A Probabilistic Method for Estimating Monitoring Point Density for Containment System Leak Detection

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Abstract

The use of physical and hydraulic containment systems for the isolation of contaminated ground water and aquifer materials associated with hazardous waste sites has increased during the last decade. The existing methodologies for monitoring and evaluating leakage from hazardous waste containment systems rely primarily on limited hydraulic head data. The number of hydraulic head monitoring points available at most sites employing physical containment systems may be insufficient to identify significant leaks from the systems. A probabilistic approach for evaluating the performance of containment systems, based on estimations of apparent leakage rates, is used to introduce a methodology for determining the minimum number of monitoring points necessary to identify the hydraulic signature of leakage from a containment system. The probabilistic method is based on the principles of geometric probability. The method is demonstrated using three-dimensional ground water flow modeling results of leakage through a vertical barrier. The results indicate that the monitoring point spacing used at many hazardous waste sites likely is inadequate to detect the hydraulic signatures of all but the largest leaks.

Introduction

Recently, the industrial and regulatory communities have focused on the use of containment technologies as supplemental or stand-alone remedial alternatives for hazardous waste sites. Subsurface vertical barriers have been used to control ground water seepage in the construction industry for many years (D'Appolonia 1980). Such barriers have been employed as components of hazardous waste containment systems to prevent or reduce the impact of contaminants on ground water resources (Rumer and Ryan 1995). While subsurface vertical barriers appear to be useful for isolating long-lasting sources of ground water contamination at many sites, the potential exists for leakage of contaminants through relatively high hydraulic conductivity zones or windows. Such windows may form during construction or result from postconstruction changes in barrier properties (Evans 1991). Consequently, there is concern that the performance of numerous hazardous waste containment systems has not been adequately evaluated or demonstrated.

This paper describes a general approach for evaluating the required number of monitoring points necessary to identify leakage through the windows within a subsurface vertical barrier. Hydraulic head distributions are generated by a numerical ground water flow model simulating leakage through a subsurface vertical barrier under a range of conceptual hydrogeologic conditions. The model data are used to illustrate the utility of the proposed probabilistic method. The resulting techniques will be useful for evaluating existing containment systems by providing insight as to how many monitoring points are necessary to determine the approximate locations of discrete leaks, given specified constraints and confidence.

Subsurface Containment Systems

Depending on the remedial objectives and complexity of the hydrogeologic setting, subsurface containment systems may be active (e.g., ground water extraction to manage hydraulic gradient) or passive (e.g., physical barriers) (Canter and Knox 1986). Frequently, containment systems employ a combination of active and passive components, which commonly incorporate low permeability vertical barriers (walls) keyed into underlying low permeability units. Many containment systems also include a low permeability cover to prevent or reduce the infiltration of precipitation, extraction and/or injection wells and/or trenches for ground water management, and a monitoring network.

Soil-bentonite slurry trench cutoff walls (slurry walls) are the most common type of subsurface vertical barriers used at hazardous waste sites and are generally installed circumferentially around the suspected source areas within a site (U.S. EPA 1984). Slurry walls are typically constructed in a two-step process consisting of trench excavation and backfilling with appropriate materials. During excavation, bentonite slurry is used to form a low permeability filter cake on the sides of the excavation and maintain

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trench stability. The excavated materials are appropriately amended and replaced in the trench. Cement-bentonite slurry cutoff walls have been widely used in Europe and are gaining wider acceptance in the United States. Other types of vertical barriers include plastic cement cutoff walls, vibrating beam cutoff walls, deep soil mixing walls, composite cutoff walls, steel sheet pile walls, and grout barriers (Rumer and Ryan 1995).

Construction defects or postconstruction property changes are potential failure mechanisms of subsurface vertical barriers (Evans 1991). Construction defects may result in the formation of high hydraulic conductivity "windows" in a low hydraulic conductivity barrier. Some of the mechanisms responsible for the formation of such windows include emplacement of improperly mixed backfill materials, sloughing or spalling of in situ soils from sides of trench, and failure to excavate all in situ material when keying wall to the underlying low permeability unit (U.S. EPA 1987). Postconstruction property changes may result from wet-dry cycles due to water table fluctuations, freeze-thaw degradation, or chemical incompatibility between the slurry wall components and nonaqueous phase liquids (Evans 1991).

Current Monitoring Practices

The performance of hazardous waste containment systems has generally been evaluated based on construction specifications. Most subsurface vertical barriers are required to maintain a hydraulic conductivity of 1×10^{-7} cm/s or less. The use of appropriate construction quality assurance (CQA) and quality control (CQC) testing during installation is essential to ensure that the design performance specifications are achieved (U.S. EPA 1987). However, preferential pathways may develop in spite of rigorous field CQA and CQC procedures.

The regulatory community recognized the need to develop procedures to verify postconstruction performance and identify unsatisfactory zones in containment systems (U.S. EPA 1987). While construction dewatering systems are deemed successful if the barriers limit ground water leakage to reasonably extracted quantities, there are no uniform methods to reliably measure and document the hydrologic performance of existing and proposed hazardous waste containment systems (Grube 1992).

