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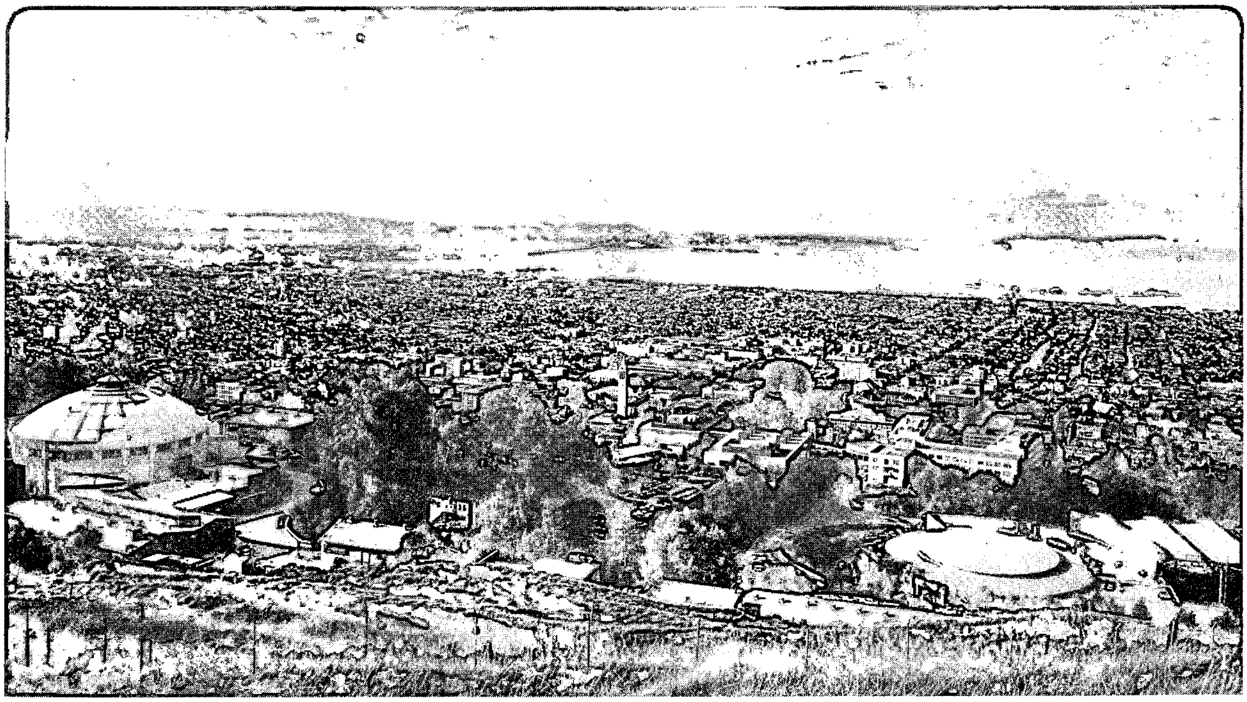

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FLOW AND TRANSPORT IN HIERARCHICALLY FRACTURED SYSTEMS

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ABSTRACT

Preliminary results indicate that flow in the saturated zone at Yucca Mountain is controlled by fractures. A current conceptual model assumes that the flow in the fracture system can be approximated by a three-dimensionally interconnected network of linear conduits. The overall flow system of rocks at Yucca Mountain is considered to consist of hierarchically structured heterogeneous fracture systems of multiple scales. A case study suggests that it is more appropriate to use the flow parameters of the large fracture system for predicting the first arrival time, rather than using the bulk average parameters of the total system.

INTRODUCTION

The potential high-level nuclear waste repository at Yucca Mountain, Nevada (Figure 1) would be built in unsaturated, fractured, welded tuff. Yucca Mountain is composed of a thick sequence (approximately 4000 m) of Tertiary Miocene ash-flow and ash-fall tuffs. A generalized stratigraphic section of the volcanic rocks at Yucca Mountain is shown in Figure 2. One possible contaminant pathway to the accessible environment, which is defined as a distance greater than 5 km from the potential repository perimeter, is transport of radionuclides by water flowing through the fractured rocks of the saturated zone. Much of the saturated zone consists of rocks of the Crater Flat Tuff, approximately 13.5 million years old in age. Fractures associated with cooling of the ash-flow and ash-fall tuffs are present in these rocks. Structural deformation during the Tertiary near Yucca Mountain resulted in different styles of faulting.[1] Within the fault blocks defined by these structural features are tectonically-induced fractures which were formed by changes in stress field of the associated fault(s). From this association a simplified conceptual model can be formulated wherein there are multiple scales of features superimposed such as faults that bound the block and fractures within the block.

