Preliminary comparison of a discrete fracture model with a continuum model for groundwater movement in fractured dolomite. [DNR-089] 1993

Bradbury, K. R.; Muldoon, Maureen A.
Madison, Wisconsin: Wisconsin Department of Natural Resources, 1993

Preliminary Comparison of a Discrete Fracture Model with a Continuum Model for Groundwater Movement in Fractured Dolomite

PRELIMINARY COMPARISON OF A DISCRETE FRACTURE MODEL WITH A CONTINUUM MODEL FOR GROUNDWATER MOVEMENT IN FRACTURED DOLOMITE

Final Administrative Report to the
Wisconsin Department of Natural Resources,
in fulfillment of DNR Contract # NRB96011

Kenneth R. Bradbury, Maureen A. Muldoon
Wisconsin Geological and Natural History Survey

WGNHS Open-File Report 93-6

December, 1993

ABSTRACT

The use of porous-media methods for describing groundwater flow in fractured-rock environments has become commonplace because simulation of flow through discrete fracture networks is difficult and data-intensive. However, the possible errors introduced by the use of the porous-media approximation are rarely addressed or are glossed over in many groundwater studies, and guidelines for when a porous-media approximation is appropriate are almost completely lacking. In this report we present the results of experiments using a two-dimensional stochastic discrete fracture flow model (the SDF model) coupled with a particle-tracking code to explore the validity of the porous-media approximation for simulating groundwater movement in fractured-rock aquifers. The study successfully adapted the fracture-flow model to a microcomputer environment, added capabilities for simulating pumping and injection wells, and developed an advective particle tracking module.

Using statistical descriptions of natural fracture patterns and other hydrogeologic data collected from field sites in Door County, Wisconsin, the SDF model was used to simulate the effects of model domain size, anisotropy, and fracture density on the shape of capture zones for pumping wells. Comparison of the SDF model with a porous-media (MODFLOW) model of the same area shows that even in densely fractured aquifers, the zone of contribution determined by the fracture-flow model is significantly larger than the capture zone determined by porous-media-based models. However, the reliability of the porous-media approximation increases and the effects of fracture anisotropy become less significant as the overall size of the problem domain increases.

This project provides guidelines for groundwater studies in fractured-rock environments similar to Door County. The types of investigations that could benefit from this project include wellhead protection studies, remedial investigations, the design of groundwater monitoring systems, and water supply studies.

INTRODUCTION

Objectives

The objective of this project is to begin to determine guidelines for the appropriate use of the porous-media approximation in simulating groundwater flow in fractured-rock environments. Most current groundwater investigations, including monitoring projects, remediation projects, water supply investigations, and wellhead protection studies in fractured rock, assume that the fractured rock can be treated as a porous medium for purposes of analysis, yet little work has been done to determine when and where this approximation is valid. This project tests the validity of the porous-media approximation for groundwater flow in fractured dolomite in Door County, Wisconsin by application of both a porous-media model and a fractured-media model to the same set of field data.

Background

Fractured-rock aquifers underlie nearly one-half the surface area of Wisconsin. Major fractured-rock aquifers in the state include the Silurian dolomite of eastern Wisconsin, which extends from the Illinois border to the tip of the Door Peninsula; the Sinnipee and Prairie du Chien groups (dolomite and limestone) which occur in east-central, southern, and western Wisconsin; and the Precambrian crystalline rock aquifers covering most of northern Wisconsin. Thousands of private and public water supply wells in the state derive water from these fractured aquifers. Nationally, fractured aquifers cover vast areas of the United States (Fig 1).

Numerous water-quality and water-quantity problems have occurred in fractured rocks in Wisconsin. Contaminants detected in fractured aquifers in the state include pesticides (atrazine, alachlor), nitrates, volatile organic compounds (VOC's), hydrocarbons, sulfates, bacteria, and radioactivity. Water-quantity problems have also occurred in fractured-rock aquifers in various parts of the state (Hennings and others, 1991).

Hydrogeologic investigations in fractured-rock terranes usually fall somewhere between the "discrete" approach and the "continuum" approach. The discrete approach considers each fracture individually and requires measurement of fracture length, orientation, aperture, wall roughness, and overall connectivity between fractures. The continuum approach assumes that the fractured medium approximates a porous medium at some working scale and that the properties of individual fractures are not as important as the properties of large regions or volumes of fractured material.

Long and others (1982) provided theoretical criteria for determining when fractured systems behave as porous media. They suggested that "fracture systems behave more like porous media when (1) fracture density is increased, (2) apertures are constant rather than distributed, (3) orientations are distributed rather than constant, and (4) larger sample sizes are tested" (Long and others, 1982). Bradbury and others (1991) suggest that investigators could use a combination of subjective criteria to determine whether a fractured-rock aquifer can be

treated as a porous medium at the scale of the wellhead protection area. These criteria include the ratio of fracture scale to problem scale, log-normal distribution of hydraulic conductivity measurements, limited variations in water chemistry, smooth configuration of the water-table surface, and pumping test responses such as circular or elliptical drawdown cones, smooth time-drawdown curves, and linear increases in drawdown with increasing discharge rate. Rigorous testing of these criteria for field situations is difficult and expensive and none of the criteria can be used as an unequivocal test of the validity of the porous-media approximation. Critical errors can result if the porous media approximation is applied in situations where it does not hold.

Practically all previous investigations and monitoring studies of fractured-rock aquifers in Wisconsin have relied on porous-media approximations. Over the past few years the Wisconsin Geological and Natural History Survey (WGNHS) has conducted two projects dealing exclusively with groundwater movement in fractured rocks. In one of these projects (Bradbury and others, 1991) we developed a Technical Guidance Document for the U.S. EPA for the delineation of wellhead protection areas in fractured rock settings. This project included field studies at fractured-rock sites in Door County and Portage County. The second WGNHS project involved long-term monitoring of groundwater movement and groundwater quality in a small area of Door County, where fractured dolomite occurs at or near the land surface (Bradbury and Muldoon, 1992; Bradbury and Muldoon, 1990; Muldoon and Bradbury, 1990; Bradbury and others, 1988; Blanchard, 1988). The U.S. EPA project included the construction and calibration of a numerical flow model that treated the fractured rocks as an equivalent porous medium. A key problem identified during that study was the lack of clear criteria for justifying the use of such porous-media models in fractured-rock settings.

Acknowledgements

This project was funded by the Wisconsin Department of Natural Resources through the State of Wisconsin joint solicitation of proposals to conduct research and monitoring on groundwater. Many people assisted with various aspects of this project. Angshuman Guha and Todd Rayne adapted the SDF model for use in a microcomputer environment, altered the code so that field-mapped fracture traces could be entered into the model, and added the capability to simulate pumping or injection wells. Kathy Shrawder carried out numerous model runs and assisted with portions of this report.

Disclaimer

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the Wisconsin Geological and Natural History Survey or by the State of Wisconsin.

METHODOLOGY

This project was carried out in several distinct steps. The first step was the acquisition and modification of Rouleau's (1988) stochastic discrete fracture (SDF) computer code for simulating groundwater flow in fractured rocks. This code is described in detail below. The second step was assembly of fracture pattern data for the Door County test area. We did this using areal photographs of the test area for various years and growing seasons and also using scanline fracture surveys in an area of exposed bedrock. The third step was selection of the specific model area and construction of the models themselves. The modeled area was a subarea of the larger, existing Door County model, and was chosen for hydrogeologic simplicity and known boundary conditions. A potentiometric surface map, based on field-measured hydraulic heads (Bradbury and others, 1991) had been constructed for the model area. Field-measured hydraulic conductivity values, as well as other information were also available. For this area, two models were constructed, one using the well-known USGS Modular Code, commonly called MODFLOW (McDonald and Harbaugh, 1988), and PATH3D particle-tracking code (Zheng and others, 1990), the second using a modified version of the SDF discrete fracture code (Rouleau, 1988). Both two-dimensional models were calibrated to the steady-state hydraulic head distribution measured in the field. For the USGS Modular model the main calibration parameter was hydraulic conductivity. For the SDF model the main calibration parameter was fracture aperture.

Following calibration, a series of numerical experiments was conducted to determine how the choice of a model affected simulated groundwater flow paths, flow rates, and travel times for particles started at various points within the model domain. Special emphasis was given to the delineation of capture zones around pumping wells because of the current interest in Wisconsin and nationally on developing methods for delineation of wellhead protection areas in fractured rocks.

In this report we use the statistics of field-measured fracture sets as a starting point to explore the effects of scale, anisotropy, and fracture density on groundwater movement using the SDF model coupled with a particle-tracking code. First, we examine the effects of fracture density and orientation on the shape of the zone of contribution of a pumping well. We then explore the effects of problem scale on directional hydraulic conductivity values. Finally, we compare the results of a the MODFLOW model with results of the SDF model. The modeling experiments were conducted with the assumptions of fully penetrating vertical fractures and two-dimensional, steady-state groundwater flow.

The Stochastic Discrete Fracture Model

The Stochastic Discrete Fracture (SDF) model (Rouleau, 1988) is a computer model composed of four modules: NETWRK, NETFLO, NETRANS, and APEGEN. The modular approach was developed so that programs could be modified as needed by the user and results from each module could be analyzed separately. The model simulates fractures as openings

between smooth parallel plates. Major assumptions incorporated into the model include (1) steady state, laminar flow, (2) two-dimensional flow of an incompressible viscous fluid, and (3) an impermeable rock matrix (no matrix storage). In this study, only the first two SDF modules were used. In addition to these two modules, a modified version of NETFLO (WELFLO) and three accessory programs PARTRACK, NODES, and FRACS, were used. The accessory programs were developed at the Wisconsin Geological and Natural History Survey by Angshuman Guha and Todd Rayne. The program NETWRK generates two-dimensional fracture networks. The program NETFLO simulates fluid flow in the generated networks. WELFLO is a version of NETFLO modified to include the addition of pumping or recharge wells. PARTRACK is a program that tracks advective particle movement in the generated network through space and time. NODES and FRACS are post-processors used to reformat output data from NETWRK and NETFLO. The following sections contain overviews of each of these programs.

NETWRK

The program NETWRK uses a Monte Carlo approach to generate two-dimensional discrete fracture networks based on statistical descriptions of fracture parameters. Fracture parameters used by the model include fracture orientation, length, aperture, and density. Fracture orientation [deg] refers to the angle of the fracture trace with respect to a reference direction. Fracture length [L] is the total distance of a fracture trace measured along its orientation direction. Fracture aperture [L] is the fracture width, or distance between the two sides of the fracture. Fracture density [L/L^2] is defined as the sum of fracture lengths per unit surface area. A fracture network is composed of one or more fracture sets. Fracture sets are fractures grouped together on the basis of having similar mean orientations, lengths, and apertures.

The SDF model uses a monte carlo technique to produce samples, or realizations, of fracture networks with specified statistical distributions for the fracture parameters. Different fracture networks with the same overall fracture statistics can thus be produced by changing a random number seed. For each fracture set, one realization consists of a pattern of lines with a specified fracture density as well as specified distributions (uniform or lognormal) and values for the mean and standard deviation of fracture lengths, apertures and orientations. The sets are created one fracture at a time and represent fracture traces in a rock mass one unit in thickness.

Model boundaries may be either circular or rectangular, and delineate two model areas, one contained within the other (see appendix B). Because generated fractures tend to be less dense near the area boundaries, NETWRK generates the line patterns over the entire region of the outer area and then uses the inner area to trim all sides of the network. The inner area corresponds to the study domain and is the only area considered in subsequent programs.

Upon completion of the line generation, subroutines within NETWRK locate all fracture intersections that are part of a continuous flow path within the network ("effective" intersections). Finally, NETWRK defines all "elements", or line segments that lie between two

consecutive effective fracture intersections and records the node numbers corresponding to the ends of these "elements" for future identification.