The minimum number of monitoring points necessary to determine whether a containment system is functioning as designed may be relatively small (Ross and Beljin 1998). For example, in some cases, it may be possible to determine if leakage is occurring by simply analyzing the water-level trends in monitoring wells located inside and outside the confines of the system. It may also be possible to estimate the volume and rate of leakage based on water-level trend data. The approximate volume of leakage into or out of a containment system may be estimated by a volumetric analysis. The average rate of leakage due to the decline in the hydraulic head can be determined by dividing estimated volume of leakage by the time over which the change in occurs. While estimating the rates of leakage from a system may be relatively straightforward, determining the locations of specific leaks will require significantly more information.

Significant leakage from a containment system may require an assessment of the potential risks to human health and the environment posed by the leakage. Inyang and Tumay (1995) relate the risks to human health from exposure to ground water contaminants in terms of the probability of a toxic response of an individual to a hazardous substance. The risk associated with leakage from a containment system may also be related to a hypothesis test in which the null hypothesis (H_0) states that no detectable leakage is occurring from the containment system. Conversely, the alternate hypothesis (H_1) states that the containment system has detectable leakage. There are two ways of making an incorrect decision with respect to the stated hypotheses (Conover 1980). First, if the null hypothesis is true (i.e., no detectable leakage) and is mistakenly rejected, a type I error occurs. The health risks associated with such an error are minimal, since no discharge of contaminants to the environment occurs. A type I error may result in increased costs arising from the installation of unnecessary wells and/or verification sampling and analysis of existing wells. The wrongful acceptance of a null hypothesis that is false, such that the monitoring system does not detect a leak when one is present, results in a type II error. The probability of making a type II error is defined, and is referred to by Gilbert (1987), as the consumer's risk. A consumer's risk of = 0.1 indicates that there is a 10% probability of not detecting a leak when one is present. The potential health risks associated with a type II error depend on the mass flux of contaminants out of the system.

Subtle variations in the hydraulic head distribution associated with leakage through a subsurface barrier may be identifiable if sufficient hydraulic head data are available for analysis. Such an undertaking would generally be considered prohibitively expensive due to the high cost of installing a piezometer network capable of adequately defining the hydraulic head distribution. However, the recent development of relatively inexpensive installation techniques may make it feasible to install a sufficient number of small-diameter piezometers to identify the hydraulic signatures associated with significant containment system leakage.

Alternative Approach to Leakage Assessment

The process of locating a leak in a hazardous waste containment system can be analogous to mineralogical prospecting where a compromise is sought between the cost of exploration and the thoroughness of the search. For mineral exploration applications, the expected benefit of a search is the sum of the value of each target multiplied by the probability of finding it, assuming that the target exists in the search area (Singer 1972). For containment system leak detection, the expected benefit of a search is the potential reduction in risks to human health and the environment associated with the detection and abatement of significant leaks. An increase in the number of monitoring points will result in increased costs but may also result in the reduction in risks associated with potential hazardous waste discharge to the environment if leakage is occurring.

Gilbert (1987) presents a methodology that can be used to (1) determine the grid spacing required to detect randomly located highly contaminated areas or hot spots at a given level of confidence; or (2) estimate the probability of finding a hot spot of specified dimensions, given a specified grid spacing. The methodology is based on the work of Singer (1972), Singer and Wickman (1969), and Savinskii (1965), who developed statistical tables to calculate the probability of success in locating circular and elliptical targets using grid configurations. The probability of detecting a target using a specific grid spacing is determined by the method of geometric probability, which is a function of the ratio of the area of the target to the area of one cell of the grid. Recently, a probabilistic method for evaluating whether a monitoring system will be capable of detecting contaminant plumes was presented by Warrick et al. (1998).