Preliminary results from crosshole hydraulic-stress tests at the UE-25c-hole complex (Figure 1) in the saturated zone suggest that apparent transmissivity values are highly localized, and related to fractures and a brecciated zone associated with a fault.[2] Combined with the fact that the tuff has a very low matrix permeability, flow in the saturated zone can be presumed to be mainly controlled by fractures, at least at the scale affected by the aquifer tests. These fractures are often non-uniformly distributed and possess highly heterogeneous flow properties, which must be accounted for by the conceptual and numerical models.

It is necessary to understand how flow and transport occur in such a system to reliably characterize the hydrology of the saturated zone. The most direct information regarding fracture flow can be obtained by conducting in-situ hydraulic-stress and tracer tests. However, such tests can be done only at a limited number of locations and scales. It is virtually impossible to characterize every detail of the geometry and flow properties of fractures at all scales. Therefore, simplifying assumptions must be made to model flow through heterogeneous fracture systems. One such assumption is that not all of the geometric details of the fracture system are important. Another is that the overall fracture flow system consists of discrete features of multiple scales that are superimposed on top of each other. In this paper a discussion on how the flow and transport in fractures is conceptualized is presented. Then a case study of flow and transport simulation in a hypothetical hierarchical fracture system is given.

CONCEPTUAL MODEL OF FLOW IN FRACTURES

For this paper, a conceptual model is defined as conceptualization of the system geometry and the controlling physical properties and a numerical model refers to incorporation of the conceptual model into a computer program that simulates physical processes such as fluid flow and transport in the identified system geometry. Therefore, the numerical model consists of input data and the numerical code. Numerical models have the advantage of being able to simulate flow and transport in complexly fractured systems at scales larger than those represented by a single borehole or aquifer test, and may be used for the testing of hypotheses about flow through fractured rock.

Many investigations of fracture flow have been undertaken using parallel plate assumptions.[3,4,5] More recently, however, various field and laboratory observations have indicated that flow in a fracture is not entirely identical to flow between two smooth parallel plates.[6,7,8] Fractures generally have contact areas where no flow occurs, and the fracture walls are not always smooth. Because of these irregularities, the velocity profile may deviate from that predicted by Poiseuille's Law and there may

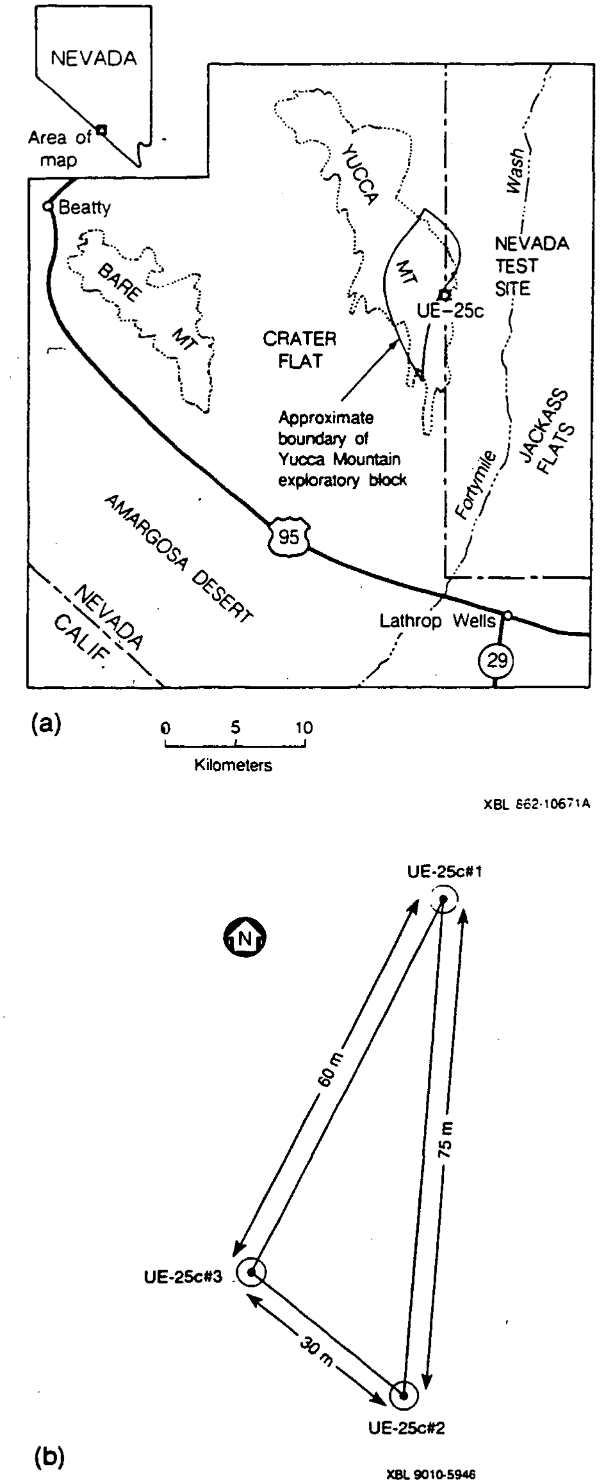
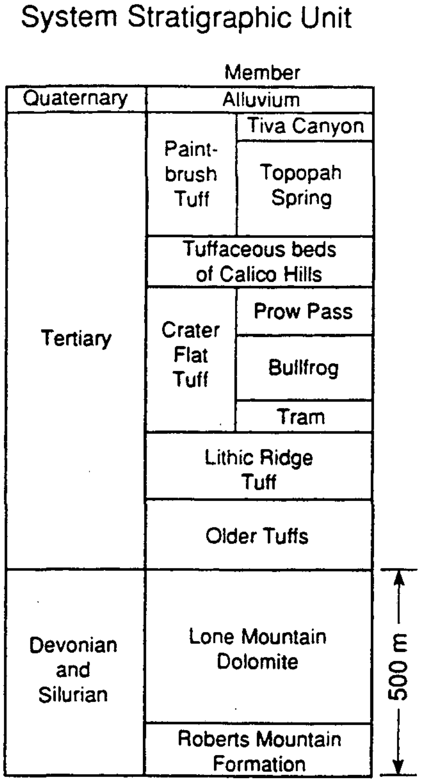