Output from the program NETWRK includes summary information on the line patterns generated, on fracture apertures, lengths, and orientations, and on the total and effective porosity of the network. Thus, when used alone, NETWRK provides information on the physical, internal characteristics of the created fracture system, i.e., degree of fracture interconnection, effective porosity, and total porosity. NETWRK produces input files for other programs, such as NETFLO (or WELFLO) which simulate fluid flow conditions through the network.

NETFLO

The program NETFLO simulates fluid flow in discrete fracture networks with specified boundary conditions and hydraulic heads using a theory of two-dimensional flow through a fractured rock system with an impermeable rock matrix. The boundary conditions can be one of the three following types (1) constant head, (2) linear or log decreasing head, or (3) no-flow. The flow theory used is based on the Navier-Stokes equation for steady state flow of an incompressible, viscous fluid between two smooth parallel plates. The equation defines the flow rate per unit width as

$$q = -\frac{W^3 \gamma \Delta h}{12 \mu \Delta x} \qquad (1)$$

where
q= flow rate per unit width [L^2/T]
W= plate separation (fracture aperture)[L]
γ= fluid weight density [F/L^3]
μ= dynamic viscosity [FT/L^2]
h= hydraulic head [L]
x= distance along the plates [L].

If we introduce the parameter e,

$$e = -\frac{W^3 \gamma}{12 \mu} \qquad (2)$$

which is the conductivity of a fluid conduit, and then rewrite equation 1 by substituting e;

$$q = e\left(\frac{\Delta h}{\Delta x}\right) \qquad (3)$$

the equation 3 looks very similar to Darcy's law, except that e replaces the hydraulic conductivity term. Note that the "fracture conductivity" is a function of the cube of the fracture aperture. Fracture aperture is thus critical in controlling groundwater flow rates. We used fracture aperture as a calibration parameter in the SDF model.

In summary, NETFLO:

1. reads in the input boundary conditions, heads, and line network data created by NETWRK;
2. identifies the boundary condition for every node that intersects a boundary;
3. renumbers nodes (to save computer memory);
4. solves a matrix of equations similar to equation 3 for unknown head values;
5. calculates flow rates in each segment, the total flow rate at each boundary, and cumulative flow parameters for every 10 degree range of direction.

Output files from NETFLO contain all of the information listed in (5) above.

WELFLO

The original version of NETFLO was modified to a program called WELFLO in order to incorporate the use of pumping/injection wells in the fracture flow simulations. In WELFLO, a well is simulated by specifying a head at a specific point within the boundary domain. By choosing a head at a point with a lower value than would exist at that point in the absence of a well, pumping is simulated. Conversely, specifying a point with a higher head than would exist in the absence of a well simulates the presence of an injection well. Multiple wells may be simulated in this fashion. The output from WELFLO is the same as NETFLO except the flow rate at the well (pumping/injection rate) is also included.

PARTRACK

An accessory program to be used with the SDF model, PARTRACK tracks advective particle movement through the fracture network and fracture flow system created by NETWRK and NETFLO (WELFLO) respectively. Particle movement is simulated based on the volumetric flow rates in each segment. Specifically, particles undergo complete mixing at fracture intersections. Then, the probability of a particle entering a specific fracture at each intersection is calculated based on the flow information contained in output files of NETFLO (WELFLO). The proportion of particles moving on to a specific fracture corresponds to the proportion of flow moving through that fracture. PARTRACK also computes particle travel times through the network based on distance travelled and particle velocity. Particle velocity is calculated by dividing the flow rate in the segment by the fracture aperture of that segment. PARTRACK is

capable of simulating both forward and reverse particle tracking through time. Output files from PARTRACK include information on particle coordinates and corresponding elapsed travel times throughout the whole travel period, total travel time to a boundary, and information on what caused the particle to stop moving (i.e., boundary reached or dead end fracture).

NODES and FRACS

Both NODES and FRACS are accessory post-processing programs that use output files from NETWRK and NETFLO to generate files compatible with the commercial contouring software package *SURFER* (Golden Software, 1990). NODES uses output from NETFLO to create files of node locations and heads. FRACS uses output from NETWRK to create files of fracture coordinates. NODES is useful in creating maps for which hydraulic head contours are needed. FRACS is useful in creating maps of the generated fracture patterns.

SDF Model Requirements

The SDF model was originally designed to be used with a mainframe computer system. For this project, the program was recompiled using the Lahey version 5.01 FORTRAN compiler with the Phar Lap DOS Extender for use on 386- and 486-class personal computers. A minimum of eight megabytes of RAM is required to run the SDF model for field scale problems. The time required to run the SDF model depends on the number of fracture sets, fracture density, problem scale, and computer speed. For this project, the computing time to produce one fracture network on a 33 mHz 80486 CPU computer ranged from approximately three minutes for a very small scale (5 m x 5 m), low density (0.1 m/m^2) problem to approximately three hours for a large scale (750 m x 750 m), low density (0.18 m/m^2) problem.

Code Documentation

Appendix A provides documentation of the SDF model and utility programs. Appendix B summarizes the data input required to run the models.

FIELD DATA ACQUISITION

This project utilized field data from hydrogeologic research sites in Door County, Wisconsin (figure 2). In Door County, dolomite of Silurian age is often either exposed at the land surface or covered by only very thin (less than 1 m) soils. Thus, fracture patterns are frequently expressed in the vegetation and in outcrop (figure 3). Available hydrogeologic data included field measurements of hydraulic conductivity and horizontal hydraulic gradients in the dolomite (Bradbury and others, 1991).

In this report, "discrete" data refers to measurements of the characteristics (length, orientation, density, etc) of individual fractures or fracture sets, while "global" data refers to measurements of areally-lumped hydrogeologic properties such as hydraulic conductivity or hydraulic gradient.

Discrete data

Two sources of field fracture data at two different scales were used in this study. The first was a compilation of fracture patterns observed on aerial photographs in a 5 square mile area in the Town of Sevastopol (T28N, R26E) (figure 3). Fractures were compiled from a variety of low-altitude aerial photographs available from the Wisconsin Department of Transportation and from the U.S. Soil Conservation Service as well as from oblique 35mm slides taken by the Wisconsin Geological and Natural History Survey and optically corrected to a vertical projection. These data were compiled on a base map and the two vertices of each fracture were then digitized for computer storage and plotting. Fracture orientations and lengths were computed using a computer spreadsheet. This methodology produced data on 714 fractures ranging in length from 2 m to 268 m.

The second source of fracture data consisted of a scanline survey (LaPointe and Hudson, 1985) of a small area of bare dolomite at a site where topsoil had been removed for landscaping material. This site was located near the Town of Peninsula Center, Sec 23, T 30N, R 27E. The survey was conducted in June, 1992 by the University of Wisconsin Hydrogeology Field Class. The survey teams laid out horizontal scanlines 50 meters long oriented either due north-south or due east-west and then measured the location, length and orientation of every fracture crossing the scanlines. This survey measured 92 fractures along three scanlines.

Based on histograms and rose diagrams of fracture orientations, the fractures in Door County fall into two primary sets. Table 1 summarizes the survey results. There was little difference in the statistical results of fracture orientations based on the two surveys described above. The scanline survey examined a smaller area in more detail and so was expected to give the best estimate of fracture density. The air photo data probably captured longer fractures and so was expected to give a less biased estimate of fracture lengths than the scanline survey in which the ends of many long fractures were covered where they extended past the borders of the site.

Neither survey provided a valid measure of fracture apertures. Although fracture apertures were measured during the scanline survey, the resulting measurements seemed unrealistically large, and were obviously biased by solutional widening of the fractures near the ground surface. Fracture aperture data were therefore obtained from Shapiro and Nicholas (1989), who used a tracer experiment to estimate fracture apertures of Silurian dolomite near Chicago, Ill.

Global data

"Global" data included field measurements of hydraulic conductivity and horizontal hydraulic gradients in the dolomite at the Door County site near Sevastopol. These measurements were made using a series of slug tests, pumping tests, and analysis of specific capacity data. Bradbury and Muldoon (1992) describe the field tests and data gathered. Although the global hydraulic properties of the aquifer vary in three dimensions, the limitations of the SDF model used in this study required simplification to a two-dimensional conceptual model. The global transmissivity used for the study site was 5.5 $x10^{-4}$ m^2/sec. The regional hydraulic gradient was about 0.004, with total hydraulic head decreasing from northeast to southwest.

SDF MODEL EXPERIMENTS

Effects of Fracture Density and Orientation on Groundwater Flow

Numerous analytical and numerical techniques have been used for delineation of capture zones in porous media, but few analogous techniques exist for fractured rocks. Figure 4 shows a continuously pumping well in a uniform flow field in a homogeneous and isotropic porous medium. Particle pathlines, tracked backwards from the well to the upgradient boundary, outline the zone of contribution. The problem domain is 75 m by 150 m, and the hydraulic head decreases from left to right. The drawdown around the well forms a stagnation point downgradient of the well, and this stagnation point represents the downgradient limit of the zone of contribution. Note that upgradient of the well (to the left of the 19 m contour line) the zone of contribution becomes constant in width. Although the diagram in figure 4 was generated numerically, it could also be generated analytically using superposition.

We have used the SDF model to study how variations in the density and orientation of fractures affect the size and shape of the zone of contribution of a pumping well. Figure 5 shows results of SDF model simulations for single realizations of three fractured-rock settings having the same boundary conditions as the porous-media example in figure 4. On the left of figure 5 we show single realizations of the fracture networks; on the right, particle paths to a well. The top diagram in figure 5 represents a relatively dense fracture network having two orthogonal fracture sets. The capture zone (outlined by the particle paths) produced by this arrangement of fractures is similar to the pattern in figure 4 but is considerably wider at the upgradient boundary. This apparent dispersion, characteristic of most fracture systems we have examined, results from the complex flow paths connecting the well to the upgradient boundary.

The middle diagram in figure 5 shows the effect of fracture anisotropy on the shape of the capture zone. The fracture domain contains two fracture sets, with the NE-SW set having greater density and greater mean fracture length than the NW-SE set (north is to the

top of the diagram). The resulting zone of contribution covers almost the entire width of the problem domain even though the hydraulic gradient is from left to right.

The bottom diagram in figure 5 shows the zone of contribution in a very sparse fracture network. In this network the zone of contribution is oddly shaped and would be difficult to predict. It is interesting to note that areas immediately upgradient of the well (for example, in the area around x=80 m, y=40 m) contribute no water to the well due to the absence of connected fractures there.

Directional hydraulic conductivity versus problem scale

Permeability (or hydraulic conductivity) of fractured media varies with direction. For example, Marcus and Evanson (1961), Marcus (1962), and Bear (1972) showed that for homogeneous, anisotropic porous media, directional permeability measurements can be plotted as ellipsoids in polar space. Long and others (1982) summarized these findings and showed that for a homogeneous, anisotropic porous media, a polar plot of $1/K^{0.5}$ versus α results in an ellipse, where K is the hydraulic conductivity (L/T) and α is the angle of the hydraulic gradient. Using a numerical model for simulating two-dimensional fracture flow, they also demonstrated that plotting $1/K^{0.5}$ versus α for 15 degree increments of α can be used with fracture flow simulations as a test of porous medium behavior.

Following this methodology, we created polar plots of $1/K^{0.5}$ for problem domains ranging from 10 m x 10 m to 500 m x 500 m using the SDF model. The modeled area contained two orthogonal fracture sets based on the field data summarized in Table 1. To generate each individual plot, the model was run 12 times; for each run, the orientation of the fracture sets was rotated through 15 degree increments. This approach is slightly different than that used by Long and others (1982); they rotated the hydraulic gradient through 15 degree increments. All inputs to the model were held constant for each separate plot, except for the size of the model boundary domain, which was varied from 10 m x 10 m to 500 m x 500 m. The upper and lower boundaries were specified as no-flow boundaries and the side boundaries were specified as constant head.

