BACKGROUND DOCUMENTATION

for

Programs

POLLUTE & MIGRATE

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1. INTRODUCTION

This document provides supplementary information concerning computer programs POLLUTE and MIGRATE and should be read in conjunction with the Users Manuals for these programs (Rowe and Booker, 1983-90; 1988).

2. FINITE LAYER TECHNIQUES - MATHEMATICAL BASIS

Both programs POLLUTE and MIGRATE fall into a semi-analytic class of models known as Finite Layer Models. Like analytic solutions, finite difference and finite element methods, Finite Layer methods were first developed for application in civil engineering (e.g. heat flow, consolidation analysis, elastostatics) and were subsequently extended for applications in contaminant hydrogeology.

It has been well established, that contaminant transport in porous soil and rock can be governed by the advection-dispersion equations given in Reference 2. Depending on the problem to be solved, these equations can be written for 1-, 2-, 3-dimensional transport. In order to make an assessment of potential impact from a waste disposal site, it is necessary to solve these governing equations subject to appropriate boundary conditions. Numerous techniques have been proposed for solving these equations. Reference 1 (pages 787-789) discusses the relative merits of these techniques (including analytic solutions, the finite layer technique, boundary element techniques, finite difference and finite element techniques).

The finite layer technique is applicable to situations where the hydrostratigraphy can be idealized as being horizontally layered. For these conditions, the governing differential equations can be considerably simplified by introducing a Laplace and Fourier transform (the latter being required only for 2- or 3-dimensional problems). The transformed equations can be readily solved and an analytic solution is obtained in transformed space. This procedure parallels that adopted in the development of many analytic solutions. The difference between the finite layer technique and analytic solutions arises from the fact that in the finite layer approach the Laplace (and where relevant Fourier) transform is inverted numerically rather than analytically. As a consequence it is possible to examine more complicated and realistic situations. The formulation of the finite layer approach has been published by Rowe and Booker and is summarized for 1-, 2-, and 3-dimensional conditions in a book on numerical methods (see Reference 2). Previous publications describing the finite layer technique have appeared in refereed journals such as *The American Society of Civil Engineers, Journal of Geotechnical Engineers* (e.g. Reference 3), The *Canadian Geotechnical Journal* (e.g. Reference 4), and the British Geotechnical Society Journal *Geotechnique* (e.g. Reference 5).

It has been well established that when contaminated groundwater moves through a fractured system, attenuation occurs due to the process of the matrix diffusion. This process is discussed in References 6-9 which provide the theoretical justification for the modelling of contaminant migration through fractured media which is incorporated into computer programs POLLUTE and MIGRATE.

3. PREVIOUS USE

The computer programs POLLUTE and MIGRATE are marketed through the Geotechnical Research Centre, The University of Western Ontario, Canada. The programs have been purchased and are currently being used in Australia, Canada, Germany, Great Britain, New Zealand, and the United States of America. For example, in Canada, these programs are currently being used in the design of numerous landfills (including the Halton Landfill, the Peel Landfill, the Grimsby Landfill, the Warwick Landfill, the Tom Howe Landfill, the Port Colborne Landfill, and the Canborough Landfill, amongst others). The programs are also currently being used in the design of a number of landfills in in other countries.

References 1-9 all provide discussion and examples of application of finite layer techniques for representing advective-dispersive-diffusive contaminant transport. Reference 10 provides an overview of various factors associated with the prediction of potential impact of landfill sites on groundwater contamination. This paper discusses the relative importance of transport mechanisms such as diffusion, dispersion and advection as well as discussing the significance of attenuation mechanisms. Techniques for determining relevant parameters are outlined and the applicability of laboratory techniques for estimating diffusion and distribution coefficients is discussed. The finite layer technique has been used for predicting the observed migration beneath a number of landfill sites. For example, Reference 10 provides a comparison of the calculated contaminant migration, based on parameters determined from laboratory tests with the observed migration beneath the Sarnia Landfill.

The finite layer technique, and in particular program POLLUTE has found wide application for the analysis of laboratory diffusion experiments. This includes diffusion through both clayey type soils and porous rock (such as shale, mudstone, and sandstone). A discussion of the estimation of diffusion and distribution coefficients in clayey soils is provided in References 11 and 12. A discussion of the estimation of diffusion coefficients in intact shale and mudstone is provided in References 13 and 14.

As previously noted, the finite layer technique has been used for estimating the migration of contaminants through clay for a number of landfills (e.g. see Reference 10 for the Sarnia Landfill). The technique has also been used to analyze migration from landfills constructed on fractured rock as discussed in Reference 15.

4. ACCURACY OF NUMERICAL TECHNIQUE

Due to the semi-analytic nature of the finite layer approach, contaminant concentrations and the total mass flux into a barrier can be very accurately determined at any specified times and locations of interest without determining the entire solution field. This approach avoids the numerical problems that can arise when using finite element and finite difference techniques to solve the contaminant transport equations, for problems involving soils/rock having a high contrast in hydraulic conductivity (for example when a clay liner overlies an aquifer). The finite layer technique is particularly well suited for performing sensitivity studies to identify the potential impact of uncertainty regarding the value of key design parameters. The technique is also well suited for performing checks on the results of numerical analyses using finite element or finite difference techniques.

4.1 Inversion of Transforms

Because of the semi-analytic nature of the finite layer method, it is possible to determine an exact analytic solution for concentrations within a layer in transformed Laplace (& Fourier) space. The only numerical aspect of the solution arises from the inversion of the Laplace (and where appropriate Fourier) transforms. The Laplace transform can be very accurately inverted using a numerical technique proposed by Talbot (Reference 16). This numerical algorithm is extremely stable for most practical applications.

Computer program POLLUTE includes error checking code which makes a preliminary assessment as to whether default parameters used in the Laplace transform inversion are adequate and will repeat the calculation if there is a clear indication of numerical error. The user can also control a selection of Laplace transform parameters and may repeat the calculation for different choices of these parameters. When insufficient integration has been used, it is usually manifest by clearly incorrect results towards the bottom of the layer. In general, the more integration, the greater the depth to which an accurate solution can be obtained. As noted previously, the default parameters built into the program POLLUTE will provide accurate results for most practical situations, however it is the user's responsibility to check that sufficient integration has been used in the inversion of the Laplace transform. The selection of Laplace transform parameters is discussed in the user's manual for program POLLUTE.

