using bentonite-water slurry.

B) W1 was 30.5 cm wide and W2 and W3 were 61 cm wide.

C) The bentonite content in the soil-bentonite for W1 and W2 was 1%. The relatively higher hydraulic conductivity with this bentonite content was desired to produce higher, easier-to-measure flow rates through the cutoff walls. In order to reduce the influence of the bentonite filter cakes in W3, 3% bentonite was used for the soil-bentonite, which reduced the hydraulic conductivity by approximately an order of magnitude compared to the 1% mixtures.

Use of the bioslurry, composed solely of PFW and guar gum, lead to the formation of defects in W1 and W2. The defects were attributed to breakdown of the bioslurry's viscosity in the trench. The decrease in viscosity caused an increased settling rate of sand and an inability of the bioslurry to remove sand from the trench as it was displaced during backfilling. From the experiences with W1 and W2, a slurry composed solely of guar gum in water is discouraged for use in excavating a trench for a cutoff wall. It is important to note that the use of additives to prevent degradation of the guar gum was not studied in this research.

There is sometimes uncertainty regarding the state of bentonite filter cakes after backfilling. Do the cakes remain intact or do they get scraped off to some degree by the moving backfill? In the case of W3, the filter cakes remained intact. This finding supports the claim that bentonite filter cakes remain intact during backfilling and may lower the equivalent hydraulic conductivity of cutoff walls.

8.4 Methods of Measuring the Hydraulic Conductivity of the Pilot-Scale Walls (Chapter 5)

Five methods were used to measure the hydraulic conductivity of the pilot-scale cutoff walls: 1) API tests on grab samples, 2) global measurement of average hydraulic conductivity, 3) piezometer tests, 4) piezocone pore pressure dissipation tests, and 5) lab tests on undisturbed samples. The API tests and piezocone pore pressure dissipation tests were performed and interpreted according to established procedures. Important points from the new work done in this research on the other three test methods are described below:

A) *Global measurement of average k*. In this test, the flow rate through the wall was measured for a given head drop across the wall. The average hydraulic conductivity of the wall was evaluated by finding the uniform hydraulic conductivity for a representative wall in a theoretical model that produced the same flow rate in the model as that measured through the actual wall. Three theoretical models were used, ranging from simple to complex. Each model produced similar relationships between flow rate and hydraulic conductivity.

B) *Piezometer tests*. 3D shape factors specifically for Hvorslev (1951) analyses of single-well tests in cutoff walls were developed in this research. The finite-difference computer program MODFLOW was used for this work. In addition, a series of 2D finite element analyses using SEEP2D were performed to investigate the influences of filter cakes, deviation in the position of the piezometer from the centerline of the wall, and the formation soil hydraulic conductivity on the shape factors. The following conclusions were made from these SEEP2D studies:

1. The hydraulic conductivity evaluated using a shape factor that does not account for filter cakes is always less than or equal to the actual soil-bentonite hydraulic conductivity and greater than or equal to the equivalent hydraulic conductivity of the wall. A chart was created for evaluating the equivalent hydraulic conductivity for a given estimate of filter cake permittivity.

2. The results of piezometer tests are not significantly different for piezometer positions anywhere within the middle half of the cutoff wall.

3. The assumption of constant head at the trench walls is appropriate when the formation soil hydraulic conductivity is at least 100 times greater than the soil-bentonite hydraulic conductivity.

Hydraulic fracture in single-well tests was also studied. Hydraulic fracture pressures were determined both experimentally and theoretically. The hydraulic fracture pressure at two points each in W1 and W2 was found experimentally by running a series of constant head piezometer tests with increasingly higher positive excess heads. Hydraulic fracture pressures were evaluated theoretically using the Bjerrum et al. (1972) approach. There was good agreement between the experimental and theoretical hydraulic fracture pressures. It turned out that the low vertical effective stresses in the pilot-scale cutoff walls controlled the critical hydraulic fracture pressures. Vertical stresses in cutoff walls are less than geostatic due to arching.

C) *Lab tests on undisturbed samples*. A procedure was developed for obtaining undisturbed samples from the pilot-scale walls and using the sampling device as a consolidometer permeameter for measurement of hydraulic conductivity. This procedure is useful for obtaining and testing samples from the pilot-scale walls during destructive evaluation, where a surface of soil-bentonite can be exposed at any point in the wall for sampling, but the procedure is not applicable to real, working cutoff walls.