As the model domain increases in size, the polar plots of $1/K^{0.5}$ become more elliptical. Figure 6 illustrates the results of the polar plots for several of the model areas tested. For small areas (10x10 m, 25x25 m, and 50x50m) the permeability plots are irregular, and single fracture, or groups of fractures, control groundwater flow. Clearly, at these small scales, the fracture system does not approximate a porous medium. For the mid-range areas (75x75 m and 100x100 m), the data are relatively elliptical, suggesting that the simulated fracture system approximates an anisotropic porous medium at these scales. For the larger areas (350 x 350 m and 500 x 500 m), the plots are nearly circular, suggesting that at this scale, for the fracture density simulated, the fracture system approximated an isotropic porous medium. For cases where the polar plot approximates an ellipse, the ratio of K_{max}:K_{min} can be used as a measure of the degree of anisotropy of the medium (Khaleel, 1989). Figure 7 illustrates these observations graphically by plotting K_{min}, K_{max}, and the

K_{min}:K_{max} ratio versus the problem dimension. Above a problem size of 75 m x 75 m K_{min} and K_{max} begin to converge and the K_{min}:K_{max} ratio begins to approach 1. At the scale of 500 m x 500 m, the K_{min}:K_{max} ratio is approximately 1.2. On the basis of these results, we chose an area of 500 m x 500 m was chosen as the "porous-medium equivalent" scale for the Door County data for the purpose of subsequent capture-zone simulations.

One interesting observation from these experiments is that the anisotropy ratio at a length scale of 100 meters is about 4.0:1. This ratio compares favorable with and anisotropy ratio of 4.1:1 measured at the Sevastopol site using a pumping test (Bradbury and others, 1991). However, based on the model results, the anisotropy ratio could approach 1:1 at larger test scales which are not stressed with a traditional pumping test. The anisotropy ratio may be a scale-dependant parameter, and anisotropy ratios measured in small-scale tests in fractured rock may not apply at larger scales. This finding could have important implications for groundwater modeling and wellhead protection studies in fractured-rock environments.

Application of the SDF model to a field site

Final fracture parameters used in the SDF simulations of the Door County site were taken from measurements made on air photos and from a scanline survey, however these data had some limitations. The scale of the air photos was not suitable for precise measurement of individual fracture azimuths, and the scanline survey provided unrealistic measures of fracture aperture. For the previous experiment, the distribution of fracture apertures was estimated from published data. In the following experiments, however, results of the SDF model were to be compared to results of a porous-medium flow model for the same area. Thus, it was necessary to determine a more accurate mean value for the fracture apertures at the Door County site to be used in the SDF model simulations. We maintained a similar distribution (standard deviation) of fracture apertures and calibrated the SDF model using the known value of hydraulic conductivity at the site in order to determine the best estimate of mean fracture aperture. Using a trial-and-error approach, the SDF model was run for a 500 m x 500 m domain keeping the known values of fracture lengths, orientations, and density constant while varying the mean fracture aperture until the resulting network had the desired global, or model-wide, hydraulic conductivity.

Aperture versus hydraulic conductivity was plotted after each calibration run of the SDF model (figure 8). Note that hydraulic conductivity increases as mean aperture increases. The value of hydraulic conductivity at the site was known to be 5.5×10^{-4} m/s. This value of hydraulic conductivity was reached using the SDF model with an input value for mean fracture aperture of 1.493 mm. Based on this mean aperture size the effective porosity of the fracture network, calculated as the volume of interconnected voids divided by the volume of the model domain, was 0.05% and the total porosity was 0.06%. These porosity values are smaller than the commonly-used "ballpark" porosities of about 1% for

fractured rocks, but are believed to be representative of the fracture system simulated in this study.

Model Comparison

Capture-zone delineation

We delineated capture zones for a pumping well developed in the dolomite aquifer using both a porous media approach and the SDF model. Identical problem domain, boundary conditions, and global hydraulic conductivity values were used for both models. The problem domain was 400 m x 600 m (in the x and y directions, respectively) and the boundary conditions were specified to be consistent with field-measured hydraulic heads. For the MODFLOW experiment, a pumping rate of 0.25 x 10^{-3} m^3/sec was specified, resulting in a drawdown of 0.238 m at the well. Ten particles were then tracked through this area using the particle tracking code PATH3D (Zheng, 1991) to define the capture zone of the well. The SDF experiment was then performed, with the same specified pumping rate that was used in the MODFLOW experiment. For both experiments, particles were tracked backwards with respect to time from a well located at coordinates (x = 130, y = 70). Figure 9 illustrates the resulting particle paths. As expected, the particle paths for the porous medium simulation resulted in a smooth, uniform capture zone of the well, with no dispersion.

The SDF experiment used 20 realizations of the fracture system at the Door County site. A typical realization of the fracture network contained about 2,900 fractures and 8,900 fracture intersections. For each realization, ten particles were tracked backwards from the well to the upgradient boundary (200 paths in all). Figure 10 shows the particle paths resulting from these 20 realizations. Note the dispersion of the particles and the width of the resulting capture zone in comparison to figure 9. The SDF model produces particle paths outlining a zone of contribution significantly wider than the porous-media simulation.

Although plots such as figure 10 show potential stochastic particle paths, they do not clearly indicate a zone of contribution because the boundaries of the stochastic zone of contribution are probabilistic. One way to quantify the results of multiple realizations of such models is to calculate and plot the probabilities of particles moving through all parts of the model domain. Figure 11 is a contour plot of the probabilities of any given particle being within individual cells of a regular grid superimposed over the SDF model domain for figure 10. The contours represent the probability that a particle will travel through that portion of the model domain bounded by the contour. For example, the 99-percent contour bounds an area containing 99 percent of the particles from the ten realizations. We can then define the capture zone of the well in the fracture system on the basis of a known probability. Higher probability capture zones encompass larger areas than lower-probability capture zones.

Groundwater velocities computed by the two models are quite high and are in general agreement with field data. The mean travel times from the boundary to the wells were similar for both models, 1.56 days for the porous medium simulation and 1.24 days for the SDF simulation. In both models, the average linear groundwater velocity was about 35 m/day. This velocity compares favorably with field-measured velocities ranging from 16 m/day (small-scale tracer test) to 115 m/day (large-scale contamination event) in central Door County reported by Bradbury and Muldoon (1992). This agreement implies that the very low effective porosities used in the models (0.05%) are realistic for fractured dolomite in Door County.

SUMMARY AND CONCLUSIONS

This project was a preliminary study to determine the feasibility of applying a stochastic fracture-flow model to simulate groundwater movement in fractured dolomite, and to compare the results of such a model with results of a model using porous-media assumptions. Although simple boundary conditions and parallel-plate assumptions limit the practical applications of discrete models such as the SDF model, the models do provide insights to the use of porous media equivalent approximations for wellhead protection in fractured-rock settings. The most significant study accomplishments and findings are as follows:

1. A groundwater flow model based on stochastic simulation of discrete fractures (the SDF model of Rouleau, 1988) will run efficiently on 386 and 486 class microcomputers and can be a useful tool in simulating and understanding groundwater movement in simple fractured-rock systems.

2. Additions of the ability to simulate pumping and withdrawal wells and particle-tracking capabilities, along with post-processing routines, have significantly enhanced the usefulness of the SDF code.

3. Based on examination of fracture patterns visible on aerial photos and on scanline mapping of outcrops, dolomite of Silurian age in Door County, Wisconsin contains two statistically significant fracture sets. Significantly, the scale and method of fracture measurement have little or no effect on the statistical results.

4. A simulated fractured aquifer based on field observations of vertical fractured present in dolomite in Door County, Wisconsin begins to respond as a porous medium for simulation areas greater than about 500 m on a side.

5. As the model domain increases in size, the simulated aquifer becomes more isotropic, approaching an anisotropy ratio of 1:1 at domain sizes above 750 m on a side.

6. Global hydraulic conductivity of the fractured aquifer increases as mean fracture aperture increases. The calibrated mean fracture aperture for fractured dolomite of the type found in Door County is 1.5 mm.

7. Effective porosity of the dolomite as simulated by the SDF model is about 0.05%. Although porosities in this range are lower than generally assumed for fractured rock, they yield realistic flow velocities.

8. Even in densely fractured aquifers, and with relatively simple boundary conditions, the zone of contribution determined by a fracture-flow model is significantly larger than the capture zone determined by porous-media-based models. Therefore, a circular or smoothly elliptical permeability plot alone is not sufficient to justify the use of a porous medium model for capture-zone analysis in fractured systems. In general, most porous media models will probably underestimate the size of the capture zone for wells developed in fractured aquifers because of significant spreading of the capture zone in the direction of predominant fracture sets. This problem is particularly acute in anisotropic situations. Although discrete flow models may have limited practical use in wellhead protection, our results suggest that a large safety factor is necessary when delineating wellhead protection areas in fractured rocks using other approaches.

9. Although the model simulations reported here are based on field data collected in Door County, Wisconsin, the models represent vast simplifications of the hydrogeologic system in Door County, and should not be used to draw specific conclusions about groundwater flow there.

REFERENCES

Bear, J., 1972. *Dynamics of Fluids in Porous Media*: Elsevier, New York.

Blanchard, M.C. 1988. Investigation of the shallow fractured dolomite aquifer in Door County, Wisconsin. Unpublished M.S. Thesis, University of Wisconsin-Madison.

Bradbury, K.R., and Muldoon, M.A. 1990. Long-term monitoring of groundwater quality in an area of fractured dolomite, minor karst, and thin soils. Geological Society of America, Abstracts with Programs, v. 22, no. 7, p A371.

Bradbury, K.R., M.A. Muldoon, A. Zaporozec, and J. Levy. 1991. Delineation of wellhead protection areas in fractured rocks. USEPA Technical Guidance Document, 144 p.

Bradbury, K. R., M.C. Blanchard, and M.A. Muldoon. 1988. Hydrogeology and groundwater geochemistry in fractured dolomite, northeastern Wisconsin. In Proceedings, International Association of Hydrogeologists, Hydrogeology of Fractured Rocks, Atlanta, Ga. 1988.

Golden Software, 1990. SURFER, version 4. Golden Software, Golden, Colorado.

Hennings, R., D.E. Lindorff and M.D. Lemcke. 1991. The condition of our groundwater resource. In: Working together to manage Wisconsin's groundwater-next steps? Wisconsin Groundwater Coordinating Council, Report to the Legislature, August, 1991, Appendix I., p 13-32.

Khaleel, R. 1989. Scale dependence of continuum models for fractured basalts. Water Resources Research. vol. 25, no. 8, p. 1847-1855.

Long, J.C.S., Remer, J.S., Wilson, C.R., and Witherspoon, P.A. 1982. Porous media equivalents for networks of discontinuous fractures: Water Resources Research 18/3, p. 645-658.

Marcus, H., 1962. The Permeability of a Sample of an Anisotropic Porous Medium: Journal of Geophysical Research, 67, p. 5215-5225.

Marcus H., and D.E. Evanson, 1961. *Directional permeability in anisotropic porous media*: Contrib. 31, Water Resources Center, University of California, Berkeley, 105 p.

McDonald, M.G., and Harbaugh, A.W. 1988. A modular three-dimensional finite-difference groundwater flow model. Chapter A1, Book 6. Modeling Techniques, Techniques of Water-Resources Investigations of the United States Geological Survey, chapters paginated separately.

Muldoon, M.A., and Bradbury, K.R. 1990. Monitoring spatial and temporal variations of hydraulic head in a fractured dolomite aquifer. Geological Society of America, Abstracts with Programs, v22, No 7, P A370.

Rouleau, A. 1988. *A numerical simulator for flow and transport in stochastic discrete fracture networks*. NHRI Paper 39, National Hydrology Research Institute, Saskatoon, Saskatchewan. 204 p.