Program MIGRATE involves an inversion of Laplace transform which is conducted in the same manner as described for program POLLUTE in the preceding paragraph. In addition, program MIGRATE also involves the numerical inversion of a Fourier transform. This inversion is performed using the technique of Gauss quadrature which is described in numerous standard text books on numerical technique. Some numerical error can arise when performing the integration required for inversion of the

Fourier transform. Program MIGRATE contains a number of default sets of integration parameters which can be selected by the user through the choice of a key word. The user also has the freedom to independently select any combination of parameters to evaluate the effect of integration upon the accuracy of the solution. One of the advantages of the 2-dimensional finite layer technique, is that any numerical error arising from the inversion of the Fourier transform tends to be greatest at the surface of the deposit where the concentration is usually known or, at least, bounded (i.e. it is either specified by a boundary condition or is zero). The numerical aspects associated with inversion of the Fourier transform are discussed in detail in the MIGRATE User's Manual and a number of examples illustrating the effect of the selection of integration parameters are provided for an extremely difficult (non-typical) problem. For most practical problems involving relatively slow contaminant migration through clay into an underlying aquifer, inversion of the Fourier transform is relatively straight forward.

4.2 Space and Time Discretization

It should be emphasized that when operating program POLLUTE or program MIGRATE in its basic mode, there is **no discretization error** (i.e. the accuracy of the solution does not depend on the number of layers into which the deposit is subdivided). This is in contrast to numerical (e.g. finite element or finite difference) techniques where the accuracy of the solution is highly dependent on the choice of layering (i.e. mesh design).

It should also be emphasized, that because this is a continuous time solution there is no need to march the solution forward in time as must be done for conventional finite element or finite difference codes. The solution can be determined directly at any given time of interest without the prior determination of the solution at preceding times. **There is no need for time discretization.** As a consequence, the problems associated with oscillation of solutions and the selection of time step which must be considered in using finite element or finite difference solutions do not arise with the finite layer technique. Furthermore, problems such as numerical dispersion which can occur with conventional finite element or finite difference techniques do not arise with the finite layer technique.

4.3 Verification

Both programs POLLUTE and MIGRATE have been verified by comparison of the results obtained using these programs with the results obtained from both analytic solutions and finite solutions. For example, Figure 1 reproduces a comparison between the results obtained with finite layer program POLLUTE and those obtained from analytic solutions and finite element results reported by Yeh (1984). Details regarding this comparison are provided in Reference 17. An inspection of the results shows that the finite layer program (POLLUTE) gives identical results to the analytic solution. This problem is a relatively difficult problem for finite element solutions (the

Peclet number is 50). This can be seen by the unrealistic wiggles near the concentration fronts, (including physically impossible concentrations) which are evident in the conventional finite solution. The finite element results shown in this figure also illustrate numerical dispersion (i.e. the excessive spreading of a contaminant plume due to numerical problems). This is evident from the fact that the finite element solution under-predicts concentrations at distances less than about 4 m and over-predicts concentrations at distances more than about 4 m. As previously discussed, because the finite layer solution is based on an analytic solution in transformed space there is no numerical dispersion and it is a relatively simple matter to obtain the exact solution.

The solution for fractured systems incorporated in the finite layer technique (see References 6-9) has been incorporated into finite layer programs POLLUTE and MIGRATE. For the special case of a constant contaminant source and parallel fractures, this theory reduces to the same as that published by Sudicky and Frind (Reference 21). The implementation of this theory in the computer code can be checked by comparing results from say program POLLUTE with those obtained by Sudicky and Frind. For example, Figure 2 shows a comparison between the results obtained from program POLLUTE and those published by Sudicky and Frind (Reference 21) for contaminant migration along a parallel set of fractures at 10,000 days (27.393 years). This system is considered to be non-sorbing and the source leachate has an initial concentration of 1 mg/l and a decay constant of 0.0561 years^{-1}. Examination of Figure 2 reveals that both solutions give the same results. It is worth noting that the speed of the solution technique in program POLLUTE is far greater than the speed of the integration required to evaluate the Sudicky and Frind analytic solutions.

Another check on the implementation of the contaminant transport through fractures incorporated in these programs is to compare the results obtained for the situation where the spacing between fractures becomes very large with the analytic solution developed by Tang et al. (Reference 19). To illustrate this, consider a single 10 micrometer crack with a groundwater velocity along the fracture of 730 m/a. Assuming the diffusion coefficient in the fracture is 0.077 m^2/a, and that the contaminant is conservative with a non-decaying initial concentration of 1 mg/l the concentrations along the fracture can be calculated at say, 25 years as tabulated in Table 1. Also shown in Table 1 are the calculated concentrations obtained using the Tang et al. (Reference 20) solution and the Sudicky and Frind (Reference 21) solution. Examination of Table 1 confirms that the results obtained using the program POLLUTE are in good agreement with those obtained using other analytic solutions. In fact, it is noted that the solutions obtained using POLLUTE are more accurate than the solutions obtained using the Tang et al. solution (Reference 20) because the Laplace transform inversion gives more accurate results than polynominal approximations to complementary error functions which are used in the evaluation of the Tang et al. solution.

Results obtained from the two-dimensional pollutant migration program MIGRATE can be compared with results from analytic solutions available in the literature to evaluate the accuracy of the numerical simulation. One such solution has been proposed by Javandel et al. (1984) and coded in a computer program called TDAST.

TDAST can solve a 2D plane dispersion problem for an infinitely deep porous medium (see Figure 3) with great accuracy and speed, but overflow and underflow errors may develop for very small dispersion coefficients. Program MIGRATE can be used to calculate the concentrations below a pollutant source similar to the TDAST model (see Figure 4) provided that the base of the layer is located far enough from the source such that the contaminant does not reach the boundary during the times of interest. Under these conditions the infinitely deep deposit assumed in TDAST is equivalent to the deposit of finite depth considered by MIGRATE. It should be noted that both TDAST and MIGRATE are transport models. The base boundary shown in Figure 4 prevents contaminant transport (but not flow) across the boundary. Although this does not correspond to physical reality, it is a convenient mathematical approximation for comparing TDAST and MIGRATE for this times of interest. In reality, if there is a downward flow there is usually an aquifer to receive the flow. This can be modelled by MIGRATE but not by TDAST.