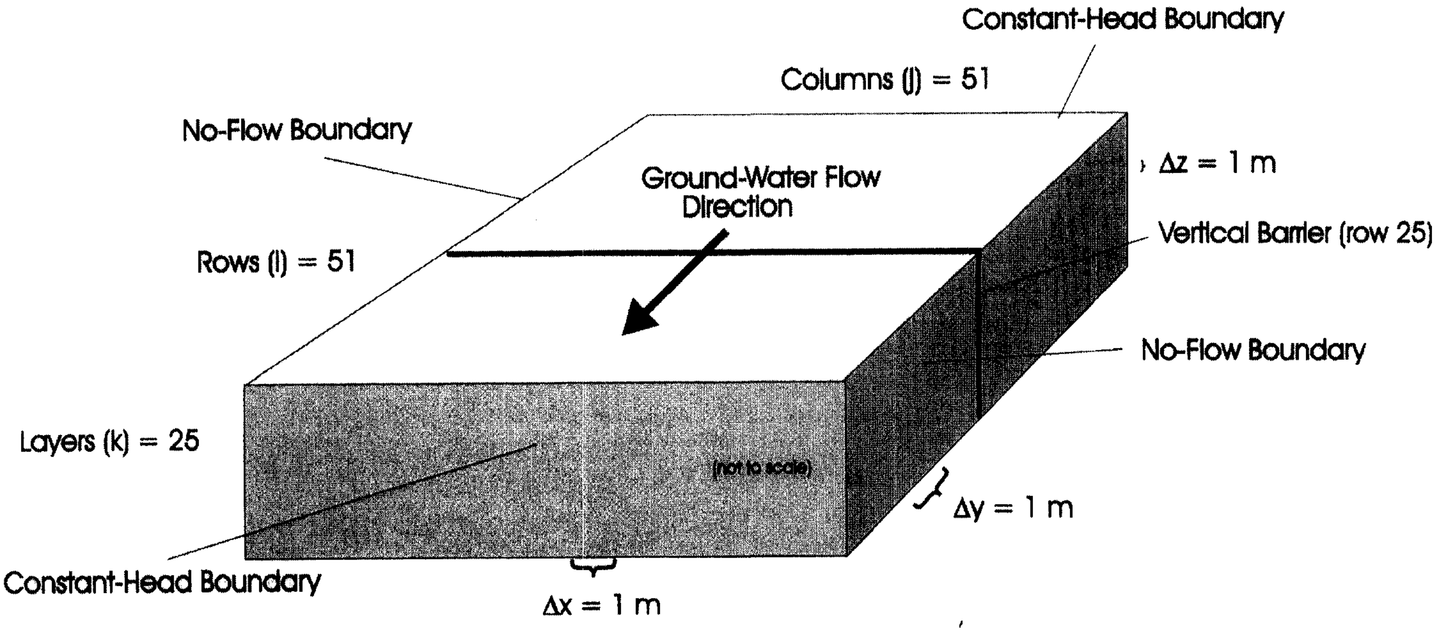


Figure 1. Conceptual model of domain and boundary conditions.

The methodology presented in the next section is based on the work of Singer and Wickman (1969), Gilbert (1987), and Zirschky and Gilbert (1984). The assumptions have been modified to address variations in the distribution of hydraulic head, rather than contaminant concentrations. The assumptions and specific details relating to the applications of the proposed method for hydraulic signature detection are discussed.

Methodology

The hydraulic signature associated with leakage from a containment system is simulated for a variety of hydrogeological settings. The modeling results provide the data on which the new method is demonstrated. The proposed method is evaluated assuming homogeneous, isotropic conditions and homogeneous, anisotropic conditions.

The conceptual model presented in this paper is based on characteristics of several specific hazardous waste sites that incorporate physical containment as a major component of the selected remedy. The conceptual containment system consists of a soil-bentonite slurry wall fully penetrating an unconsolidated surficial aquifer, keyed into an underlying aquitard. The hypothetical aquifer is discretized into 25 1 m thick layers. It is assumed that no recharge is added to the upper surface of the aquifer due to the presence of a low permeability cap over the containment system.

Hydraulic head values are assumed to be higher in the interior of the containment system, simulating a "worst case" scenario for potential contaminant losses from the system. The elevated water levels in the containment system are derived from deficiencies in the upgradient portion of the system (i.e., leakage under or through the upgradient wall). Ground water flow is assumed to be horizontal, except in the immediate vicinity of the vertical barrier. Given the long-term nature of most hazardous waste containment systems, the hydraulic heads are averaged over long time periods. Consequently, steady-state flow conditions are assumed for all simulations used in this study.

Scenario variations evaluated through sensitivity analyses include the ratio of the hydraulic conductivity of the window and wall (K_{win}:K_{wall}), the ratio of hydraulic conductivity of the aquifer and wall (K_{aq}:K_{wall}), and the magnitude of the hydraulic gradient across the wall. The boundary conditions assumed for the conceptual model include constant head boundaries for the upgradient and downgradient sides of the model and no-flow boundaries for the sides and bottom of the model oriented parallel to ground water flow (Figure 1).

The hydraulic head distribution associated with a linear segment of a conceptual vertical barrier was simulated using Visual MODFLOW® (Guiger and Franz 1995). The hydraulic head data generated by the numerical simulations are extracted, visualized, sampled, analyzed, and appropriately manipulated using several software packages. The data are extracted from output files and reformatted as image files for analysis using MODRISI (Ross and Beljin 1995). The GIS software used in this study is IDRISI, a raster GIS that provides numerous analytical capabilities that are directly applicable to this and other hydrogeologic studies (Eastman 1995). The uniform grid spacing facilitates the transfer of data from one software package to another. The raster format allows importation and exportation of uniform grid model data and also provides a robust platform for the analysis, visualization, and data manipulation.

Model Setup

The model domain consists of 51 rows, 51 columns, and 25 layers (Figure 1) and is discretized into uniform 1 m^3 blocks ($x_j = y_i = z_k = 1$ m). This configuration is sufficiently large to reduce boundary effects and provides sufficient resolution to allow identification of subtle variations in hydraulic heads associated with leakage through a vertical barrier. The conceptual soil-bentonite slurry wall is simulated as a 1 m thick barrier with uniform properties ($K_{wall} = 1 \times 10^{-7}$ cm/s), except for the window. Leakage through the wall is simulated as a window with dimensions of 2 × 3 nodes (6 m^2), located in the approximate center of the vertical barrier (row 25, columns 24 through 26, layers 12 and 13).

Boundary conditions are depicted in Figure 1. The upgradient and downgradient sides of the model are constant-head boundaries. The upgradient and downgradient constant head boundary values are set such that the resulting horizontal hydraulic gradient across the model domain is 0.0196. The usefulness of the numerical model for simulating the hydraulic head distribution associated with leakage from a containment system was demonstrated by comparing model results with data generated from a laboratory bench scale model of a soil-bentonite cutoff wall (Ling 1995). Simulated head values were within approximately 5% of physical model results, indicating that the approach described in this study is appropriate for simulating the hydraulic head distribution associated with leaking vertical barriers.