8.5 Hydraulic Conductivity Results for Tests Performed on Pilot-Scale Walls (Chapter 6)

The results of the five test methods for measuring the hydraulic conductivity of the pilot-scale walls were presented, compared, and discussed in Chapter 6. Measures of hydraulic conductivity for W1 and W2 that were influenced by the defects in the walls were not used in the comparisons.

Measures of soil-bentonite hydraulic conductivity from the different test methods used on the pilot-scale walls followed this trend in values:

$$k_{API} < k_{lab\ tests\ on\ undisturbed\ samples} < k_{piezocone\ pore\ pressure\ dissipation\ tests} < k_{piezometer} < k_{global}$$

As discussed in Chapter 6, consolidation stress could be dismissed as a factor differentiating the hydraulic conductivity results from the tests on the pilot-scale walls. Flow direction could also be dismissed as a factor because the hydraulic conductivity of the soil-bentonite was found to be approximately isotropic from lab tests on vertical and horizontal undisturbed samples. The two main factors that did influence the test results were remolding and sample size.

Remolding was the important factor differentiating the *k* results from the API tests and the lab tests on undisturbed samples, which both tested samples of similar size. The rodding of API samples during test set-up distributes the bentonite more evenly in the samples which lowers the hydraulic conductivity of the samples. The ratio of API *k* to undisturbed *k* was approximately 0.5 for all three pilot-scale walls.

From the lab tests on undisturbed samples to the global measurement in the trend shown above, remolding is believed to have less of an influence because the degree of remolding is less intense than in the API tests and the zones of remolded material are thin compared to the total volume of material tested. In the *k* trend shown above, sample size increases significantly from left to right starting with the lab tests on undisturbed samples. This is believed to be the main factor differentiating the test results.

Figure 6-15 in Chapter 6 shows the influence of sample volume on the soil-bentonite hydraulic conductivity values for W3 evaluated from the different test methods. The volumes tested by the lab tests on undisturbed samples and the piezometer tests were approximately 0.003% and 1%, respectively, of the volume tested by the global measurement. For these sample volumes, the ratios of k_{sb} from undisturbed samples and k_{sb} from piezometer tests to k_{sb} from the global measurement were 0.37 and 0.5, respectively. A possible explanation for this is the existence of higher-*k* pockets of soil-bentonite in the wall that did not get much bentonite mixed into them during mixing of the soil-bentonite. In this case, the small volume of the lab tests on undisturbed samples may have excluded such pockets, resulting in the lowest measured *k*. The larger volume tested by the piezometer may have included a small, less-than-representative proportion of such pockets, resulting in an intermediate measured *k*. The global measurement volume included the true proportion of such pockets in the wall, resulting in the highest measured *k*.

From the results discussed above, it is concluded that the results of API tests (or other lab tests) on grab samples should not be interpreted as an accurate estimate of the hydraulic conductivity of soil-bentonite cutoff walls. The remolding of the samples during test set-up distributes the bentonite more evenly in the samples and produces a pore size distribution that is not representative of the pore size distribution in the wall at a larger scale. However, API tests on grab samples are still considered useful as a quality control tool for testing the backfill mixed by the contractor in a relatively fast and easy manner.

Figure 6-16 in Chapter 6 compares values of soil-bentonite hydraulic conductivity and equivalent hydraulic conductivity for the tests in W3 as a function of sample size. Uniform, representative filter cake properties were used to interpret the in situ hydraulic conductivity test results and to evaluate equivalent hydraulic conductivities (see Subsection 4.9.1.3, "Destructive Evaluation of W3," in Chapter 4 for determination of the representative filter cake properties). As sample volume increases, the equivalent hydraulic conductivity increases at a lesser rate than the soil-bentonite conductivity. This is a positive effect, since it is the equivalent hydraulic conductivity that governs the horizontal flow rate through vertical cutoff walls.