Shapiro, A.M., and J.R. Nicholas, 1989. Assessing the validity of the channel model of fracture aperture under field conditions: Water Resources Research, 25/5, p. 817-828.

U.S. Environmental Protection Agency. 1987. *Guidelines for delineation of wellhead protection areas:* U.S. Environmental Protection Agency, Office of Ground-Water Protection, Washington, DC, chapters paginated separately.

Zheng, C., K.R. Bradbury, and M.P. Anderson. 1992. A computer model for calculation of groundwater paths and travel times in transient three-dimensional flows. Information Circular 70. Wisconsin Geological and Natural History Survey, Madison, Wisconsin, 21 p.

Tables

Table 1. Summary of fracture statistics from surveys in Door County, Wisconsin (μ = mean, σ = standard deviation).

Set	Density (m/m^2)	Orientation (deg)		Length (m)		Aperture (mm)	
		μ	σ	μ	σ	μ	σ
1	0.18	36.8	8.5	22.9	0.98	0.105	.65
2	0.18	131.7	13.6	20.9	0.93	0.105	.65

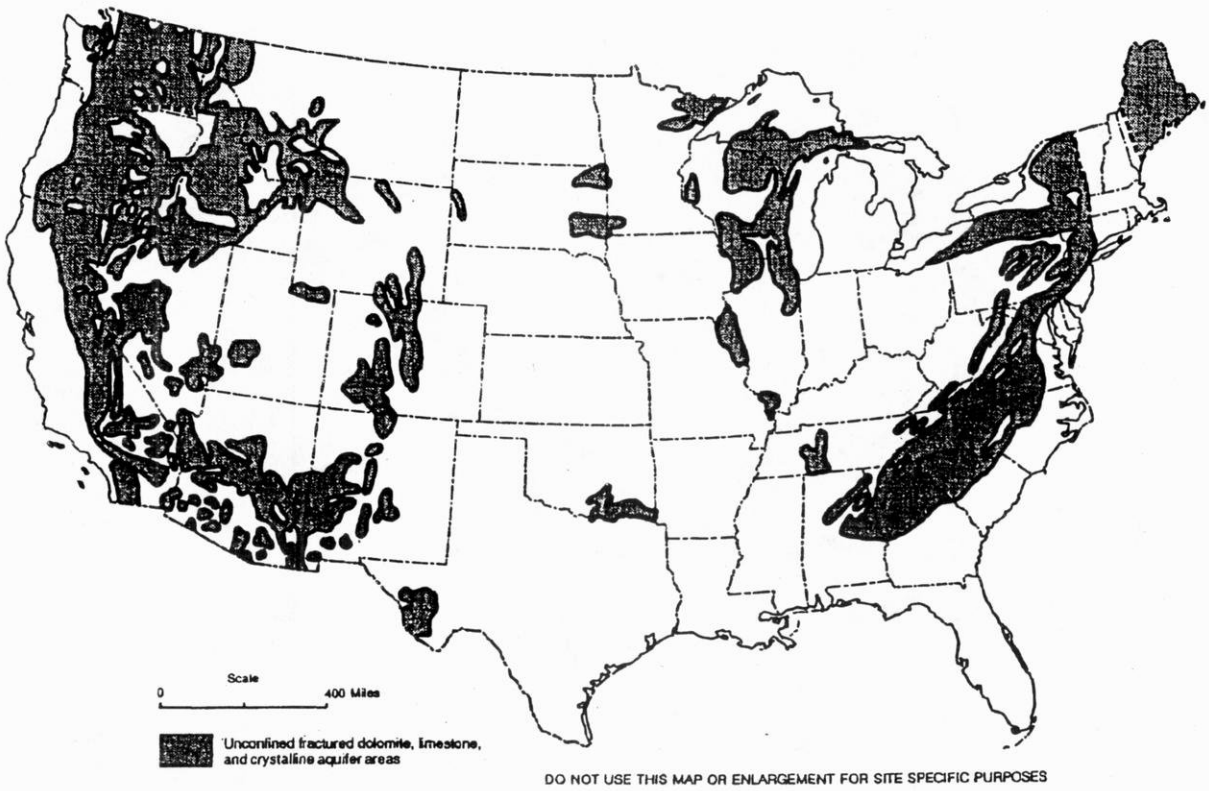


Figure 1. Location of fractured rocks in the United States.

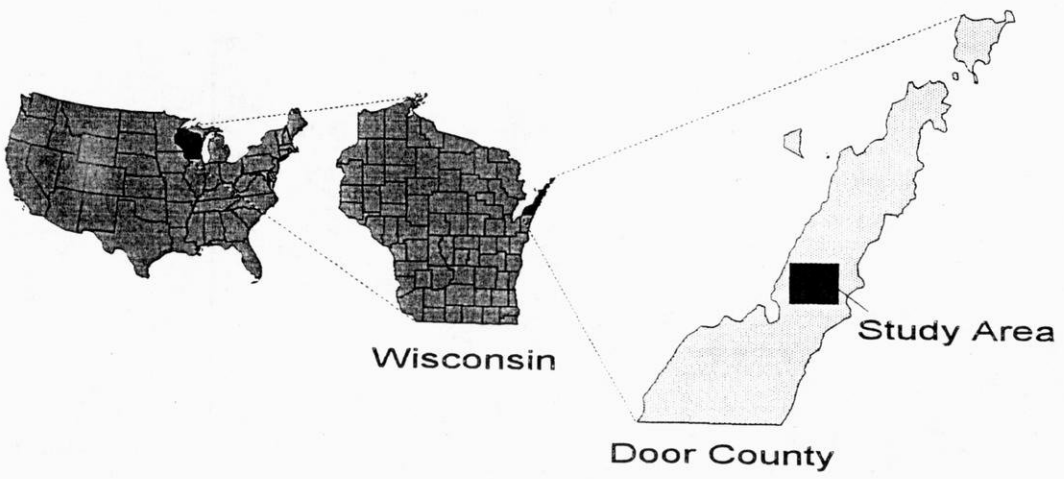


Figure 2. Location map showing Door County, Wisconsin.

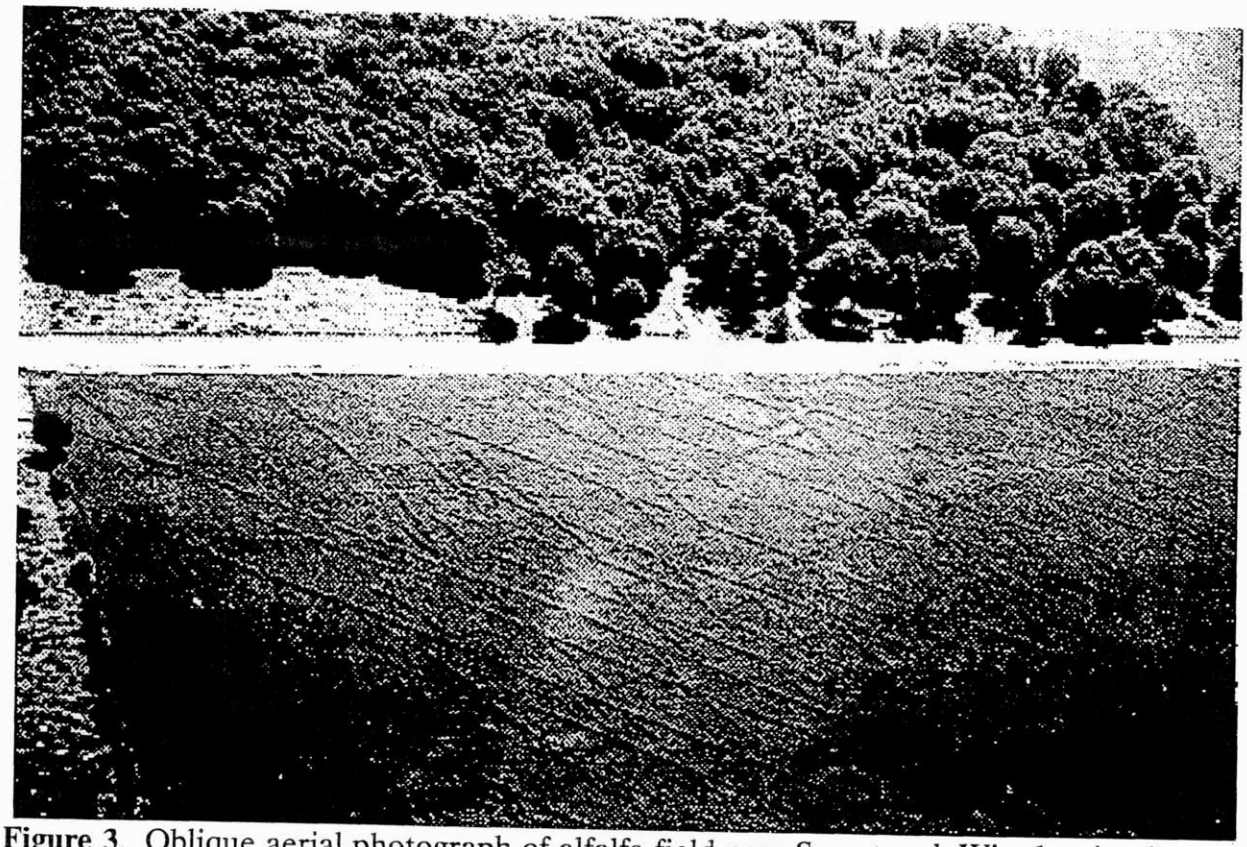


Figure 3. Oblique aerial photograph of alfalfa field near Sevastopol, Wi., showing fracture patterns.

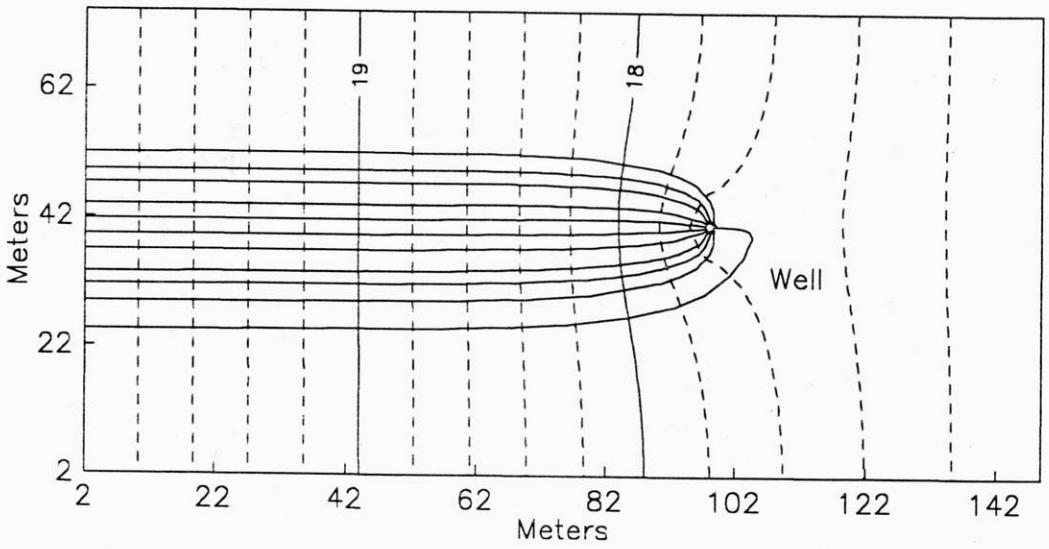


Figure 4. Particle paths from an upgradient boundary (left side) to a steadily pumping well in a uniform porous medium.