The hydraulic conductivity for the aquifer (K_{aq}) is 1×10^{-2} cm/s, falling within the range of a medium sand. The hydraulic conductivity of the vertical barrier (K_{wall}) is maintained throughout the study at 1×10^{-7} cm/s. This corresponds to the design hydraulic conductivity of most soil-bentonite slurry walls (LaGrega et al. 1994). The hydraulic conductivity values for the window (K_{win}) ranged from 1×10^{-2} cm/s to 1×10^{-5} cm/s and are assumed to be less than or equal to K_{aq}. The homogeneous scenarios were modified to simulate anisotropic conditions, where the horizontal hydraulic conductivity (K_h) differs from the vertical hydraulic conductivity (K_v). The homogeneous and anisotropic scenarios simulate the general effects of layering by varying the horizontal to vertical hydraulic conductivity ratios of aquifer materials. Small-scale anisotropy has been attributed to the preferential orientation of fine-grained materials, especially in sediments of fluvial or alluvial origin (Todd 1980). The K_h:K_v ratios were increased by one and two orders of magnitude (K_h:K_v = 10 and 100) relative to the isotropic simulations (K_h:K_v = 1). These values fall within the range of values reported in the literature (e.g., Freeze and Cherry 1979).

Hydraulic Signature Assessment Method

The methodology used to address the hydraulic head distribution associated with leakage from a containment system was developed based on the work of Singer and Wickman (1969) and Gilbert (1987). The proposed method is directly applicable to determining the grid spacing necessary to detect the hydraulic signature associated with a discrete leak in a subsurface vertical barrier. The methodology requires the following assumptions: (1) the hydraulic signature of the leak is circular or elliptical; (2) hydraulic head data are acquired on a square grid; (3) the criteria delineating the hydraulic signature are defined; and (4) there are no measurement misclassification errors.

The model results indicate that the hydraulic signatures associated with the simulated leaks range in shape from approximately circular to elliptical when viewed in vertical cross-section. An increase in the anisotropy results in the elongation of the leak signatures in the horizontal directions. The criteria for delineating the hydraulic signature of a leak from background noise are based on the average hydraulic head value ($\bar{x}_h$) of the model cross-sectional surface. For this study, hydraulic head values of $\bar{x}_h$ + 0.05 m and $\bar{x}_h$ + 0.1 m were identified as critical values (C_v), indicating the presence of a hydraulic anomaly associated with a leak. This follows the assumption that any background noise associated with the hydraulic head measurements is significantly less than 0.05 m. The dimensions of the hydraulic anomalies are determined using GIS software by image reclassification to delineate which nodes exceeds the average hydraulic head by the specified values.

The dimensions of the hydraulic signatures delineated by C_v are expressed by a shape factor (S), defined as the ratio of the length of the short axis to the length of the long axis of the hydraulic signature. The shape factor for a circular feature is 1. An increase in K_h:K_v results in the elongation of the feature and a decrease in S, where 0 < S < 1.

Table 1
General Steps for Determining Monitoring Point Grid Spacing

1. Specify the radius or one-half the length of the long semimajor axis (L) of the hydraulic signature (mound) associated with the leak.
2. Assuming a circular hydraulic signature, let the shape factor (S) equal one; for elliptical features, S may be calculated as the ratio of the length of the short axis to the length of the long axis of the hydraulic signature.
3. Specify the maximum acceptable probability (β) of not detecting the hydraulic feature (β = 0.1).
4. Knowing L, S, and assuming a value for β, determine L/G from Figure 3, and solve for G (minimum grid spacing required to detect the hydraulic anomaly associated with the leak, given the specified constraints).

The probability tables of Singer and Wickman (1969) were used to generate the nomographs relating the probability of not detecting a leak when a leak is present (β) to the ratio of the semimajor axis to grid size (L/G). The semimajor axis is defined as one-half the length of the long axis of an elliptical feature. As indicated, different curves are used for hydraulic features characterized by different shape factors. The general procedure for determining monitoring point spacing necessary to detect a hydraulic anomaly of given dimensions and specified confidence is outlined in Table 1 and in the following example.

In order to determine the minimum grid spacing necessary to identify a hydraulic feature of specified dimensions, an acceptable probability of not detecting the feature must be established. For this example, a value of β = 0.1 is assumed for a leak signature with dimensions of 5 m by 4 m, as delineated by $C_v = \bar{x}_h + 0.1$ in Figure 2a. From the nomograph in Figure 3, a value of approximately 0.64 is indicated for the ratio of the length of the semimajor axis to grid size (L/G), given β = 0.1 and S = 0.8. Therefore, by solving for G using the semimajor axis dimension L = 2.5, it is determined that a minimum grid spacing of approximately 3.9 m is necessary to identify the specified feature with a 90% probability of success. The resulting grid spacing (G) may be used to determine the minimum number of block-centered monitoring points required to detect the feature for a specified area by dividing the model cross-sectional area by the area of one square grid (G^2).