Figure 1 - a) Location map of Yucca Mountain and vicinity and b) surface layout of UE-25c-holes.



System Stratigraphic Unit

		Member
Quaternary	Alluvium	
Tertiary	Paint-brush Tuff	Tiva Canyon
		Topopah Spring
	Tuffaceous beds of Calico Hills	
	Crater Flat Tuff	Prow Pass
		Bullfrog
		Tram
	Lithic Ridge Tuff	
	Older Tuffs	
Devonian and Silurian	Lone Mountain Dolomite	
	Roberts Mountain Formation	

Figure 2 - Generalized stratigraphic section of the Miocene ash-fall and ash-flow tuffs at Yucca Mountain.

exist preferred fluid paths or channels that are more lineal in geometry, rather than sheet-like. Furthermore, the intersections of fractures can behave like linear conduits for fluid flow. Consequently, flow in a fracture system may be better approximated by a network of three-dimensionally interconnected line segments rather than planar segments. Flow in each line segment is assumed to be that of laminar flow in a one-dimensional porous medium pipe, i.e., Darcy flow.

FLOW AND TRANSPORT MODEL

A numerical model that can simulate flow and transport in complex fracture systems can be a useful tool in improving our understanding of the flow systems. The model also can be used to help design hydraulic-stress and tracer tests, interpret the results of these tests, and make predictions.

Observed transport behavior is a result of phenomena occurring at two levels; phenomena associated with transport within individual fractures and that which is a consequence of network geometry. For the reasons discussed in the previous section it is assumed that a fluid conduit in a fracture system is best approximated by a one-dimensional porous medium pipe.

The transport within each fracture, as represented by a line conduit, then can be described by the one-dimensional advection-dispersion equation:

$$\frac{\partial C}{\partial t} = D^* \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x}$$

where C is the chemical concentration, D^* is the dispersion coefficient, u is the fluid velocity, t is the time, and x is the distance variable. Dispersion as a result of spatial variability in fluid velocity is modeled explicitly by the network geometry.

The advection-dispersion equation is very difficult to solve numerically especially at large Peclet numbers, where $P_e = uL/D^*$, and L is the characteristic length. Large Peclet numbers make the advection-dispersion equation hyperbolic in nature. Conversely, small Peclet numbers result in parabolic behavior. When modeling transport in fracture networks, the Peclet number is expected to vary over a wide range of magnitudes because of the heterogeneity among fractures, especially under tracer tests with an induced flow field, such as pump-back tests and two-well recirculation tests.

Classical numerical treatment of the advection-dispersion equation inevitably introduces either an artificial (numerical) dispersion or oscillation. Many works have been devoted to the subject of avoiding these numerical difficulties.[9,10,11,12,13] Neuman[10] proposed a mixed Eulerian-Lagrangian method with adaptive gridding. However, the method of Neuman[10] retains some numerical dispersion when the advected front is projected back to the fixed finite element grid. Karasaki[13] modified the approach of Neuman[10] and proposed a mixed Lagrangian-Eulerian scheme with a moving grid. Karasaki's[13] model further minimizes numerical dispersion by creating new Eulerian grid points, instead of interpolating the advected profile back to the fixed Eulerian grid.