The appropriateness of extrapolating the hydraulic conductivity/sample volume trend lines for W3 to higher volumes in real cutoff walls is not known. The following three points should be considered in this matter. First, the level of control during the construction of real cutoff walls is less than the level of control afforded by the SBTF. With less control, the existence of high permeability zones in a cutoff wall is more probable, which may increase the influence of sample size. Second, it is not reasonable to assume that hydraulic conductivity increases indefinitely with increasing sample volume. As sample volume gets relatively large, there will eventually be a high probability that further increases in volume will not significantly change the distribution of *k* influencing the average *k* of the volume. Third, assuming that filter cake permittivity is uniform, there is a limit as to how large the equivalent hydraulic conductivity can get. As the soil-bentonite hydraulic conductivity gets very large, the equivalent hydraulic conductivity approaches the limiting value of trench width times filter cake permittivity.

Finally, it was found that the piezocone soundings in W1 provided a clear picture of the materials comprising the wall: a desiccated top, intact soil-bentonite, and a sand defect at the bottom. Observations during destructive evaluation confirmed the interpretations of the soundings. In addition, the responses of the piezocone to the soil-bentonite and the defect were similar to responses measured in similar materials in the cutoff wall at the Gilson Road site discussed in Chapter 2.

8.6 Effect of Variability in Hydraulic Conductivity on Contaminant Transport (Chapter 7)

Chapter 7 showed that variability in hydraulic conductivity may be an important factor in contaminant transport through cutoff walls. The current standard of practice is to use only the average hydraulic conductivity in cutoff wall contaminant transport analyses.

A lab experiment was performed to demonstrate the difference in contaminant transport results between 1) what is predicted to happen based on calculations with the average hydraulic conductivity and 2) what may actually happen due to variability in hydraulic conductivity. In the experiment, a hydraulic gradient was set up to oppose a concentration gradient across a specimen. Calculations with the average hydraulic conductivity of the specimen indicated a net flux in the direction of the hydraulic gradient. Due to variability in hydraulic conductivity designed and created in the specimen[1], however, the actual net flux in the experiment was against the hydraulic gradient due to diffusion through the part of the specimen with hydraulic conductivity less than the average. The results of the experiment support the hypothesis that variability in hydraulic conductivity should be considered in the analysis of some cases of contaminant transport; using only the average hydraulic conductivity may lead to significant errors in the evaluation of the contaminant flux.

The analyses of data sets of hydraulic conductivity from lab tests on soil-bentonite samples from four case histories indicated that hydraulic conductivity is best described by a log-Normal distribution. The range of values of standard deviation of –log *k* was 0.2 to 0.3. This information applies to Type 1 variability, which is variability in the soil-bentonite itself (see discussion on sources of variability in Section 8.1). Large degrees of the other types of variability (2: construction defects and 3: variability induced by the environment) in a cutoff wall may decrease the goodness of fit of the log-Normal distribution and increase the degree of variability. As a first estimate, the range of standard deviations of –log *k* of 0.2 to 0.3 may be used when incorporating variability in contaminant transport studies.

The theoretical effect of variability on contaminant transport was investigated using the one-dimensional advection-diffusion equation. Knowing the mean Peclet number and standard deviation of –log *k*, the area-weighted average flux through a cutoff wall has been evaluated at steady state and as a function of time, and graphical solutions have been presented. This analysis offers a quantitative evaluation of the effect of variability on the flux through a cutoff wall. The effect of variability is greatest when the Peclet number is negative (i.e., when the hydraulic gradient opposes the concentration gradient) and is much less when the Peclet number is positive. The goal of a circumferential cutoff wall with an inward hydraulic gradient ($P_e < 0$) is to reduce the outward tendency of the contaminant to escape due to diffusion. The results in Chapter 7

[1] A simple distribution of *k* was used, created by installing a high *k* defect in an essentially uniform soil-bentonite specimen.

show that the effect of variability in hydraulic conductivity is to reduce the effectiveness of this scheme.

8.7 Recommendations for Future Work

Based on the work and findings in this research, future work is suggested in the following four areas as described in the subsections below: single-well tests, piezocone soundings, filter cakes, and variability in cutoff wall hydraulic conductivity.

8.7.1 Single-well Tests

Of all the test methods used in this research other than the global measurement, the single-well tests performed using a push-in piezometer provided the best estimates of the hydraulic conductivities of the pilot-scale walls. The methods used for performing and interpreting the tests account for the following important items, as discussed in detail in Chapter 5: 1) hydraulic fracture, 2) the compressibility of the soil-bentonite, and 3) the proximity of the trench walls, including the influence of filter cakes, the position of the well between the trench walls, and the hydraulic conductivity of the formation soil. There are, however, still some difficulties involved in practically performing single-well tests in real cutoff walls. These difficulties are discussed below.