The probability tables of Singer and Wickman (1969) were also used to generate nomographs relating the probability of not detecting a leak (β) of specified dimensions (L), for different grid dimensions (G). The nomograph in Figure 4 illustrates this relationship for circular hydraulic signature (S = 1.0). Similar nomographs for rectangular and hexagonal grid orientations can be developed from the probability tables. The nomograph may be used to estimate the dimensions of the smallest hydraulic signature capable of being identified by a monitoring network of known dimensions within an acceptable level of confidence (1-β). For example, assuming a monitoring point spacing of 20 m, what is the smallest circular hydraulic anomaly that can be detected with 80% probability of success (β = 0.2)? From Figure 4, using the appropriate curve for the specified grid spacing (G = 20) and

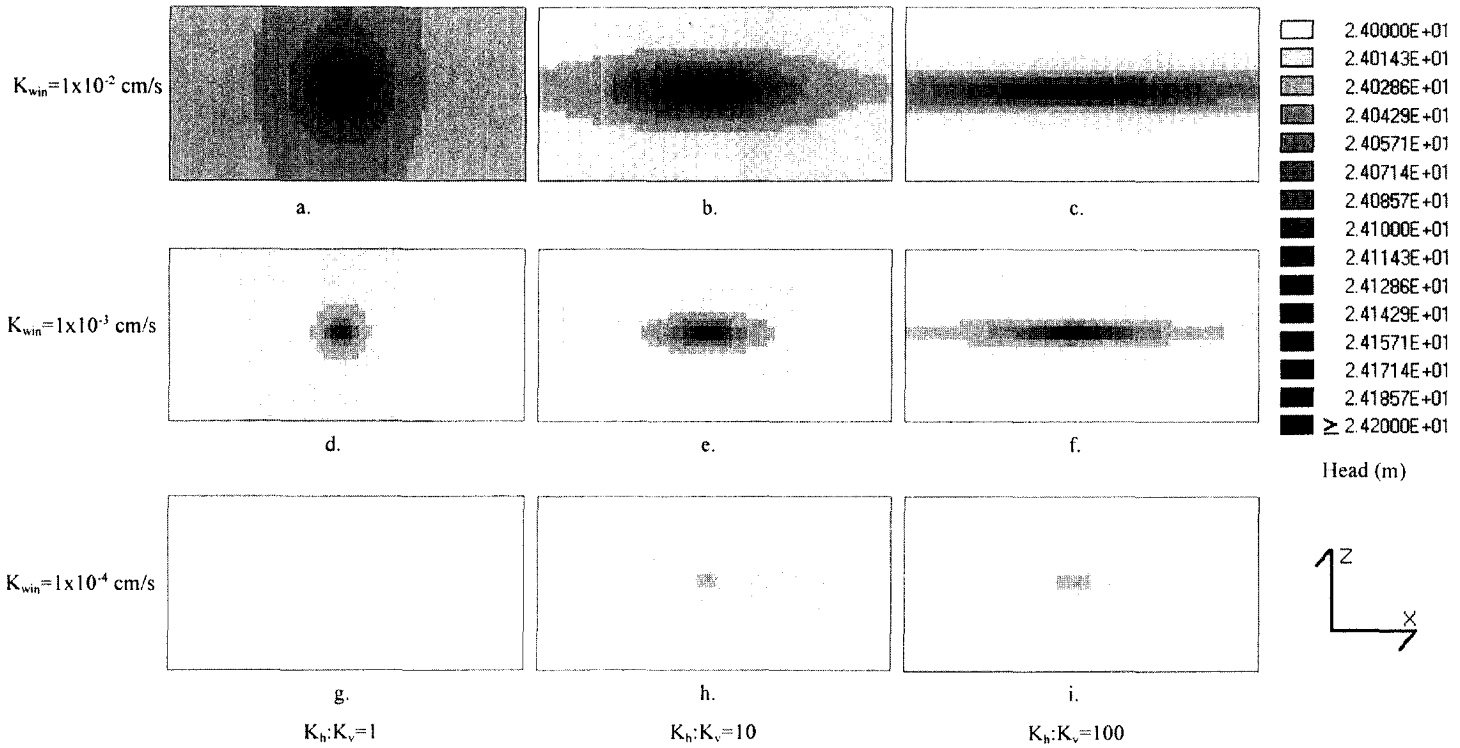


Figure 2. Vertical cross section of model results illustrating hydraulic signature (head) variations due to changes in conceptual hydrogeologic setting, ranging from homogeneous, isotropic to homogeneous, anisotropic conditions.