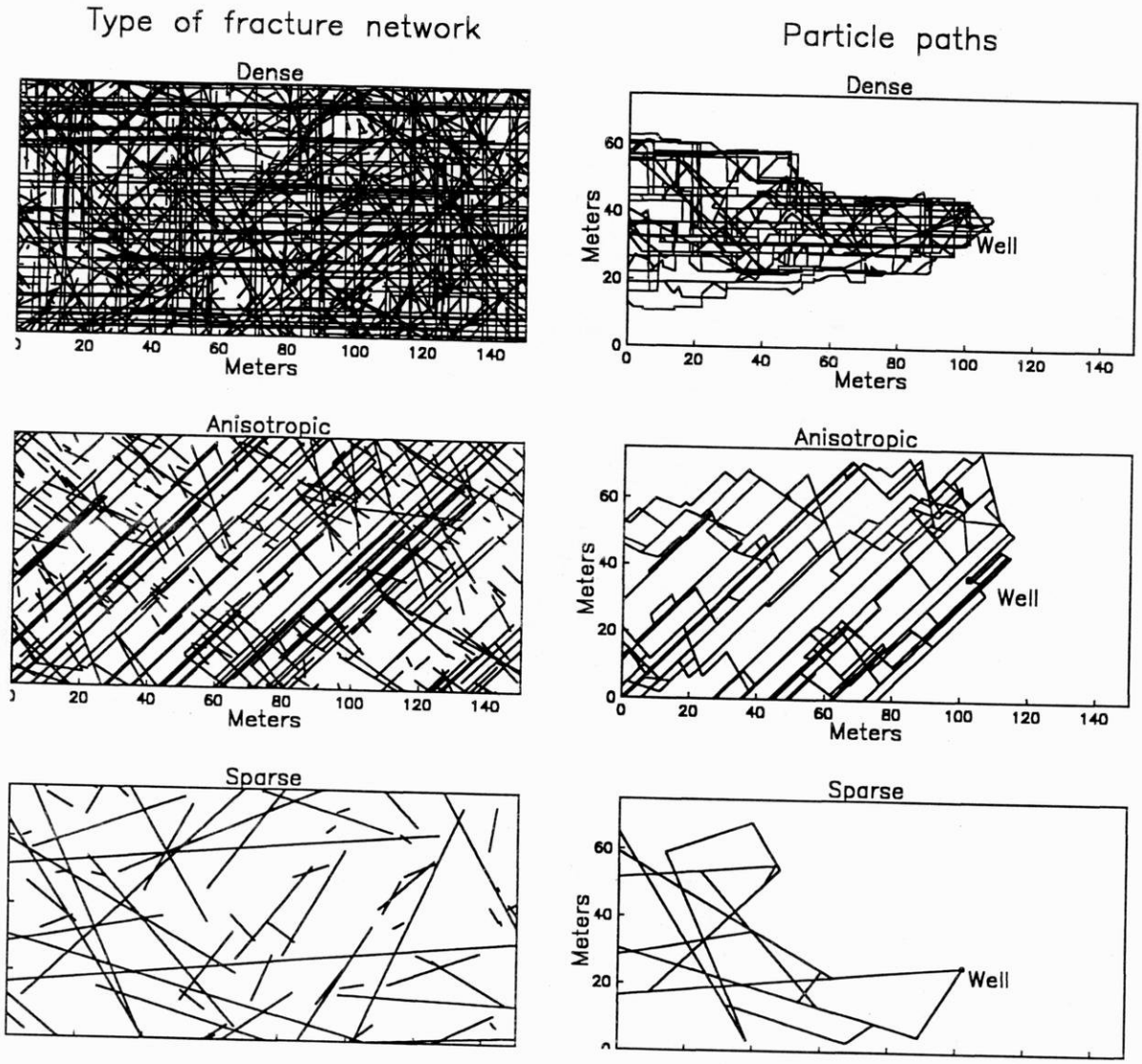


Figure 5. SDF-generated fracture patterns (left diagrams) and particle paths (right diagrams) for single realizations of three different fracture networks.

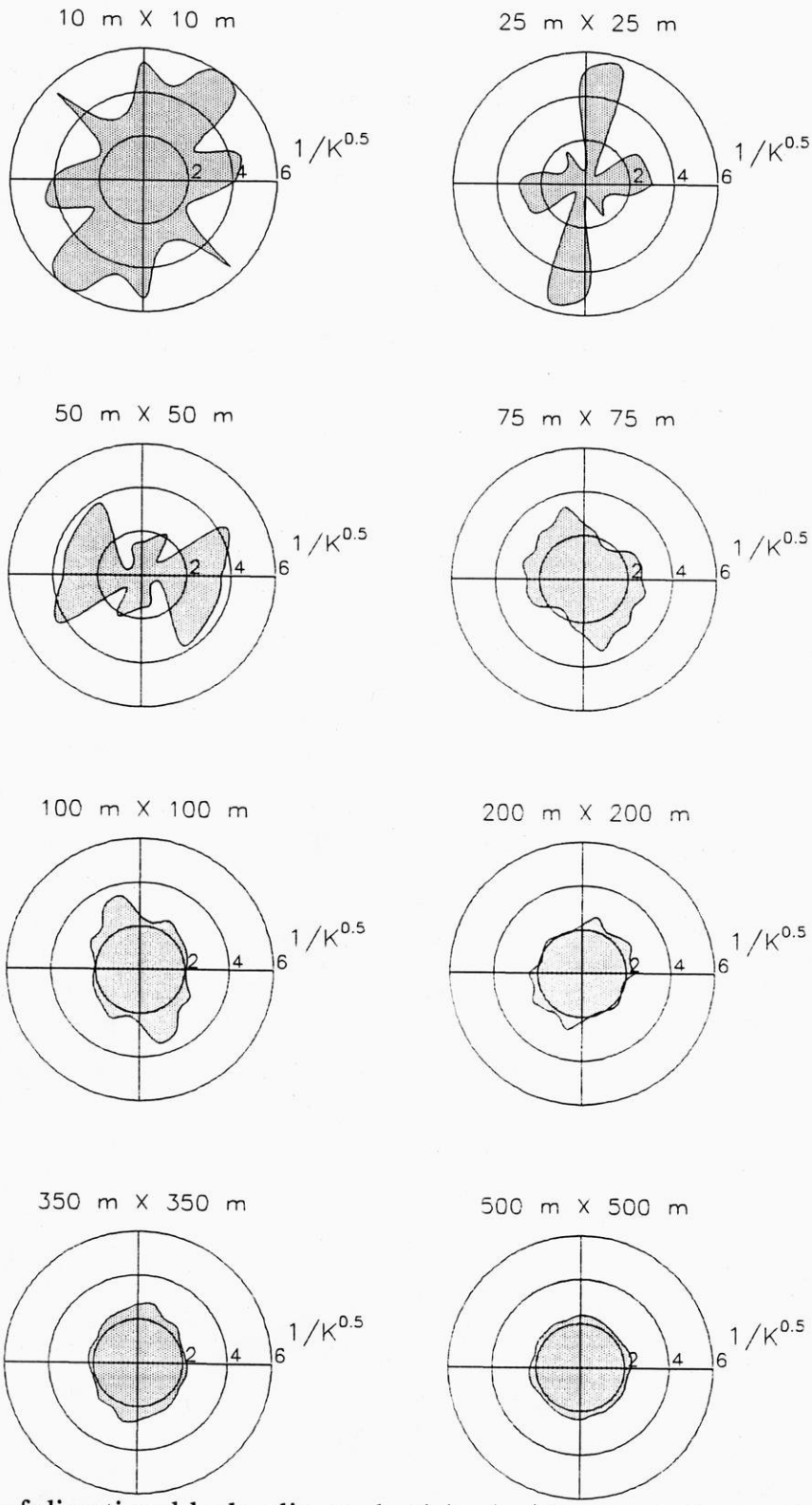


Figure 6. Plots of directional hydraulic conductivity (m/s) computed using the SDF model at various problem scales.

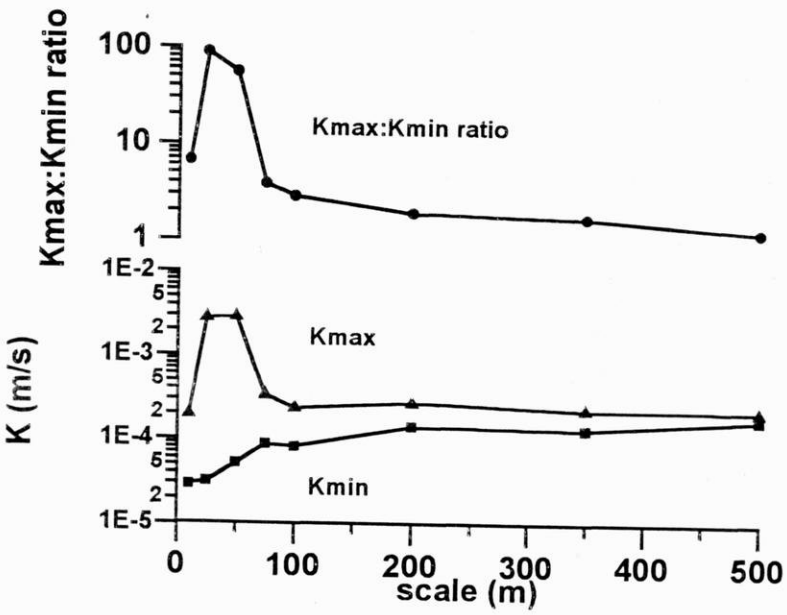


Figure 7. Minimum and maximum directional hydraulic conductivity and the K_{min}:K_{max} ratio versus scale of the problem for fracture simulations based on the Door County data.

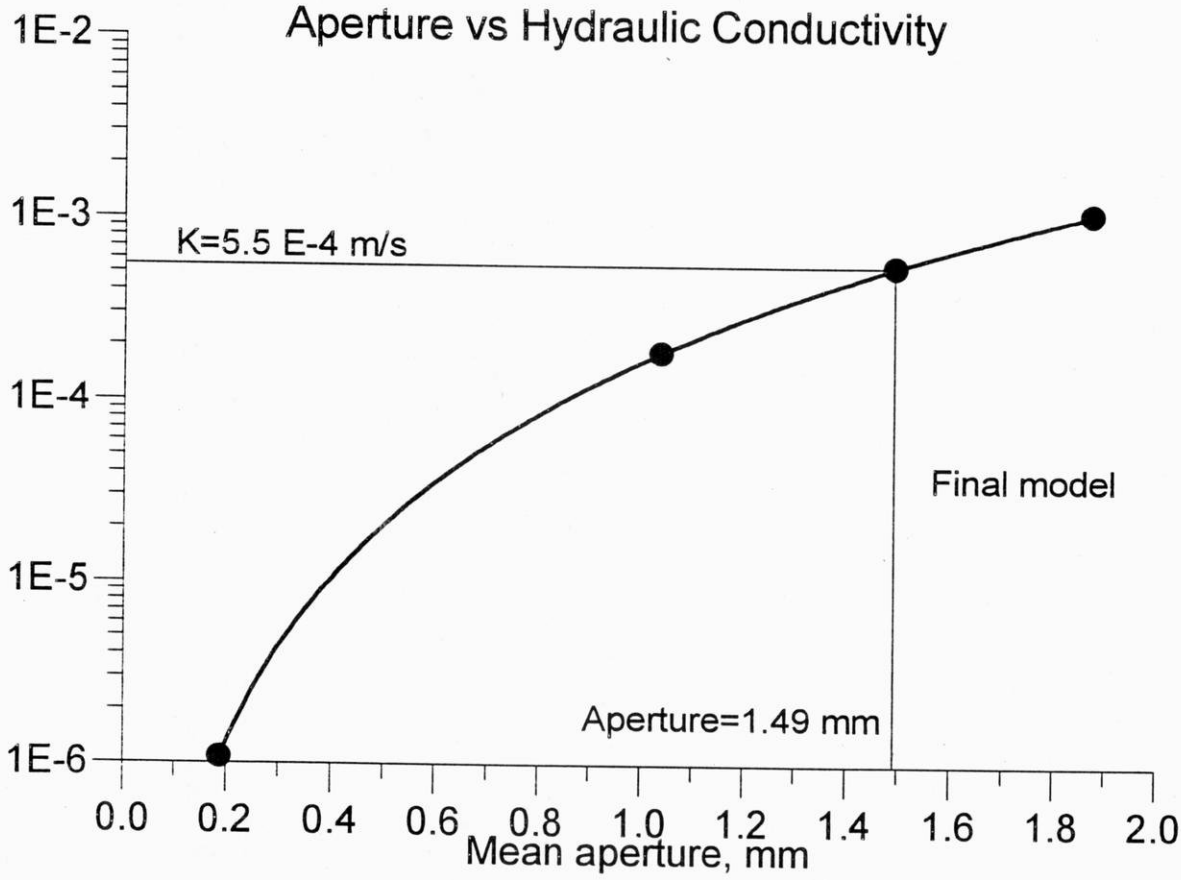


Figure 8. Mean aperture versus hydraulic conductivity for the Door County data.