Figure 4 presents results calculated by both TDAST and MIGRATE for concentrations along the source centre line in a hypothetical porous medium at 4 years for three dispersion coefficients (10, 5, and 0.01 m^2/a). An examination of Figure 5 indicates that the finite layer technique coded in program MIGRATE is in close agreement with the Javandel et al. (1984) solution programmed in TDAST. In fact, increasing the levels of integration in both programs will show that both solutions are identical. This increase in integration is proportional to the ratio of Darcy velocity v_a to dispersion coefficient D (that is, as v_a/D increases, more integration is required to invert the Laplace transport). For a constant velocity $v_a = 1$ m/a, it is not difficult to get accurate curves for $D = 10\ m^2/a$ (Case 1 in Figure 5 where $v_a/D = 0.1\ m^{-1}$), but as D is decreased to 0.01 m^2/a (Case 3; $v_a/D = 100\ m^{-1}$) considerable more integration is needed. For most practical problems involving contaminant migration through clayey liners v_a/D is usually less than 5 and the NORMAL Fourier integration and the default Laplace transform parameters (as defined in the user's manual for MIGRATE) are often sufficient. Adequacy of the integration parameters can be checked by repeating the calculation for higher levels of integration.

4.4 Mass Balance

Programs POLLUTE and MIGRATE have a number of boundary conditions which include constant specified concentrations, finite mass within a landfill, modelling of an aquifer as a boundary condition and a zero flux boundary. The finite mass of contaminant boundary condition incorporates an analytic expression which maintains conservation of mass while considering contaminant escape from the landfill into the underlying strata. The modelling of an underlying aquifer as a boundary condition also involves an analytic equation which insures the conservation of mass when considering the mass entering the aquifer from the overlying strata and the mass transported in the aquifer itself. Thus because of the analytic nature of the underlying solution, mass balance is always satisfied in Laplace transform space. Provided that sufficient integration is used in inverting the transforms, mass balance is automatically satisfied in the entire solution. The question of whether sufficient integration has been used is readily answered by repeating the calculation for two sets of integration parameters (one requiring significantly more integration than the other). If the two analyses agree, then mass balance is automatically satisfied in the solution. If they do not agree then the process should be repeated with higher integration.

The actual mass flux of contaminant entering the clay system from a landfill and the mass flux entering an underlying aquifer can be independently calculated from an analytic solution and are presented as part of the output from the programs. These quantities are determined **independant of the concentration** profile (and indeed are more sensitive to integration error than are the concentrations, if any error exists) and may be used as a cross check on mass balance.

The masses entering a soil system and an underlying aquifer are discussed in Reference 4 and a comparison is made between the calculated masses from a 1½-D (POLLUTE) solution and a 2-D (MIGRATE) solution. It has been shown analytically, that for a situation where there is downward flow from a landfill to a single underlying aquifer, the mass into the aquifer calculated for any time t and any base velocity (i.e. horizontal velocity in the aquifer) is equal to the mass calculated from program POLLUTE assuming the base velocity is zero. Thus program POLLUTE can be used to provide a mass balance check on computer program MIGRATE. This comparison and check is illustrated for a particular example in Reference 4.

5. SENSITIVITY ANALYSES

As discussed in the previous section, in their basic mode of operation neither program POLLUTE nor MIGRATE requires numerically assigned space and time discretization for the purposes of obtaining an accurate solution. The number of layers modelled is dictated by the physical differences in parameters between layers and there is no gain in accuracy by subdividing the physical layers in to sub-layers. Similarly calculations can be performed for any time of interest and the accuracy of the calculation at that time is independent of any previous evaluation of the solution at earlier times.

When operating the program POLLUTE in its **advanced mode** (i.e. using the variable parameters option) it is necessary to sub-divide physical layers in to a reasonable number of sub-layers in order to ensure an accurate solution. The number of sub-layers required when using these advanced features can be assessed by trial and error.

Programs POLLUTE and MIGRATE have been used in extensive parametric studies to investigate the effect of varying major physical parameters which affect contaminant migration from landfills.

The following summarizes key references relating to modelling of contaminant impact using the finite layer technique. Sensitivity analyses that have been performed to illustrate the relative importance of different physical parameters for a number of hypothetical landfills is also summarized. The references cited are appended to this document.

The papers are subdivided into four groups. The first group of papers provides an overview of some of the factors to be considered when performing contaminant impact assessment. These papers discuss the relative importance of different contaminant transport mechanisms, the estimation of finite mass of contaminant and how it can be represented in terms of an "equivalent height", of leachate H_f, and "reference height of leachate," H_r. These papers also provide an overview of techniques for estimating key parameters and illustrate the application of the finite layer technique for a landfill in clay (Reference 10) and in fractured rock (Reference 15).

The second group of papers provide the mathematical basis for the finite layer analysis together with sensitivity analyses illustating the relative importance of different physical parameters for a number of hypothetical landfills. These papers consider both intact and fractured porous material. Reference 9 discusses the relationship between the "equivalent height of leachate", H_f, and the "reference height of leachate", H_r which can both be used to represent the mass of contaminant.

The third group of papers describe techniques that have been used to estimate diffusion and adsorption parameters both in clay and sedimentary rock and illustrate the use of the program POLLUTE in the estimation of these parameters.

The fourth group of papers provide background references.

5.1 General Papers

Reference 1: Rowe (1988)

This paper discusses the role of modelling in the evaluation and design of barriers. Factors considered include (i) the mechanisms controlling contaminant migration through barriers; (ii) the estimation of diffusion and distribution coefficients; (iii) leachate mounding and the effect of clogging of leachate collection systems upon contaminant migration through barriers; (iv) the importance of considering the finite mass of contaminant available for transport into the soil and a method of modelling the effect of finite mass of contaminant; and (v) examples of how analysis may improve the designers feel for the effectiveness of potential contaminant attenuation mechanisms in both glacial till deposits and fractured rock.

Parametric studies reported in this paper include:

- The effect of Darcy velocity and diffusion coefficient on contaminant flux into a liner (Figure 9);
- The effect of the mass of contaminant (expressed in terms of an equivalent height of leachate, H_f) on the variation in leachate concentration with time for a specific case (Figure 12);
- The effect of the mass of contaminant (expressed in terms of an equivalent height of leachate) on the variation in concentration of contaminant at a point in a aquifer located at the site boundary for a particular problem (Figure 13 and 14);
- The outward migration of contaminant due to diffusion which can occur even when there is inward flow of groundwater into the landfill (Figure 15);
- The effect of the finite mass of contaminant (expressed in terms of an equivalent height of leachate) on contaminant concentration in fractured rock (Figure 17);
- The effect of fracture opening size and fracture spacing on an contaminant plume after 30 years migration from a hypothetical landfill in fractured rock (Figure 18 and 19).