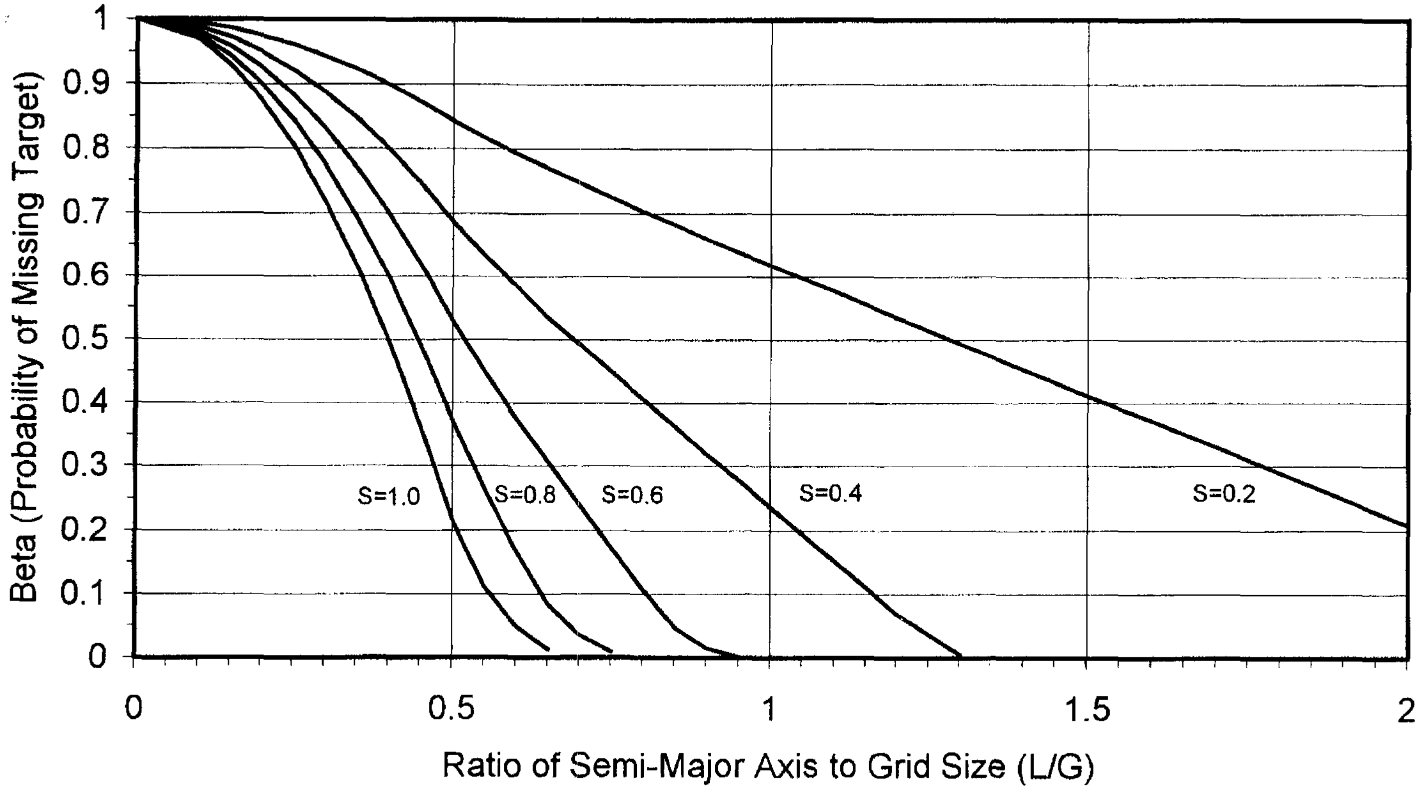


Figure 3. Nomograph relating ratio of semimajor axis of elliptical target and grid size to the probability of missing the target (β) for different shape factors using a square grid pattern.

specified probability of success (Y-axis intercept, $\beta = 0.2$), it is determined from the X-axis intercept that a circular hydraulic feature with a radius of approximately 10.1 m can be detected. The probability of not detecting the feature will increase as the radius of the hydraulic signature diminishes.

Results and Discussion

The dimensions of the hydraulic signatures associated with leakage through a subsurface vertical barrier are a function of the hydrogeologic properties of the aquifer, vertical barrier, and zone of leakage. The parameters evaluated in the following section include variations in K_{win} and K_h:K_v. Assuming all other variables remain constant, the magnitude of the hydraulic signature dimin-