Single-well tests may be performed using either an installed well or a piezometer. As discussed in Subsection 5.3.2.3.2 in Chapter 5, the results of the tests do not change drastically if the well or piezometer is within roughly the middle half of the wall. It was possible to carefully control the position of the piezometer in the pilot-scale walls. When installing wells or piezometers in real cutoff walls, however, one cannot be sure where the instrument is between the trench walls, especially at greater depths. There may be deviations from verticality in both the installation of the instrument and the wall itself. The test results will be misinterpreted if the instrument is believed to be more or less in the center of the wall, but is actually very close to a trench wall. A useful contribution would be to design a scheme to control the position of an instrument within a cutoff wall as it is being installed. For example, a member might be designed that attaches to the rod above a push-in instrument and acts to laterally constrain the rod relative to the trench walls during pushing, preventing the rod from getting within a certain distance of a trench wall. It would have to be ensured that such a scheme would not compromise the integrity of the cutoff wall.

In Chapter 5, the excess heads at which hydraulic fracture would occur in the piezometer tests were predicted using the Bjerrum et al. (1972) approach. It turned out that the low vertical effective stresses in the walls due to arching controlled the magnitudes of excess heads that could be applied. This prediction was confirmed by the hydraulic fracture tests performed in W1 and W2. It was possible to apply small excess heads in the tests in the pilot-scale walls because 1) the water table was at the top of the barrier pit and 2) the devices controlling the heads were set up at approximately ground level at the top of the below-grade mixing and storage pit (see Figure 3-1). There are two issues related to hydraulic fracture that deserve attention when performing single-well tests in real cutoff walls.

First, will the vertical effective stress in the wall always control the magnitude of excess head that can be applied? It would be useful to perform a parametric study to see under what conditions the three mechanisms given by Bjerrum et al. (one governed by the radial effective stress, one governed by the circumferential effective stress, and one governed by the vertical effective stress) controlled the excess head that could be applied. Variables in this study would include: depth, wall width, effective friction angle of soil-bentonite, depth to water table, unit weights of soil-bentonite above and below water table, stiffness of the soil-bentonite, and stiffness of the trench walls (including horizontal earth pressure coefficient at zero horizontal strain, i.e., rigid trench walls). Vertical effective stresses would have to be calculated using both arching and lateral squeezing theory to see which one controlled. Furthermore, it would be useful to perform hydraulic fracture tests in cutoff walls under conditions where the Bjerrum et al. approach predicted the radial or circumferential effective stresses to control the hydraulic fracture heads. This would test the accuracy of the Bjerrum et al. predictions of these mechanisms.

The second issue is, how can small excess heads be applied and measured in slug tests in real cutoff walls? The importance of this issue is greatest when the water table is relatively deep. Suppose the Bjerrum et al. approach predicts that the critical excess head for hydraulic fracture is less than the depth of the water table. How can a falling head slug test be performed when the excess head cannot be raised above the ground surface? In the slug tests performed at the SBTF, excess heads could be measured by observing the water level in the piezometer standpipe near the ground surface. This type of measurement may not be possible if the water level in the standpipe of a well or a piezometer is required to be below the ground surface in order to avoid hydraulic fracture.

Based on experience with the push-in piezometer used in this research, the following are needed in a push-in instrument in order to apply and measure excess heads in cutoff walls where the hydraulic fracture excess head is less than the depth of the water table. First, consider installation of the instrument. During insertion, the filter element should be saturated and sealed to prevent soil particles from entering the filter pores. In the piezometer tests performed at the SBTF, the standpipe was saturated all the way to the ground surface where it was sealed during insertion. This would not work if the excess head in the filter could not be above the ground surface, because unsealing the standpipe to perform a slug test would cause hydraulic fracture. If the instrument is to have a standpipe, the standpipe must be able to be sealed at some safe depth below the ground surface where unsealing the standpipe will not cause hydraulic fracture. A standpipe, however, may not necessarily be the best way to apply the excess head in the filter when performing slug tests. Another option would be a device (saturated, sealed, and located near the filter) connected to the saturated filter that applies a slug of water pressure, possibly through a forced change in volume in the device. A sensor could be designed into the device to measure water pressure. During the slug test, the return in water pressure to equilibrium could be measured with time. The hydraulic conductivity of the cutoff wall could be evaluated from this excess pressure dissipation rate and a shape factor for the filter and cutoff wall geometry.