Reference 10: Rowe (1989)

This paper provides an overview of factors to be considered when attempting to predict impact of landfill sites on groundwater contamination. It provides a summary of results contained in a number of other papers (including References 1 and 17) as well as a comparison between observed and calculated behaviour beneath the Sarnia Landfill.

Reference 17: Rowe (1987)

Methods of predicting contaminant transport through clay barriers are reviewed. Particular consideration is given to the relative importantance of advection and dispersion as transport mechanisms, the soil properties controlling transport, contaminant transport through barriers and into adjacent aquifers, and methods of obtaining solutions to the transport equations. Parametric studies are reported as summarized below:

- The relative contribution of dispersion and diffusion to the coefficient of hydrodynamic dispersion are examined as a function of advective velocity (Figure 1);
- The importance of considering both advection and diffusion when examining potential impact associated with contaminant migration through clay liners is illustrated by examining the mass flux through a 1.2 m thick clay liner for the cases where (a) advection is ignored, (b) diffusion is ignored and (c) where both advection and diffusion are considered. The error associated with not considering coupled advective-diffusive-dispersive

transport is illustrated as a function of Darcy velocity (Figure 2, 3 and 4).

- The range of velocities over which diffusion or mechancial dispersion controls the coefficient of hydrodynamic dispersion and the range of velocities over which diffusion or advection dominates the peak contaminant flux through a 1.2 m thick clay liner is illustrated (Figure 5);
- The modelling of contaminat migration using analytic solutions, finite layer techniques, boundary elements, finite difference and finite element methods is discussed. A comparison of concentration variation with distance as calculated from an analytic solution, finite layer program POLLUTE and two finite element analyses reported in the literature is illustrated for a test case (Figure 8). This test case has been discussed in a previous sub-section and is illustrated in Figure 1 of this document.

Reference 19: Rowe (1990)

This paper examines a number of factors that warrant consideration when performing contaminant impact assessments. The modelling of the finite mass of contaminant within a landfill is discussed and the representation of the mass of contaminant in terms of a reference height of leachate H_r is discussed and illustrated by a numeric example. The paper illustrates the effect of the assumed mass of contaminant, infiltration into the landfill and the contaminant transport pathway on the contaminating lifespan of the landfill (where the contaminating lifespan is defined as the period of time during which the landfill produced contaminants at levels that could have unacceptable impact if they were discharged into the surrounding environment). The concept of developing "triggers" to initiate leachate control measures, and the associated potential impact on groundwater, is discussed in the context of the potential design life of the primary engineering in a landfill. The effects of fracturing of a till, beneath a hypothetical landfill, on the potential impact of contaminants in an underlying aquifer is examined. The influence of both a man-made (compacted clay liner) and natural intact clay layer in contact with the fractured till is examined. Consideration is given to:

- The effect of initial concentration, mass of contaminant and infiltration upon the variation in leachate strength with time (Figure 1);
- The effect of the thickness of the fractured layer and of the compacted clay liner assuming the fractures are not hydraulicly transmissive and assuming that migration does occur primarily along the fractures (Figure 3 and 4);
- The development of trigger concentrations and levels of leachate mounding for the hypothetical landfill being considered.

5.2 Mathematic Basis

Reference 2: Rowe and Booker (1987)

This chapter of the text *Numerical Methods for Transient and Coupled Problems* provides a description of the finite layer technique for 1, 2 and 3-dimensional conditions. It also presents the results of a sensitivity study performed, as summarized below:

- The variation in concentration within an aquifer due to advective-diffusive transport from a landfill is shown as a function of time for a conservative and retarded contaminant species and the effect of considering the finite mass of contaminant is illustrated (Figure 2.2);
- The effect of the advective velocity on impact in an aquifer beneath a clay liner is examined by considering the three different advective velocities: one inward, zero velocity, and one outward velocity (Figure 2.3);
- The effect of the mass of contaminant (expressed in terms of the equivalent height of leachate H_f) on the maximum impact in an aquifer beneath a hypothetical landfill is examined for both a conservative and a retarded contaminant species (Figure 2.4);
- The modelling of a system involving a landfill underlain by a clay liner, underlain by a sand aquifer, underlain by a second clay liner is examined with respect to the choice of boundary conditions used to model migration using computer program MIGRATE. The impact calculated

from the 1½-D program POLLUTE is then compared with that calculated using a 2-D program MIGRATE (Figures 2.5 and 2.6).

Reference 3: Rowe and Booker (1985a)

This was the original paper introducing the finite layer method for contaminant transport problems to the referred literature. The solution presented in this paper is for one dimensional transport through a clay liner into an underlying aquifer. This model was generalized for multi-layer systems in Reference 2. This paper also presents an analytic solution (see Appendix 1) for a layer of finite thickness with a constant source concentration and zero concentration at the base. The finite layer program POLLUTE was checked against this and other analytic solutions. The paper contains a parametric study for a hypothetical landfill which examines the effects of:

- the mass of contaminant (expressed in terms of the equivalent height of leachate H_f) (Figure 2, 4, 6, 7, 8, 9, 10, 11, 12 and 13);
- The effect of the base velocity within the aquifer (Figure 3, 4, 8, 9, 10, 11, 12 and 13);
- The effect of sorption (Figure 5, 6, and 7);
- The effect of the thickness of the clay barrier beneath the landfill (Figure 9, 10, 11 and 12);
- The effect of the vertical Darcy velocity (flux) through the clay (Figure 13).

Reference 4: Rowe and Booker (1985b)

The two-dimensional finite layer technique is introduced in this paper for a single layer underlain by an aquifer. This solution was generalized to multi-layer systems in References 2 and 5. The parametric study included consideration of an aquifer separated from a landfill by a 2 m thick clay barrier. This study examined:

- The development of a contaminant plume with time and distance away from the source (Figure 2-6);
- The effect of the horizontal velocity within the underlying aquifer (Figure 4);
- The effect of variation in the horizontal coefficient of hydrodynamic dispersion in the base aquifer (Figure 5);
- The concentration profile through the clay at the edge of the landfill and at the property boundary for a hypothetical case (Figure 6);
- The comparison of results obtained from the 1½-D solution using program POLLUTE with those obtained from full 2-D solution using program MIGRATE (Figure 7 & 8 and Table 1).