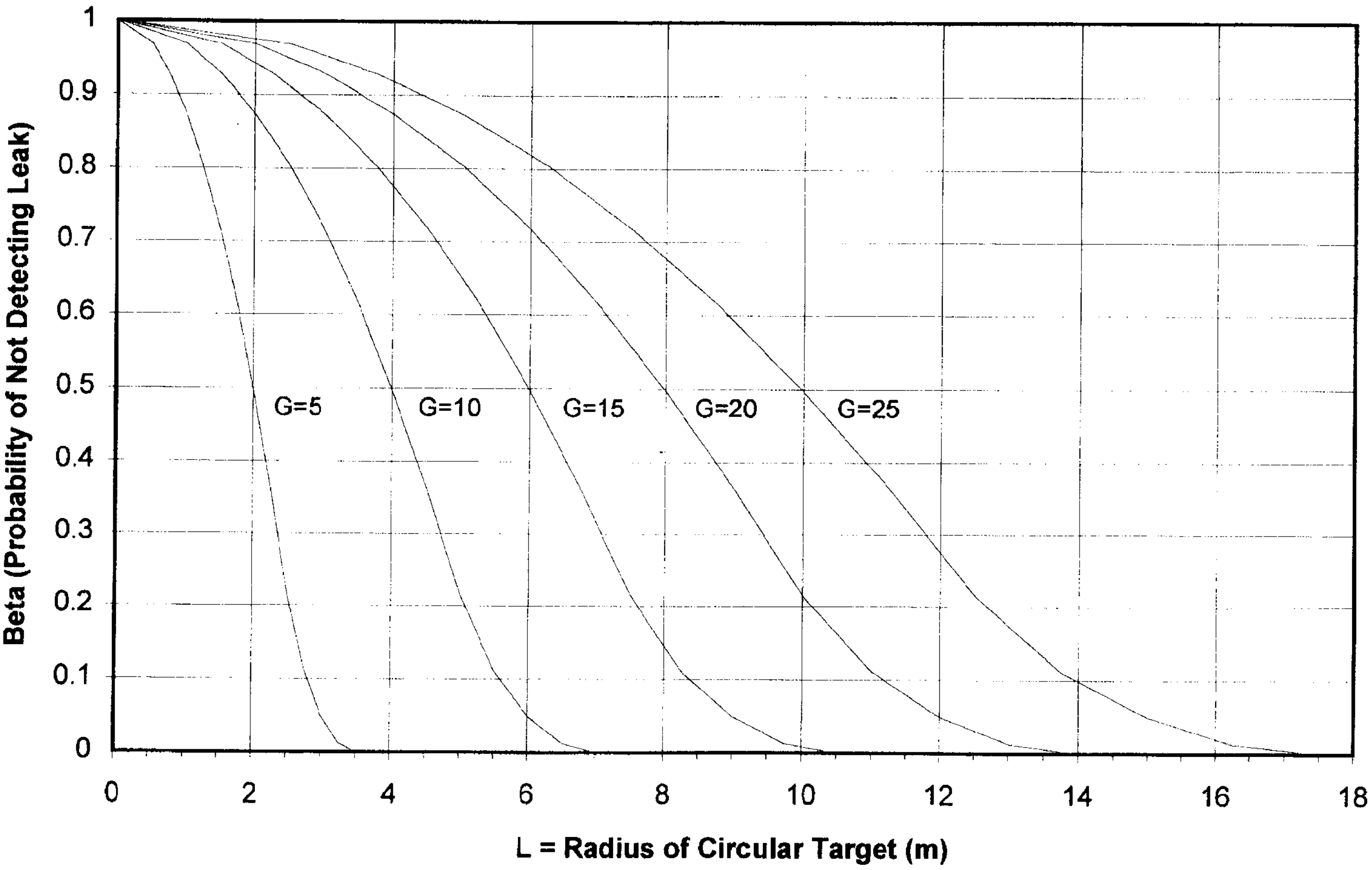


Figure 4. Nomograph relating radius of circular hydraulic signature to probability of not detecting leak (β) for different grid spacings.

ishes significantly as the hydraulic conductivity of the window decreases (Figure 2). The hydraulic signature of leakage through the 1×10^{-2} cm/s hydraulic conductivity window (Figure 2a) becomes less prominent as K_{win} is reduced to 1×10^{-3} cm/s (Figure 2d). As K_{win} is further reduced to 1×10^{-4} cm/s, the hydraulic signature becomes discernable only immediately adjacent to the window (Figure 2g). All head values for the simulations of ground water flow through the 1×10^{-5} cm/s window are within a range of approximately 0.002 m.

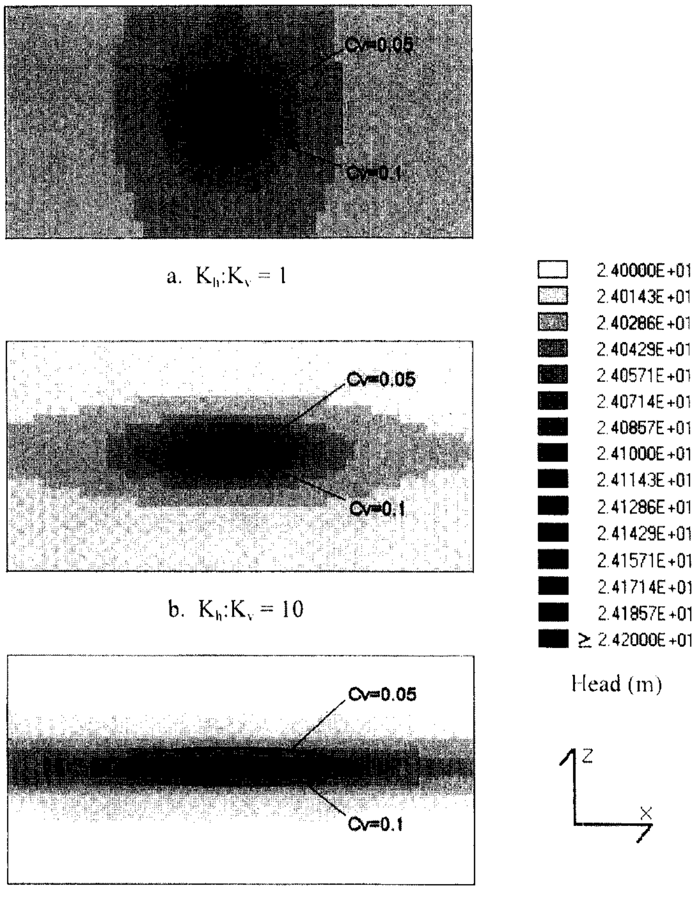
The effect of varying the horizontal-to-vertical hydraulic conductivity values is illustrated in Figure 2. For example, the hydraulic signature from leakage through a window with a hydraulic conductivity of 1×10^{-2} cm/s under homogeneous and isotropic ($K_h = K_v$) conditions forms an approximately circular feature (Figure 2a). However, as the horizontal-to-vertical hydraulic conductivity ratio increases one order of magnitude (K_h:K_v = 10), the hydraulic signature of the leak becomes elliptical (Figure 2b). As the ratio increases to K_h:K_v = 100, the hydraulic signature of the leak becomes highly elongated (Figure 2c).