The moving grid technique is generally difficult to apply. However, application to linear elements is relatively easy. Therefore, Karasaki's[13] model is well-suited to the conceptual model discussed in the previous section. In the following section a case study is presented, using the conceptual model discussed above and the numerical model of Karasaki.[13]

HIERARCHICAL FRACTURE SYSTEM

Rock heterogeneities exist at all scales. This is particularly true for fractured rocks such as those encountered at Yucca Mountain. Roughly stated, there are three different scales of interest: small; intermediate; and large. A number of works have been published on hierarchical porous media.[14] Schwartz and others[15] also have investigated a stochastic approach of modeling transport in fractures.

At a small scale, defined as the scale which can be studied in the laboratory, research indicates that there is a large variation in the aperture within a single fracture, and that fluid flows preferentially in tortuous channels with varying flow properties. Tsang and Tsang[8] proposed a model to describe such channelized flow in fractures. The channeling effect is observed to be further enhanced when stress is applied across a fracture.[16]

At an intermediate scale, defined as the scale of a block of rock affected by hydraulic-stress tests, the transmissivity often is observed to vary markedly along the length of a borehole and from borehole to borehole. In general, the more fractures an interval in a borehole includes, the more transmissive the interval is. However, an interval with few fractures can sometimes be more transmissive than one with many more fractures. This is because the fracture conductance itself can differ greatly from one fracture to another, as well as within a fracture. The transmissivity of an interval also depends on how the particular conductive fractures in the interval are connected to the rest of the fractures that constitute the flow system. The heterogeneous transmissivity observed at this scale is a compound effect of the variability in the fracture density, mineralization, conductance, and connectivity. Features such as faults and fracture zones can also affect the transmissivity.

At the large scale, defined as the scale beyond which the effects of hydraulic-stress tests can be observed, heterogeneities can be attributed to large faults and changes in the geologic setting. The manner in which the smaller scale features affect the next larger scale phenomena must be understood. This is especially the case for large scale hydrology, because a direct measurement of hydraulic properties at such a scale is not possible. Generally, hydraulic test results conducted at the intermediate-scale have somehow to be extrapolated. Similarly, to analyze intermediate-scale tests, an understanding of the small-scale phenomena are necessary.

A CASE STUDY

A case study of flow and transport phenomena in hierarchical fracture systems is presented in this paper. A simplified hierarchical system was constructed by superimposing fracture systems of different scales. Figure 3 shows an example of a two-dimensional system created by superposition of two fracture systems with distinctly different scales. In the present case a conductivity contrast of 100:1 magnitude was chosen.

Both fracture systems are assumed to be continuous. Thick lines, in Figure 3, represent high transmissivity fractures associated with block-bounding features. Thin lines, in Figure 3, represent fractures with small permeability, such as joints within fault blocks. Although the present model appears similar to a classical double porosity model, one important difference is that in the model discussed herein, flow is allowed to take place through the blocks. Furthermore, mechanical dispersion as a result of the fracture network is considered explicitly in the present model. Radially converging tracer tests were simulated by releasing a solute at various locations on the perimeter of the network, the boundary of which was held at constant pressure, and by simulating a well withdrawing water in the center of the model. In order to focus on the effects of hierarchical structure on dispersion, diffusion within individual fractures was not modeled. Only one eighth of the system is modeled, assuming radial symmetry; the sides are designated to be no-flow boundaries. This assumption is somewhat inconsistent, because complete mixing is assumed at interior fracture intersections, whereas no mixing is allowed to occur at the intersections on the side boundaries.

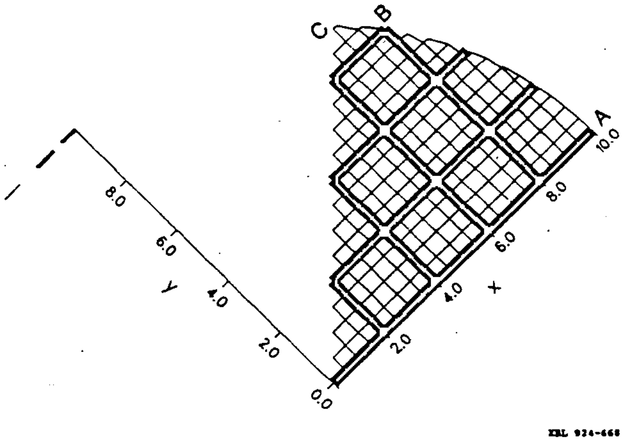


Figure 3 - A simplified hierarchical fracture system.