Reference 5: Rowe and Booker (1986)

This paper presented the generalization of the finite layer technique for multi-layer systems and 2 or 3-dimensional conditions. The paper presents the results obtained for 2-dimensional conditions using computer program MIGRATE.

The parametric studies included an examination of a hypothetical landfill overlying a layered system involving two sand aquifers and two clay aquitards. The parametric study included consideration of:

- The effect of the coefficient of hydrodynamic dispersion within the aquifer (Figure 3 and 5);
- Attenuation of contaminant with distance (Figure 3, 4, 5, 6, 7 and 8);
- The effect of the Darcy velocity (flux) in the upper aquifer (Figure 6);
- The effect of the thickness of the upper aquifer (Figure 7);
- The effect of the size of the landfill (Figure 8).

Reference 6: Rowe and Booker (1989)

This paper presents a semi-analytical solution for contaminant transport of a conservative contaminant species in fractured media having a regular 2- or 3-dimensional fracture network. This solution has been incorporated in the program POLLUTE. The solution for a single set of parallel fractures evolves as a special case of the general theory presented in this paper. The paper presents a parametric study for a fractured system which examines the effects of:

- The finite mass of contaminant (expressed in terms of the equivalent height of leachate H_f) (Figure 2);
- The nature of the fracturing (i.e. 1D, 2D or 3D) (Figure 3);
- The effect of diffusion coefficient in the matrix of the intact material adjacent to the fractures and the effect

of matrix porosity (Figure 4, 5 and 6);

- The effect of fracture spacing (Figure 7);
- The effect of dispersivity along the fractures (Figure 8, 9, 10 and 11);
- The effect of fracture opening size (Figure 11);
- The effect of Darcy velocity (flux) (Figure 12 and 13);

Reference 7: Rowe and Booker (1990a)

This paper extends the theory presented in Reference 6 to include consideration of reactive contaminants (i.e. contaminants which experience sorption either on the fractured surface or within the matrix adjacent to the fractures or those that experience biological or radio-active decay). The paper then expands on the parametric study presented in Reference 6 and considers:

- Effect of fractured spacing and numerical considerations associated with calculation of impact for 2-D and 3-D fractured systems (Figure 2 and 3);
- The development of a contaminant plume in a fractured media for a one-dimensional and three-dimensional fractured system (Figure 4, 5, 6, 7, 8 and 9) including an examination of the effect of fracture spacing and the Darcy velocity through the fractured system;
- The effect of sorption within the matrix of the material adjacent to the fractures (Figure 10, 11, 12, 13 and 14);
- The effect of the mass of contaminant (expressed in terms of the equivalent height of leachate) (Figure 14 and 15);

- The effect of sorption on the fracture surface (Figure 16).

Reference 8: Rowe and Booker (1990b)

This paper combines concepts presented in Reference 3 and Reference 7 to develop a finite layer technique which considers contaminant migration through a fractured layer (e.g. clay till) into an underlying aquifer. This theory has been implemented in the program POLLUTE v5. The paper examines the hypothetical situation of a landfill separated from an underlying aquifer by a fractured till. The paper examines the following:

- The effect of fracture spacing (Figure 2, 3, 5, 6 and 7);
- The effect of the porosity of the matrix of the till (Figure 4);
- The effect of the thickness of the layer (Figure 6 and 7).

Reference 9: Rowe and Booker (1990)

This paper combines concepts presented in Reference 4 and Reference 7 to develop a finite layer technique which considers contaminant migration through a fractured layer system for full 2-D migration.

The paper discusses the representation of the mass of contaminant in terms of the reference height of leachate H_r and the equivalent height of leachate H_f. It illustrates the relationship between these two representations and describes the theory that can be used to model a functioning leachate collection system while performing contaminant transport calculations.

This paper examines hypothetical landfill separated from an underlying aquifer by a fractured system which in turn is separated from a second underlying aquifer by a second clay layer which may or may not be fractured.

The parametric study presented in this paper examines:

- The decay of leachate concentration with time in a landfill (Figure 4);
- The effect of fracturing and hydraulic conductivity upon contaminant migration for a number of different combinations of fracturing.

Reference 15: Rowe and Booker (1989)

The effects of fracture spacing, fracture opening size, Darcy velocity and dispersion upon the calculated contaminant plume in a fractured shale are examined. It is shown that the calculated contaminant plume, based on reasonable hydrogeologic input is consistant with the observed, very limited, extent of the contaminat plume at a fifteen year old landfill at Burlington, Ontario. The results suggest that matrix diffusion can play a very significant role in the attenuation of contaminant migrating in fractured porous media.

5.3 Techniques for Estimating Parameters using POLLUTE

Reference 11: Rowe et al.(1988)

This paper describes a technique for estimating the diffusion coefficient and distribution coefficient for contaminants passing through clay soil samples. The technique is illustrated with reference to a number of laboratory tests involving advective-diffusive migration of potential contaminants through an intact clay soil from Sarnia, Ontario, Canada. Program POLLUTE is used to model contaminant movement through the clay soil. The diffusion and distribution coefficients are estimated for a number of single salt solutions passing through the clay soil. On the basis of these tests it is suggested that, for the Sarnia soil considered and advective (Darcy) velocities up to the maximum examined (.035 m/a), mechanical dispersion does not measurably affect the magnitude of the coefficient of hydrodynamic dispersion. (i.e. it is equivalent to the diffusion coefficient and there is no significant dispersion). It is also suggested that the effective porosity corresponds to that deduced from water content for this soil.

<u>Reference 12: Barone et al. 1989)</u>

This paper extends the work reported in Reference 11. The techniques described in Reference 11 are used to estimate diffusion and adsorption parameters for a number of components of domestic waste leachate as they migrate through clay soil. Comparisons are made between the diffusion coefficients obtained when there is multiple contaminant migration from a real leachate with those obtained using a single salt solution as the contaminant source. It is shown that both the diffusion coefficient and the distribution coefficient are influenced by the types and amount of co-diffusing species present in the initial source solution. It is recommended that laboratory tests conducted to estimate diffusion parameters for use in design should be run with soils and source solution as near as practicable to those expected in the field.

Reference 13: Barone et al. (1990a)

An experimental investigation of diffusive transport of a nonreactive solute (chloride) in saturated, intact Queenston shale is described in this paper. The experimentally determined diffusion coefficient for chloride in this shale is reported.