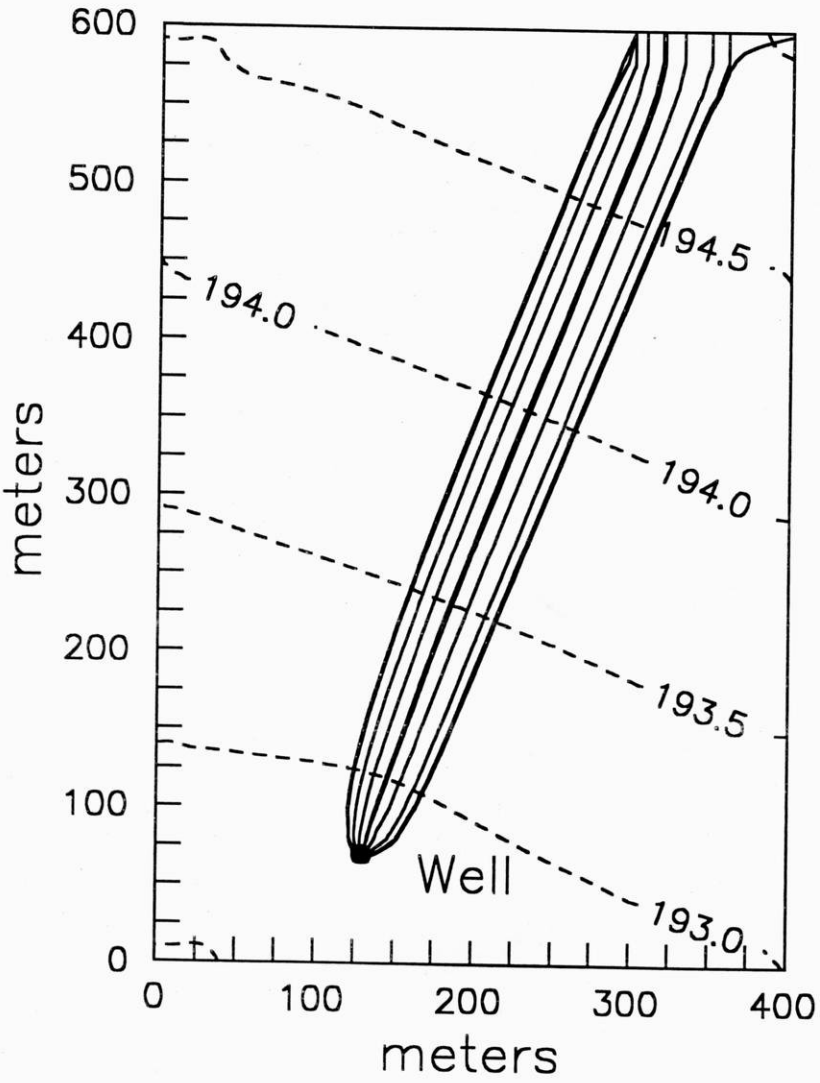


Figure 9. Capture zone for the Door County field site delineated using a porous-media model. Equipotential lines show simulated hydraulic head in meters above mean sea level.

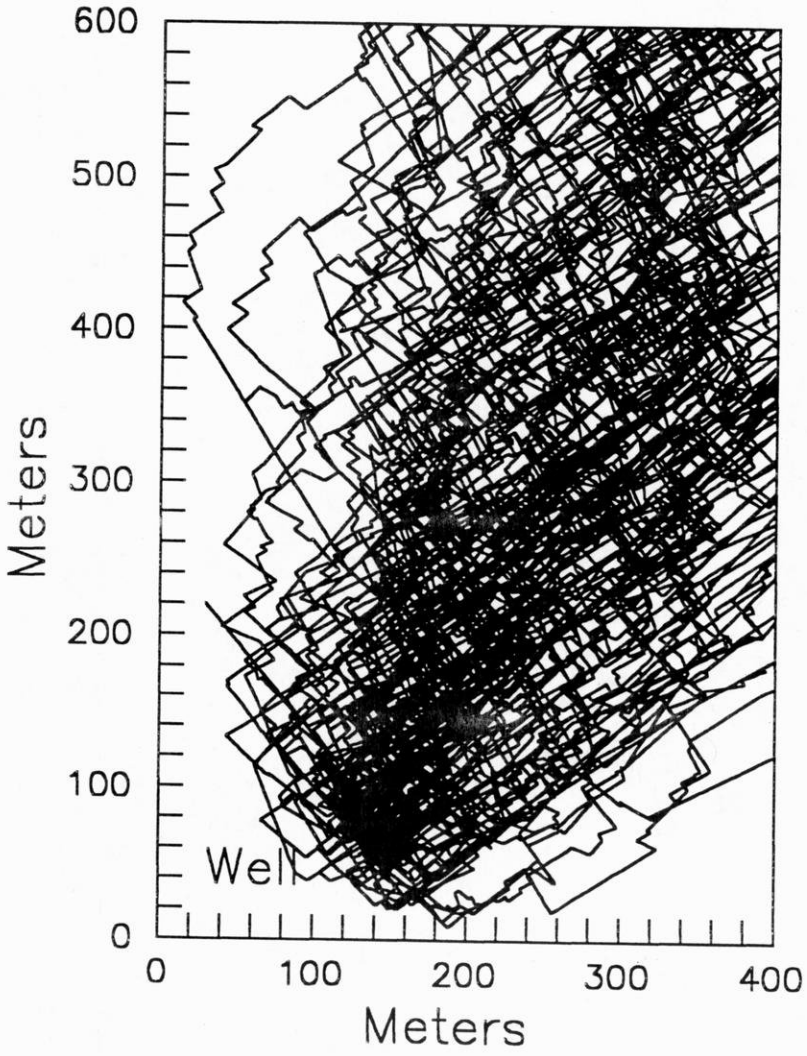


Figure 10. Particle paths for the SDF capture zone experiment in the same domain as figure 9. The plot represents 20 realizations of 10 particles each.

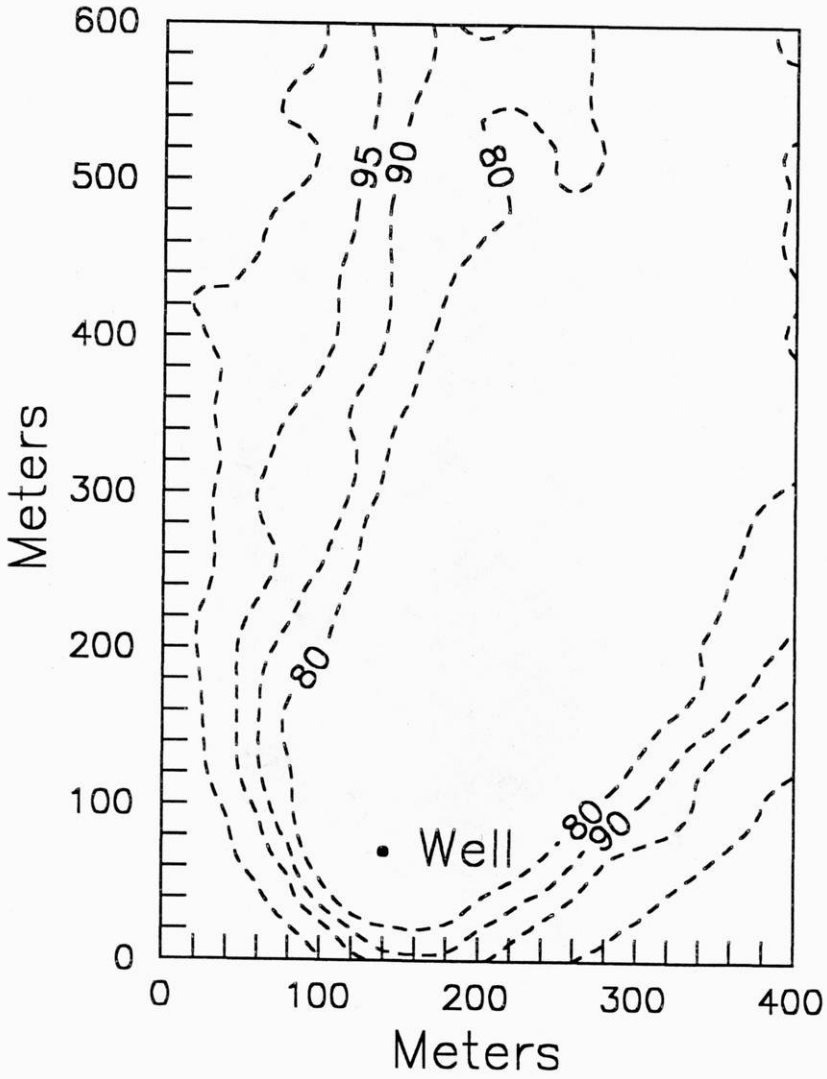


Figure 11. Percentage of particles captured in space for the SDF model simulation shown in figure 10.

APPENDIX A

USERS GUIDE TO THE SDF CODE AND FRACTURE MODELING

This appendix is a summary of the modifications to the Stochastic Discrete Fracture (SDF) model of Rouleau (1988) made by Angshuman Guha and Todd Rayne. The SDF model consists of three main programs: NETWRK, NETFLO, and NETRANS. Modifications were made to NETWRK and NETFLO only. This guide includes a list of modifications, instructions for changing the dimensions of the arrays, and instructions on how to execute the programs. In addition to the modifications to the main programs, several accessory programs were written to facilitate displaying the results and to perform deterministic particle tracking through the domain. Instructions on the use and modification of these programs are also included in this paper. Execution commands are shown within <angle brackets>. The brackets should not be included when typing the command.

MAIN PROGRAMS

NETWRK

The program NETWRK uses a stochastic method to generate lines with distributed lengths and orientations that represent two-dimensional fracture traces. Fracture apertures from a specified distribution are assigned to each line. The number of fractures, fracture intersections, and elements (segments of fractures between intersections) is dependent on the amount of RAM on the machine on which NETWRK is run and on the way this memory is managed, which is machine-dependent.

At present, the dimensions of these parameters are:

MAXFRA	6000	maximum number of fractures
MAXINT	30000	maximum number of intersections
MAXELT	30000	maximum number of elements.

These dimensions have been changed several time to their present size, and seem to be large enough for our applications. They are easily changed by modifying the appropriate lines of NETWRK and recompiling the code.

NETWRK is executed by typing <NETWRK <FILES.TXT>. The batch file FILES.TXT is a listing of the appropriate input and output files used by the SDF programs.

NETFLO and WELFLO

The programs NETFLO and the modified code WELFLO solve equations 3.1 through 3.10 in Rouleau (1988) for the fracture network generated by NETWRK. The

output from NETFLO and WELFLO are a series of files with head and flow information at nodal points and boundaries.