This subsection has discussed important practical difficulties involved in performing single-well tests in cutoff walls: 1) knowing the position of the well in the wall and 2) applying and measuring excess heads when small excess heads will cause hydraulic fracture. Future work in the development of single-well test technology should be to develop an instrument for performing slug tests in cutoff walls that addresses these issues. In addition, a parametric study is suggested to determine under what conditions the three mechanisms described by Bjerrum et al. will control hydraulic fracture and what the values of the hydraulic fracture pressures typically are. It may also be useful to experimentally confirm the Bjerrum et al. predictions when the hydraulic fracture mechanisms are controlled by the radial and circumferential effective stresses.

8.7.2 Piezocone Soundings

The results of piezocone soundings in W1 were presented in Chapter 6. The soundings delineated three distinct zones in the wall: a desiccated top, intact soil-bentonite, and a sand defect at the bottom. There was good agreement between where the piezocone indicated these zones to be and where the zones actually were based on observations from destructive evaluation of the wall. Also, the responses of the piezocone to the intact soil-bentonite and the defect were similar to responses measured in the soil-bentonite wall at the Gilson Road site discussed in Chapter 2.

There are a few issues that still need to be resolved for piezocone probing in cutoff walls. Perhaps the biggest issue is sidewall penetration, i.e., penetration of the piezocone into the trench sidewall. This may occur if the piezocone drifts away from vertical during a sounding or if the cutoff wall itself is not perfectly vertical. If sidewall penetration occurs, the response of the piezocone may be incorrectly interpreted as a defect in the wall. This makes sampling of the wall desirable in order to check the interpretation where the piezocone appears to indicate a defect. Drilling into the wall to sample, however, has the same problems with verticality as the piezocone sounding itself. It would be useful to have a way to prevent sidewall penetration from happening when probing cutoff walls with the piezocone. Also, there are difficulties involved in measuring the response of soft materials such as soil-bentonite with the piezocone. These difficulties include the importance of accurate calibration when loads are small and potential baseline shifts during probing that are significant compared to the small loads.

8.7.3 Filter Cakes

The existence of filter cakes in a cutoff wall may greatly improve the performance of the wall. In areas of the wall where the backfill hydraulic conductivity is high, the existence of low-permeability filter cakes results in an equivalent hydraulic conductivity that is less than the backfill conductivity. To better understand the performance of cutoff walls, a better understanding of the state of filter cakes in real cutoff walls is needed. Answers to these questions for real cutoff walls would be useful:

- Can filter cakes be expected to remain intact or do they tend to get removed or heavily disturbed during backfilling?
- If filter cakes can be expected to remain intact, can their in situ properties (especially hydraulic conductivity and thickness) be reliably predicted from lab test studies and theoretical considerations?
- How much variation in filter cake properties can be expected?
- How susceptible are filter cakes to degradation from contaminants?

Reliable predictions of the state of filter cakes would lead to more reliable estimates of flow rates through cutoff walls in both design and analysis. In addition, reliable predictions of filter cake properties would improve the interpretation of in situ hydraulic conductivity test results, such as those obtained from piezometer tests.

8.7.4 Variability in Hydraulic Conductivity of Cutoff Walls

In Chapter 7, data sets of hydraulic conductivity were analyzed for four case histories. The results indicated that soil-bentonite hydraulic conductivity best fits a log-Normal distribution, with a range of values of standard deviation of $-\log k$ of 0.2 to 0.3. It is suggested to analyze data sets of hydraulic conductivity from more case histories to increase the confidence in the above results. Furthermore, when the practice of measuring the hydraulic conductivity of cutoff walls in situ has become more well developed, it would be useful to assess the in situ variability in hydraulic conductivity of cutoff walls and compare this variability to that estimated from grab samples. A better knowledge of in situ variability would increase the accuracy of contaminant transport studies.