The results of the diffusion tests reported in this paper formed the basis for the analysis of contaminant migration from the Burlington Landfill reported in Reference 15.

Reference 14: Barone et al. (1990b)

This paper reports the results of diffusion tests conducted to estimate the diffusion coefficient for chloride through mudstone. Program POLLUTE was used in the analysis of these results.

Reference 18: Rowe and Booker 1989b)

This paper examines contaminant migration from a hypothetical buried, saturated, landfill with a 1 m thick clay cover and a 2 m thick clay liner assuming that the liner is underlaying by an aquifer. Consideration is given to contaminant migration both through the clay cover and through the clay liner into the underlying aquifer using both the 1½-D program POLLUTE and the 2-D program MIGRATE. Consideration is given to:

- The development of the contaminant plume in the underlying aquifer (Figure 3);

- Continuation of impact with distance away from the landfill (Figure 4, 5 and 6);
- The proportion of the total initial mass of contaminant which escapes through the clay cover by upward diffusion at a given time for a number of assumed parameters (Figure 7);
- The effect of assumptions concerning the diffusion coefficient in the landfill and cover, the vertical Darcy velocity, and the horizontal velocity in the aquifer (Figure 7, 8 and 9)

5.4 Other References

Reference 16: Talbot (1979)

This paper provides the theoretical basis for the inversion of Laplace transforms implemented in computer programs POLLUTE and MIGRATE.

Reference 20: Tang et al. (1981)

An analytic solution for contaminant migration along a single fracture is described. This solution was used to check the implementation of fracture modelling in Program POLLUTE.

Reference 21: Sudicky & Frind (1981)

The solution presented in Reference 20 is extended to a system of parallel fractures. This is used to check implementation of fracture modelling in program POLLUTE.

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* Where a reference number is given, it implies that a copy of this paper is included with this document under the tab corresponding to the reference number.

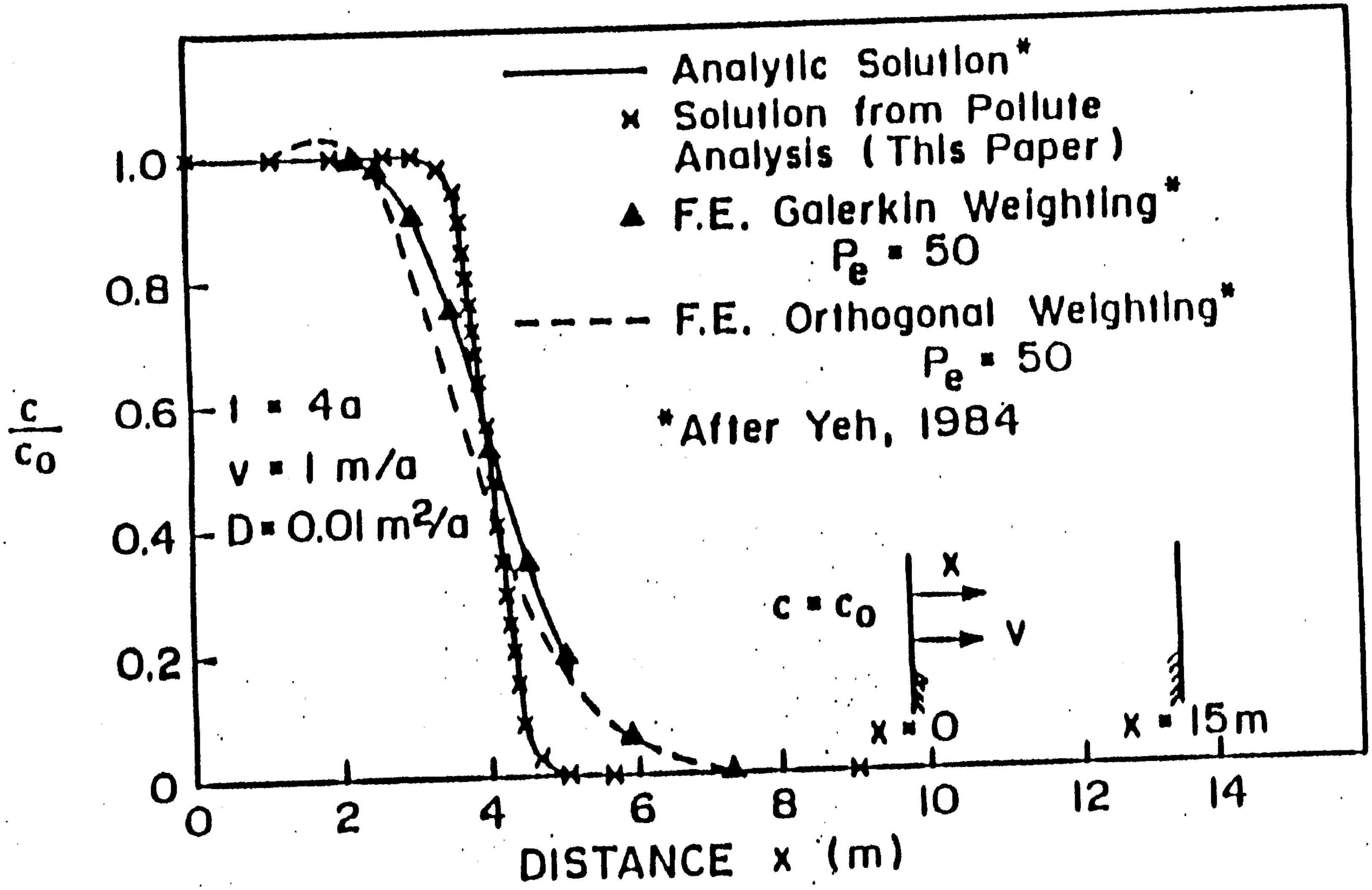


Figure 1. Comparison of concentration variation with distance as calculated from: analytical solution, finite layer program POLLUTE, and two finite element analyses reported by Yeh (1984).