The program NETFLO has been superseded by the program WELFLO, but can still be used if wells are not simulated in the fracture network. As in NETWRK, the dimensions of arrays used in NETFLO are memory (and thus machine) dependent. At present, the dimensions of the arrays in WELFLO and NETFLO are:

MAXELT	30000	maximum number of elements
MAXNOD	10000	maximum number of nodes, which are effective elements (elements which are not dead ends)
MAXFRE	9500	maximum number of free nodes, which are designated with varying head (non-specified head).
MAXA	750000	maximum number of entries in matrix A, the node conductance matrix (Equation 3.6).

These dimensions can be changed by the user in the NETFLO or WELFLO code. The program must then be recompiled. Some of the machines at WGNHS have large amounts of RAM and will compile NETFLO or WELFLO with larger arrays than those listed. These machines must be used for simulating large domains (greater than about 500 m x 500 m) or high fracture density (greater than about 0.7).

WELFLO is a modification of NETFLO that allows wells to be simulated within the domain. The program also calculates the discharge of the well. The well is simulated as a specified head point boundary within the domain. WELFLO looks for a file called WELLS.DAT, which specifies the location and head of the well(s). Currently, a maximum of 50 wells can be simulated; this dimension can be easily changed. If WELLS.DAT is not included, the program prints a message to the screen and assumes no wells are in the domain. The format of WELLS.DAT is one line for each well, with the information: x location, y location, head. The values are in free format, with a space between values. No commas are necessary.

NETFLO and WELFLO are executed by typing <WELFLO (or NETFLO) <FILES.TXT>. The file WELLS.DAT should be in the same directory as the main input file (R990.IN1).

NETWRD and NETWRD1

The programs NETWRD and NETWRD1 are modifications of NETWRK. The modifications bypass the stochastic generation of the fractures and allow the user to specify the coordinates and apertures of the fractures. This program is useful for profile simulations, with regularly or variably spaced horizontal fractures representing bedding planes with different apertures intersected by vertical fractures with varying apertures.

The program NETWRD has been superseded by NETWRD1, but both are available. NETWRD will not allow the fracture apertures to be specified. The output files from NETWRD1 is used by WELFLO or NETFLO for solving for the flow field within the fracture network.

NETWRD1 looks for an input file called NETWRD.IN1 which contains the fracture coordinate and aperture information. The format of NETWRD.IN1 is:

line 1: number of fractures (I3) n
line 2 through n: four real numbers (4F6.2) specifying x1, y1, x2, y2

After the x and y coordinates, fracture apertures are specified by:

line N+1: number of fractures (I3) n
line N+2 through n: one real number (F10.8) specifying aperture (m).

In addition, if fracture apertures are specified, the main input file R990.IN1 must be modified slightly. The variable APDSTR(I) should be set to 3.

NETWRD and NETWRD1 are executed by typing <NETWRD or NETWRD1 < FILES.TXT>. The input file NETWRD.IN1 should be in the same directory as the other data files. The dimensions of the arrays in NETWRD1 are the same as those in NETWRK, and can be changed in the same manner (Figure 1).

ACCESSORY PROGRAMS

PARTRACK

The program PARTRACK tracks particles through the fracture network created in NETWRK and WELFLO. The program uses volumetric flow information contained in output files from the main programs to move particles through the fracture network. At fracture intersections, the program calculates the probability of the particle entering a particular channel by using the flow rates and a random number generated internally. Therefore the particle movement is a stochastic process. PARTRACK will do both forward and reverse particle tracking, and at present has a limit of 200 particles. This is easily changed by the user.

The input file is named PARTRACK.IN1. The format is:

line 1: F10.6, F6.4, I5 (time limit, random number seed, number of particles)
line 2 through # of particles: 2F10.6 (x-y coordinates of particles)

The time limit is expressed in years. If it is negative, the particle movement is simulated backwards. The random seed should be between 0.0000 and 1.000 exclusive. If 0 is entered, the system clock is used for a seed. The maximum number of particle, currently 200, can be changed by changing the include file named PARAMS.TXT. This file is

used to dimension arrays in PARTRACK and several other accessory programs.

PARTRACK generates two output files, PARTRACK.OUT and PARTRACK.OU2. PARTRACK.OUT contains particle locations, elapsed time, and information about why the particle stopped. PARTRACK.OU2 contains the particle location data in SURFER format. Input and output times are in units of years. PARTRACK is executed by typing <PARTRACK>.

PARQUERY

The program PARQUERY allows the user to locate all particles at any time. The program uses the output from PARTRACK to locate the particles. The program is user-interactive, and generates an output file named PARQUERY.OUT which contains particle location data for all user-specified times. As in PARTRACK, all times are in years. PARQUERY is executed by typing <PARQUERY>. The program will then ask the user for a time (yrs). If the time is greater than the time required for all particles to reach a boundary, the message "no information for particle *i*" will appear on the screen and no output file will be created. The program is terminated by typing a negative number.

NODES

The program NODES uses the output files of WELFLO to generate SURFER-compatible files of node locations and heads. It also uses the include file PARAMS.TXT to dimension the arrays of number of nodes and number of elements. NODES will create a SURFER file with a maximum of 8185 data values. This is approximately the limit of SURFER. If the SDF output files contain more than 8185 nodes, NODES will automatically eliminate some data until there are 8185 nodes. This is done by: (1) sorting the nodes by ascending x-y location, (2) eliminating nodes that are within 0.5%, then 1.0%, then 1.5%, etc. until 8185 nodes remain. This method insures that only redundant data for contouring is deleted. This data elimination process does not change the original SDF output files.

NODES is executed by typing <NODES>. The output file used by SURFER is called NODES.TXT.

FRACS

The program FRACS use the output files from NETWRK to generate a SURFER-compatible file of fracture coordinates. The program is written in PASCAL and the output file used by SURFER is named FRAC2.TXT. FRACS is executed by typing <FRACS < FILES.TXT>.

APPENDIX B

DATA INPUT INSTRUCTIONS

The following information is reprinted from Rouleau (1988).

Format of Input Data

General Input File (Unit 1)

Record 1

Columns I to 80: TITLE (20A4).

Record 2: general information.

-	Columns	1	to	5:	NSET	(I5).
-	Columns	6	to	10:	ISP	(I5).
-	Columns	11	to	15:	COEF	(F5.0).
-	Columns	16	to	20:	SEED	(F5.0).
-	Columns	21	to	25:	PLTSIZ	(F5.0).
-	Columns	26	to	30:	IGEOM	(I5).
-	Columns	31	to	35:	NAP	(I5).
-	Columns	36	to	40:	NAAP	(I5).
-	Columns	41	to	50:	DAAP	(F10.0).
-	Columns	51	to	55:	IPRT	(I5).
-	Columns	56	to	60:	NPART	(I5).
-	Columns	61	to	65:	TRAVDIS	(F5.0).
-	Columns	66	to	68:	NMAP	(I3).

Record 3: location of the rectangular boundaries. These are required even for circular model.

-	Columns	1	to	40:	XMINO, YMAXO, XMAXO, YMINO, XMINI, YMAXI,XMAXI, YMINI (8F5.0). (in that clockwise order)

Record 4 and following: other information on model boundaries. One record for each on the NBO boundaries: for a rectangular model there are 8 boundaries, for a circular model there are 6 boundaries (I= 1 to NBO).

-	Columns	1	to	5:	ISHAP(I)	(I5).
-	Columns	6	to	10:	R(I)	(F5.0).
-	Columns	11	to	15:	XB(I)	(F5.0).
-	Columns	16	to	20:	YB(I)	(F5.0).

-	Columns	21	to	25:	IBC(I)	(I5).
-	Columns	26	to	30:	HDB(I)	(F5.0).
-	Columns	31	to	35:	HDE(I)	(F5.0).

Following records: first series of information on the fracture network. One record for each one of the NSET fracture sets (I = 1 to NSET).

-	Columns	1	to	10:	DENS(L)	(F10.0).
-	Columns	11	to	15:	LDSTR(L)	(I5).
-	Columns	16	to	20:	THDSTR(L)	(15).
-	Columns	21	to	25:	APDSTR(I)	(I5).
-	Columns	26	to	30:	ITERM(L)	(15).

Following records: parameters of the statistical distributions for the fracture network. One record for each one of the NSET fracture sets (I = 1 to NSET).

-	Columns	1	to	10:	ALE(L)	(F10.0).
-	Columns	11	to	20:	BLE(I)	(F10.0).
-	Columns	21	to	30:	ATHP(I)	(F10.0).
-	Columns	31	to	40:	BTHP(I)	(F10.0).
-	Columns	41	to	50:	ATH(I)	(F10.0).
-	Columns	51	to	60:	BTH(I)	(F10.0).
-	Columns	61	to	70:	AAP(L)	(F10.0).
-	Columns	71	to	80:	BAP(I)	(F10.0).

Last record:
array of NMAP particle numbers for which the detailed trajectory is to be printed (I = 1 to NMAP)

-	Columns	1	to	30:	MPART(I)	(10I3).

Supplementary Input File for the Program APEGEN (Unit 21)

Record 1

-	Columns	1	to	80:	TITLE	(20A4).

(It is suggested to make this title similar to the title on the general input file, and to add an identification for the aperture generation run.)

Record 2: general information.

-	Columns	1	to	5:	IPRT	(I5).
-	Columns	6	to	10:	APDSTR	(I5).
-	Columns	11	to	15:	NAP	(I5).
-	Columns	16	to	20:	NAAP	(15).
-	Columns	21	to	30:	OAAP	(F10.0).
-	Columns	31	to	35:	SEED	(F5.0).
-	Columns	36	to	40:	NSET	(I5).
-	Columns	41	to	45:	IOR	(I5).

Record 3 and the following: parameters of aperture distributions. One record for each one of the NSET fracture sets (I = 1 to NSET).

- Columns 1 to 10: AAP(I) (F10.0).
- Columns 11 to 20: BAP(I) (F10.0).

Input/Output Files

Unit no.	Mnemonic name	Description
1	INP1	General input data.
2	SUMNET	Summary information on the generated line network, on fracture apertures (from the program NETWRK) and on porosity.
2+	SUMNET	All the above plus information on individual fracture traces.
3	SPACNG1	Spacing data generated by the subroutine SPCNG1.
4	SPCNG2	Spacing data generated by the subroutine SPCNG2.
5	NODES	Unformatted file containing node data.
6	ELEM	Unformatted file containing element data.
7	APER1	Unformatted file containing aperture data generated by the program NETWRK.
15	NODFO	Formatted equivalent of the file No. 5.
16	ELEFO	Formatted equivalent of the file No. 6.
17	APEFO1	Formatted equivalent of the file No. 7.
21	INP2	Input data on aperture distribution for the program APEGEN.
22	APER2	Unformatted file containing aperture data generated by the program APEGEN.
23	APEF02	Formatted equivalent of the file No. 22.
31	SUMFLO	Summary of the flow calculations, including the directional parameters.

31+	SUMFLO	The above plus rose diagrams of flow rates.
31++	SUMFLO	The above plus rose diagrams of all the directional parameters.
32	DIRPAR	Unformatted file of directional parameters.
33	FLOALL	Results Of flow calculations for all the elements.
34	FLOMAT	Detailed information on node renumbering and on flow matrices.
41	TRANSIT	Statistics and plots of transit times.

Input Files and Options of Output Files for Each Program

Program	Input unit no.	IPRT	Unit no.
NETWRK*		1	2,3,4,5,6,7
		2 or 3	2+,3,4,5,6,7, 15,16,17
APEGEN	21,5,6,7	1	22
		2 or 3	22,23
NETFLO	1,5,6,7**	1	31,32
		2	31+,32,33
		3	31++,32,33,34
NETRANS	1,32	1, or 2, or 3	41

* NETWRK also generates a plotting file if the input parameter PLTSIZ is positive.
** In NETFLO, the input unit 7 must correspond to either the output unit 7 from NETWRK (APER1) or the output unit 22 from APEGEN (APER2).