The described method was applied to different hydraulic signatures developed from three-dimensional ground water flow simulations of leakage through a vertical barrier. Delineation of the hydraulic signature of leakage through a window ($K_{win} = 1 \times 10^{-2}$ cm/s) in a homogeneous, isotropic aquifer ($K_{aq} = 1 \times 10^{-2}$ cm/s, $K_h = K_v$) is illustrated in Figure 5a. The approximate dimensions of the vertical hydraulic mound as defined by $C_v = \bar{x}_h + 0.05$ and $\bar{x}_h + 0.1$ are 7 m by 6 m, and 5 m by 4 m, respectively. An increase in the anisotropy of the simulated aquifer by one order of magnitude (K_h:K_v = 10) produces a vertically compressed and horizontally elongated hydraulic signature (Figure 5b). Similarly, increasing the anisotropy of the simulated aquifer by two orders of magnitude (K_h:K_v = 100) results in even greater compression and elongation of the hydraulic signature in the vertical and horizontal directions, respectively (Figure 5c).

Hydraulic signatures for leakage through a window with a hydraulic conductivity value of 1×10^{-3} cm/s exhibit similar trends in response to increases in anisotropy (Figures 2d through 2f). However, the overall dimensions of the hydraulic signature of the window are decreased significantly relative to that of the previous example. This results in a lack of head values greater than the threshold for $C_v = 0.1$ for the homogeneous isotropic simulations. All hydraulic head values associated with leakage through windows with hydraulic conductivities $< 1 \times 10^{-3}$ cm/s were less than $C_v = 0.05$ and, therefore, could not be evaluated using the method described previously.

The shape factors for the hydraulic features described were calculated using C_v = m and $\bar{x}_h + 0.1$ m, as previously described. The ratio of the length of the semimajor axis to grid size (L/G) necessary to identify the hydraulic features with a 90% probability of success (β = 0.1) were obtained from the nomograph in Figure 3. The grid size was determined by dividing L/G by the length of the semimajor axis (L). The number of sampling points (Ns) necessary to identify the hydraulic features within the domain of the model cross section is determined by dividing the cross-sectional area of the model (1275 m^2) by the area of one square grid spacing (G^2). The results are listed in Table 2.

The number of monitoring points required to identify the hydraulic signatures of the simulated leaks using the prescribed con-



a. K_h:K_v = 1

b. K_h:K_v = 10

c. K_h:K_v = 100

Figure 5. Vertical cross section of model results illustrating variations in hydraulic head values due to changes in anisotropy ($K_{aq} = 1 \times 10^{-2}$ cm/s, $K_{win} = 1\ (10^{-2}$ cm/s). The ellipses define the approximate boundaries of the hydraulic features defined by specified critical values ($C_v = \bar{x}_h + 0.1$ m and $\bar{x}_h + 0.05$ m).

straints and confidence ranged from approximately 40 to more than 300. The wide range of values is a function of the variability in the size and shape of the hydraulic features. This variability results from the use of different critical values to define the hydraulic signatures of the leaks and the wide range of shape factors resulting from the three orders of magnitude range of K_h:K_v values used to simulate aquifer anisotropy.

Conclusions

Numerical modeling of ground water flow through high hydraulic conductivity windows in subsurface vertical barriers was conducted to provide data sets for use with a probabilistic method for determining the grid spacing necessary to identify the hydraulic signature associated with the leaks. The proposed method represents a potential tool that may be used to evaluate the adequacy of existing and proposed hazardous waste containment systems for identifying containment system leakage. The utility of the proposed method is demonstrated using simulated data. Based on the application of the presented method using the simulation results, the following conclusions are made:

- The number of points necessary to identify the hydraulic signature of a discrete leak within prescribed constraints is a function of the criteria used to delineate the feature.
- By using the nomographs, the probability of failing to detect the hydraulic signature of a leak can be estimated for a given monitoring well spacing and specified dimensions.
- The dimensions of the smallest hydraulic signature detectable with a given monitoring point spacing can be estimated, given the appropriate constraints and specified confidence.
- The monitoring point spacing used at many hazardous waste sites is likely inadequate to detect the hydraulic signatures of all but the largest leaks.
- The method for delineating the hydraulic signature of a leak using the average hydraulic head plus specified values is sensitive to changes in anisotropy.

Table 2
Parameters and Results Obtained from Hydraulic Assessment Method

K_{win} (cm/s)	K_h:K_v	Critical Value (C_v)	Grid Size (m)	Number of Points
1×10^{-2}	1	0.1	3.91	84
1×10^{-2}	1	0.05	5.65	40
1×10^{-2}	10	0.1	2.14	280
1×10^{-2}	10	0.05	4.3	69
1×10^{-2}	100	0.1	2.14	280
1×10^{-2}	100	0.05	4.3	69
1×10^{-3}	1	0.1	N/A	N/A
1×10^{-3}	1	0.05	2.03	311
1×10^{-3}	10	0.1	2.03	311
1×10^{-3}	10	0.05	2.14	280
1×10^{-3}	100	0.1	2.14	280
1×10^{-3}	100	0.05	2.14	280

N/A All head values below critical value threshold.

Disclaimer

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