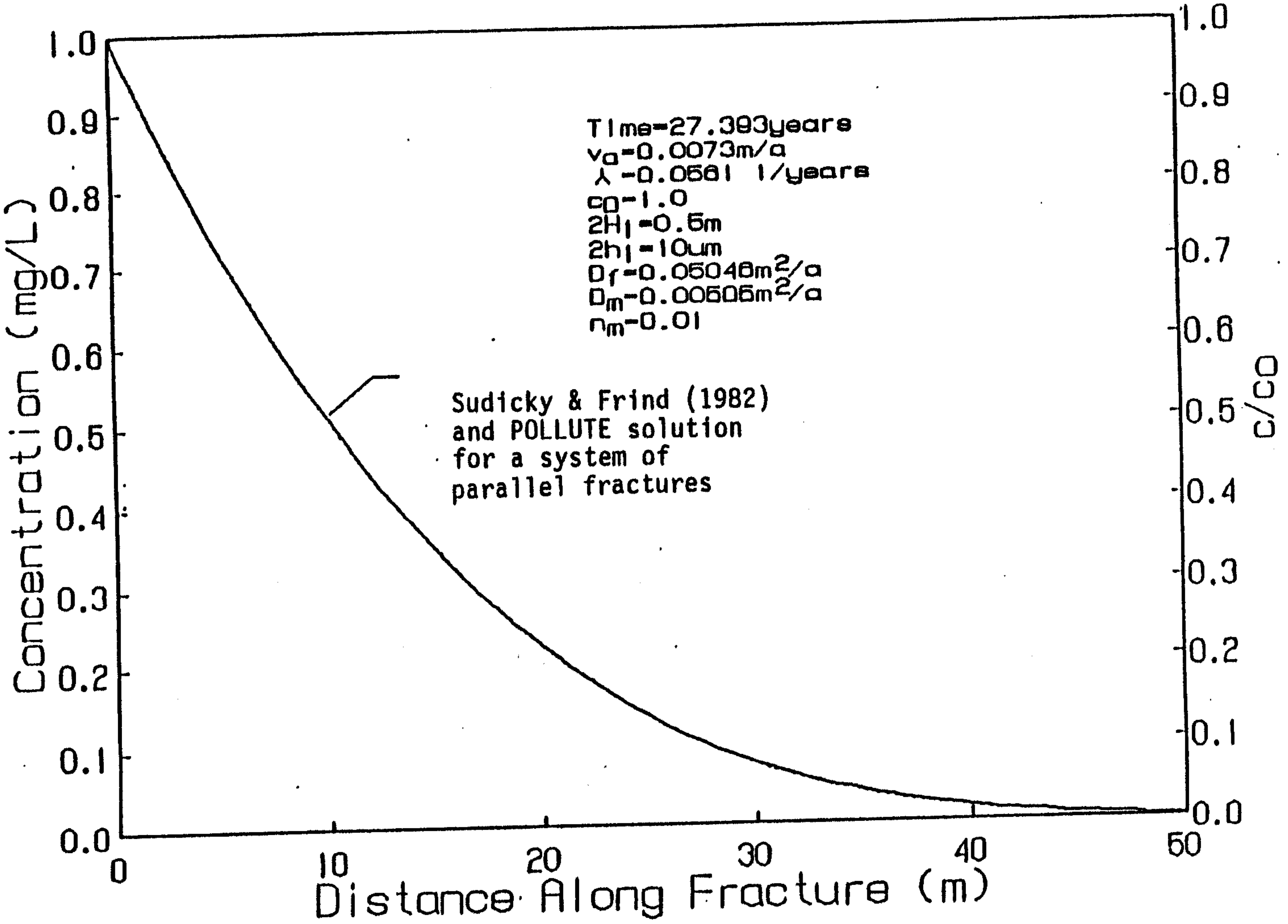


Figure 2 Parallel cracks solution at 10,000 days

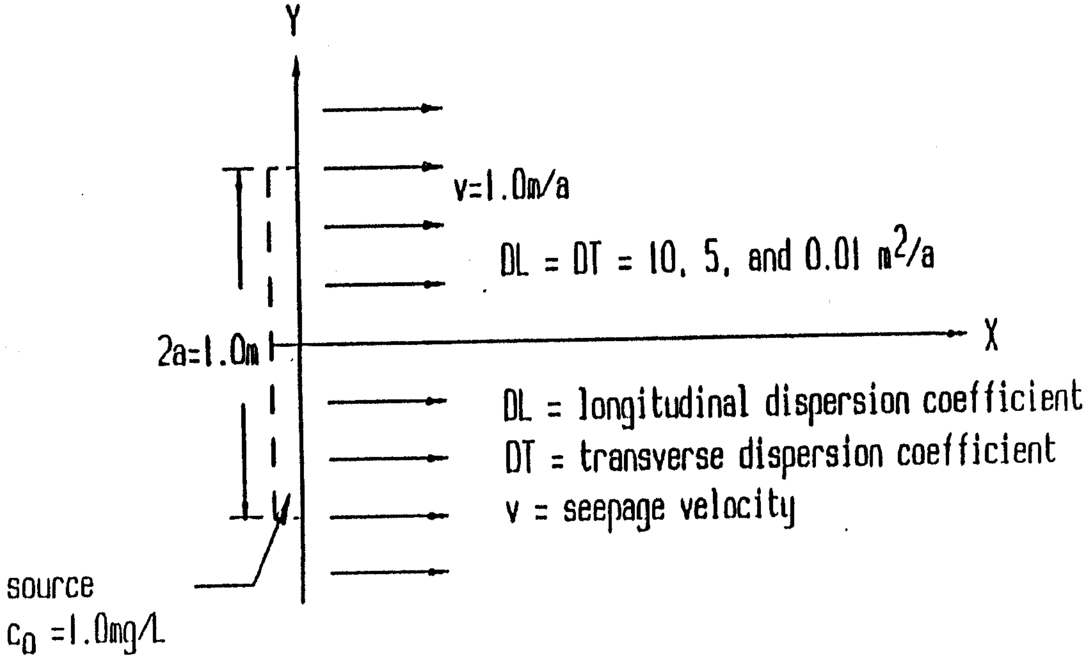


Figure 3. Schematic of model analyzed by TDAST

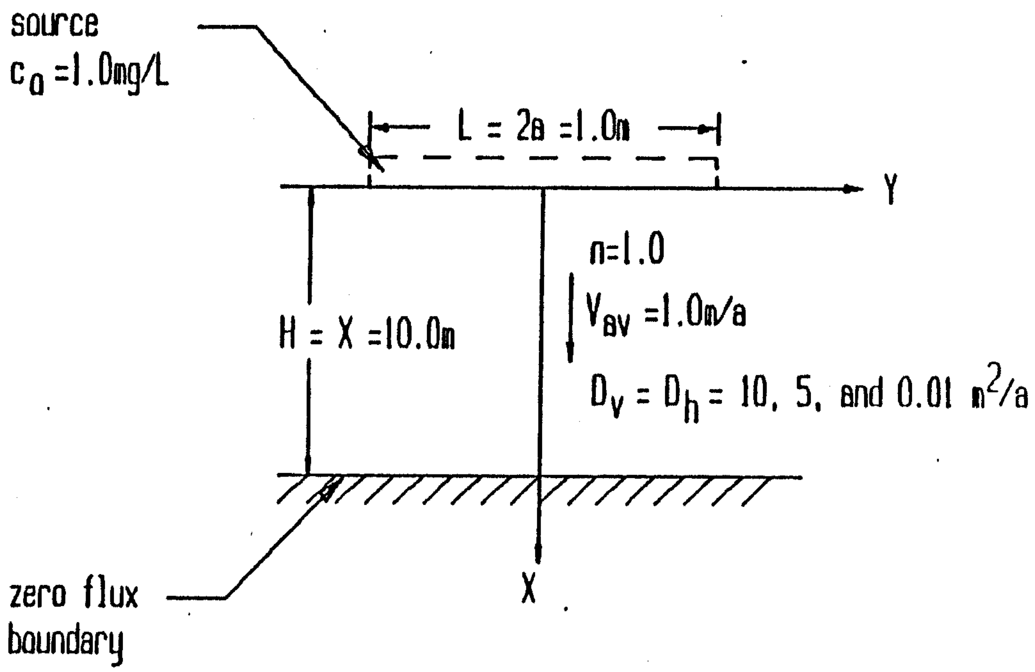
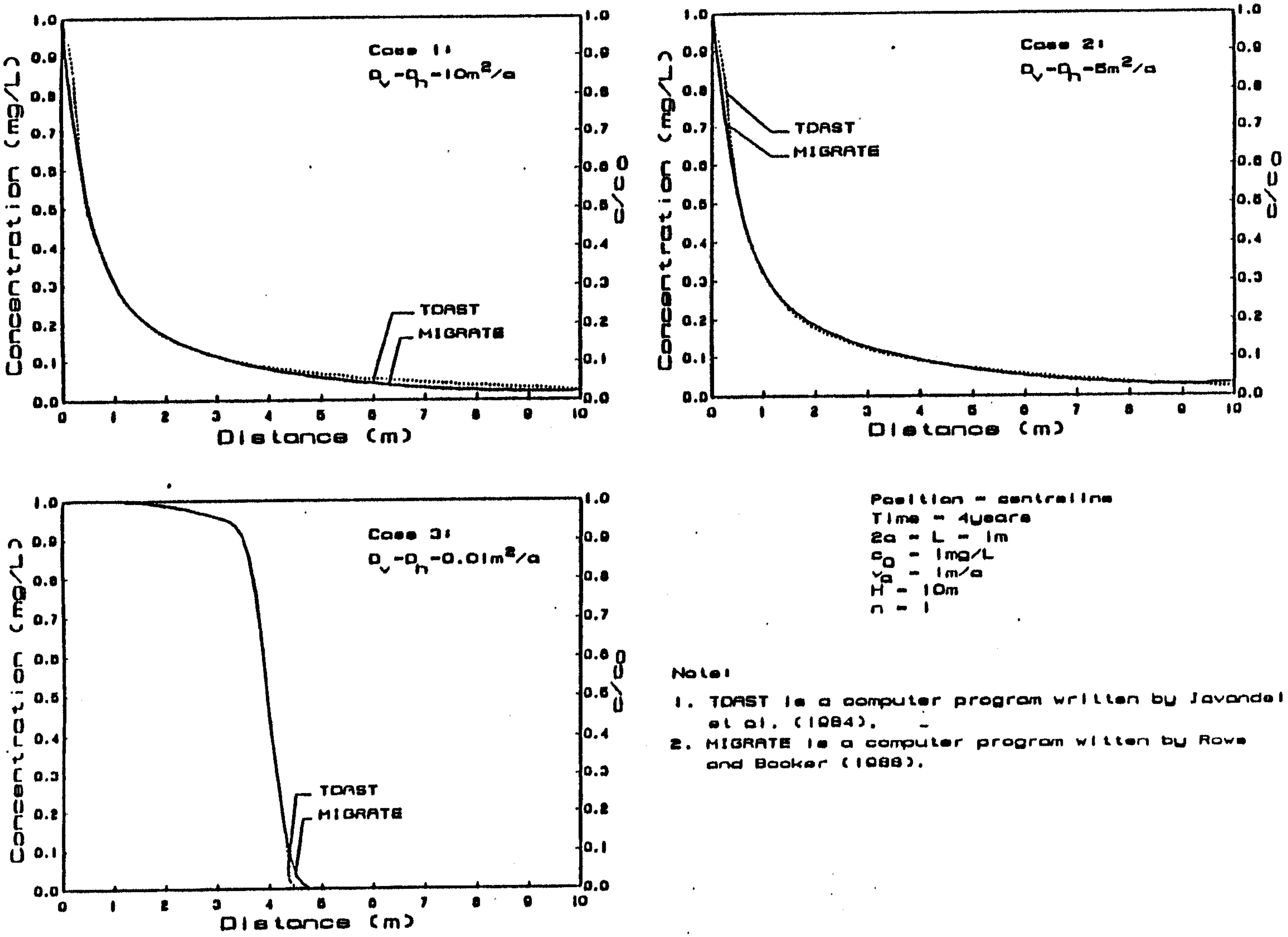


Figure 4. **Schematic of model analyzed by MIGRATE**



Position = centreline
Time = 4years
$2a = L = 1m$
$c_0 = 1mg/L$
$v_a = 1m/a$
$H = 10m$
$n = 1$

Note:

1. TDAST is a computer program written by Javandel et al. (1984).
2. MIGRATE is a computer program witten by Rowe and Booker (1988).

Figure 5 Comparison of solutions obtained by TDAST and MIGRATE

Table 1

Single crack solution using three techniques

Distance (m)	c/c_0		
	Rowe & Booker (1988)	Sudicky & Frind (1982)	Tang et al. (1981)
100	0.5947	0.5947	0.5930
200	0.2860	0.2860	0.2838
300	0.1085	0.1085	0.1069
400	0.0319	0.0319	0.0311