List of the Main Variables Used in the Programs NETWRK (NW), APEGEN (AP), NETFLO (NF) and NETRANS (NT)

List of Input Parameters

AAP(I) and BAP(I) (NW,AP): first and second parameters of the distribution of apertures for fracture set I. For APDSTR=L, AAP is the aperture value and BAP is not used. For APDSTR=2, AAP and BAP are respectively the mean and the standard deviation of the (natural) log-transformed aperture. Note that the aperture is expressed in metres; (m).

ALE(I) and BLE(I) (NW): first and second parameters of the distribution of trace lengths for the fracture set I. For LDSTR=L, ALE is the trace length and BLE is not used. For LDSTR=2, ALE and BLE are respectively the mean and the standard deviation of the (natural) log-transformed trace length values; (m).

APDSTR(I) (NW, AP): type of distribution for apertures of fracture set I: (1) single--valued variable, (2) log-normal distribution; see AAP and BAP

ATH(I) and BTH(I) (NW): first and second parameters of the distribution of trace angles within the simulation plane forfracture set I. For THDSTR=1, ATH is the angle value and BTH is not used. For THDSTR=2, ATHP and BTHP are respectively the mean and the standard deviation of the angle values.

ATHP(I) and BTHP(I) (NW): first and second parameters of the distribution of angles between the simulation plane and the fractures of set I; ATHP(I) should be within the range 0^0-180^0. Angles are expressed as measured within the simulated rock slice, on the right-hand side of the fracture trace while looking in the direction ATH(I); see Figure D.1; (degree). For THDSTR=I, ATHP is the angle value and BTHP is not used. For THDSTR=2, ATHP and BTHP are respectively the mean and the standard deviation of the angle values.

BAP(I) (NW, AP): see AAP(I).

BLE(I) (NW): see ALE(I) .

BTH(I) (NW):see ATH(I).

BTHP(I) (NW):see ATHP(I).

COEF (NW): coefficient used to multiply a preliminary estimated number of fractures in a set, in order to get a value of ESTNFR (see subroutine GENLIN) large enough for most realizations; typically COEF should be in the range 2.0 to 6.0.

DAAP (NW,AP): increment between different values of the aperture distribution parameter AAP.

DENS(I) (NW): density of fracture set I, defined as the surface area of fractures per unit volume of rock (m^{-1}).

HDB(I) and HDE(L) (NF): input value of hydraulic head at the beginning and at the end point respectively, of the boundary segment 1; moving clockwise along the boundary; not used for the no-flow boundaries; see Figure D.3; (m).

IBC(I) (NW,NF): code for the boundary condition for flow along the boundary segment 1; (0) no-flow bndr., (1) constant head along the bndr., (2) linearly decreasing head along the bndr., (3) logarithmically decreasing head along the bndr.; in the latter case, the bndr. must not cross a zero axis; see Figure D.3.

IGEOM (NW,NF,NT): code for the general geometry of the model; (1) for a rectangular model, (2) for a circular model; see Figure D.3.

IOR (AP): code for the aperture generation mode; (0) if no use is to be made of orientation data, (1) if the orientations to be considered; the second option is not operational yet.

IPRT (NW,AP,NF,NT): code for the level of information desired in the output files; possible values are 1, 2, and 3, with increasing level of detail (see Table B.2). Also, the fracture and the node numbers are not written on the computer plot with IPRT = 1.

ISHAP(I) (NW,NF): code for the shape of the boundary segment I; (0) when its lengthis zero, (1) for a linear segment, (2) for a circular segment.

ISP (NW): code for the type of sampling for spacing values between traces of fractures of the same set; (0) if no sampling is desired, (1) for sampling along lines perpendicular to the mean orientation of the traces (subroutine SPCNG1), (2) for sampling along randomly oriented lines (subroutine SPCNG2).

ITERM (1) (NW): termination mode for fracture set I; (0) free extremities, (1) extremity one (i.e., higher y-value) is abutting on fractures of any set with index <I; ITERM(l) cannot equal 1.

LDSTR(I) (NW): type of distribution of trace lengths for the fracture set I; (1) for a single-valued variable, *(2)* for a log-normal distribution; see ALE and BLE.

MPART(IO) (NW): array of particle numbers for which a detailed record of the track is desired; there are NMAP such particles.

NAAP (NW,AP,NF,NT): number of different values of AAP to be used in the aperture generation.

NAP (NW,AP,NF,NT): number of aperture distributions to be generated with the same distribution parameters.

NMAP (NT): number of particles for which a detailed record of the track is desired (see MPART).

NPART (NT): number of particles to be tracked (generally 50).

NSET (NW,AP,NF): number of fracture sets; maximum = 5.

PLTSIZ (NW): length (in inches) of the longer axis of the plot to be generated; if PLTSIZ $\leq$ 0, no plot is made.

R(l) (NW): radius of the boundary segment I; it is used only for circular segment, i.e., with ISHAP(I)=2; see Figure. D.3; (m).

SEED (NW,AP): seed number for the random number generation routines; double precision number in the range 1 to 2147483647.

THDSTR(I) (NW): type of distribution of angles for the fracture set 1; (1) for a single-valued variable, (2) for a normal distribution; see ATH, BTH, ATHP, and BTHP.

TRAVDIS (NT): distance a particle must travel to make it through the system (m); its value does not have to be the same as the size of the model for the generated network.

XB(I) and YB(I) (NW,NF): coordinates of the beginning of the boundary segment I, moving clockwise along the boundaries; (m).

XMAXI, XMINI, YMAXI
YMINI (NW): inner boundaries of the rectangular model; see Figure D.3; (m).

XMAXO, XMINO, YMAXO
and YMINO (NW): outer boundaries of the rectangular model; required even for a circular geometry model

YB(I) (NW,NF):
see **XB(I).**

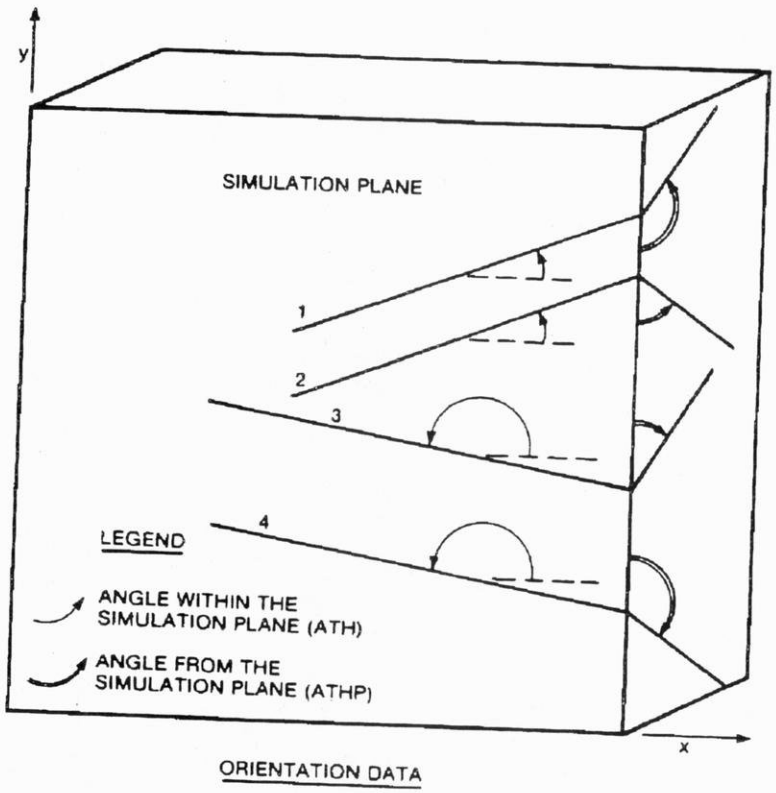
YMAXI and YMINI (NW):
see **XMAXI.**

YMAXO and YMINO (NW):
see **XMAXO.**

Conventions for Angles, Directions, and Boundary Geometry

Conventions for Angles

Figure B.1 explains the convention used to express the angles within the simulation plane (ATH, TH, and ELOR) and the angles from the simulation plane (ATHP, THP, and ELORP).



ORIENTATION DATA

FRACTURE	ATH (degrees)	ATHP (degrees)
1	20	135
2	20	45
3	170	45
4	170	135

Figure B1. Conventions for angles.

Conventions and Limitations on Boundary Geometry

1. Every non-circular side of a model may be divided in two segments, each one having a

different type of boundary condition.

2. Flow boundaries are numbered clockwise, starting with the vertical boundary on the left- hand side of a model (Fig. B2). A rectangular model must have 8 flow boundaries, a circular model must have 6. In a rectangular model, flow-boundary numbers 1, 3, 5, and 7 must always be present (i.e., ISHAP(I) > 0). Flow-boundary numbers 2, 4, 6, and 8 may have a zero length (i.e., I SHAP(I) =0) .In a circular model, the compulsory flow-boundaries are numbers I , 3, 4, and 6; the optional boundaries are 2 and 5. Note that if the flow-boundary I has zero length (i.e., ISHAP(I)=0), the flow boundary numbered I-1 must apply to the entire length of the side of the model where it is located.

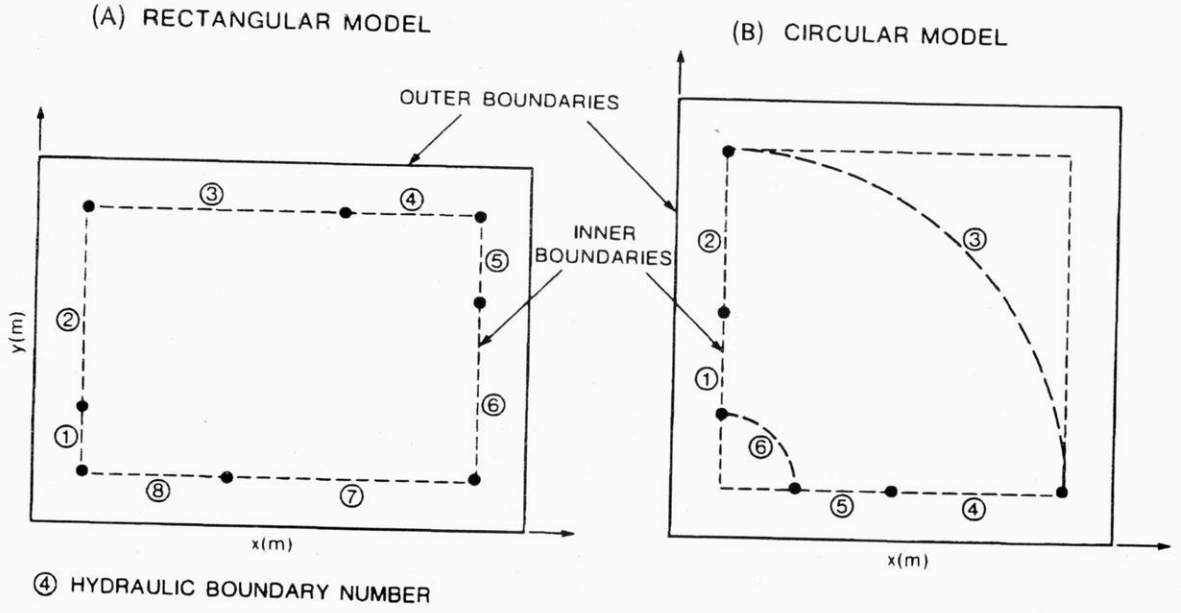


Figure B2. Boundary conventions.

3 . The input mean orientation (ATH) should be within the range 0^0 to 180^0.

4. All rectangular boundaries (i.e., XMAXI... etc., and XMAXO... etc.) must be included in input data even for a circular model.

5. A circular boundary must correspond to the upper right quadrant of a circle and be centered at the point (XMINI, YMINI).

6. The present version of NETRANS can be used only for rectangular models.

Preliminary Comparison of a Discrete Fracture Model with a Continuum Model for Groundwater Movement in Fractured Dolomite