RESULTS AND DISCUSSION

Figure 4 shows breakthrough curves for tracers released at points A, B and C in Figure 3. A is located on the x axis, B is located approximately 37 degrees from the x axis on an intersection of the large fracture system, and C is located 45 degrees on the small fracture system. Case A, Figure 4, indicates that the solute stays entirely in the large fracture system and that breakthrough occurs in a plug-flow fashion. For Case B, Figure 4, the breakthrough of concentration takes roughly twice the time of Case A. In addition, there is slow and steady increase in tracer concentration after a sharp breakthrough as compared to Case A. The longer breakthrough time of Case B can be attributed to the fact that flow toward the simulated well follows a more tortuous pathway, which includes tangentially-oriented fracture segments. The hydraulic gradient is small in these tangentially-oriented segments. The solute effectively samples twice the porosity in Case B as compared to the more abrupt breakthrough in Case A. Figures 5a and 5b illustrate solute concentration distribution as a function of time, for Case B. The thickness of the lines in Figures 5a and 5b are proportional to the solute concentration. After 10,000 seconds (2.7 hours), Figure 5a, most of the solute stays in the large fracture system, but later in time at 20,000 seconds (5.5 hours), Figure 5b, some portion of the solute travels through the small fracture system. This phenomena accounts for the slow and steady increase in solute concentration after the sharp breakthrough for Case B. No breakthrough occurs for Case C, Figure 4, in a period comparable in duration to the time for breakthrough in Cases A and B. The solute in Case C is in a relatively stagnant zone which is bypassed by the major water-bearing fractures.

One purpose of this study is to investigate how to simplify, scale-up, and model the hydrologic behavior of a complex fracture system, while still retaining the salient flow and transport properties as measured in the field. One simplification might be treating the hierarchical fracture system as a single fracture system with equivalent bulk permeability and porosity as the system of hierarchical fractures. Shown in Figure 4 is breakthrough curve S, which represents this hypothetically equivalent fracture system. Comparison of Case S, Figure 4, with Cases A, B, and C indicates that simple volume-averaged transmissivity and porosity cannot adequately describe the variability in transport properties of hierarchical fracture systems. For the cases considered, it is probably more appropriate to use the flow parameters of the large fracture system for predicting the first arrival time rather than using the bulk average parameters of the total system, although the prediction is likely to err on the conservative side.

The case study discussed in this paper is a simple example of how fractures in rock may be represented by a hierarchical system of interconnected linear conduits and how solute is transported in such a system. In constructing a numerical model of complexly fractured rock, one goal is to represent the fracture network with minimum complexity and still account for the more important physical processes that take place in the network. Initial modeling demonstrates that hierarchical representation of fractured rock seems to be a reasonable approach for representing the fracture network. Also, this conceptual model intuitively is consistent with the way in which faults and fractures are formed in rock.

The large fracture or the fault system may not form a continuous pathway as depicted in Figure 3. It instead may be more accurately simulated by the type of model as shown in Figure 6. In Figure 6, the large fracture system is discontinuous. In such a system there may be an appropriate set of average parameters for predicting flow and transport phenomena. The study of discontinuous networks is currently being performed.

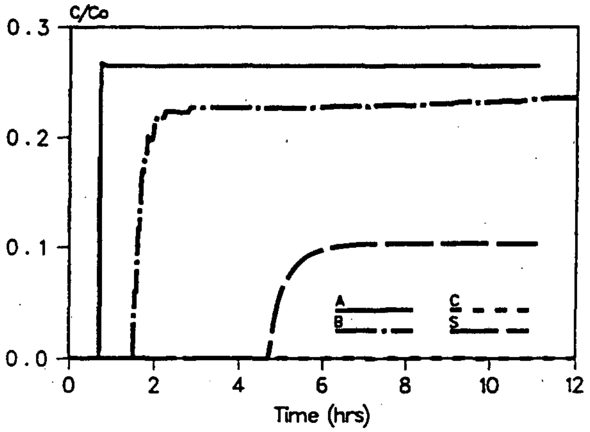


Figure 4 - Breakthrough curves for Cases A, B, C and S for radially convergent tracer tests.

SUMMARY AND CONCLUSIONS

The overall structure of discontinuities within the rocks at Yucca Mountain is considered to consist of hierarchically structured heterogeneous fracture systems of multiple scales. A current model, presented in the case study, assumes that the flow in the hierarchical fracture system can be approximated by a

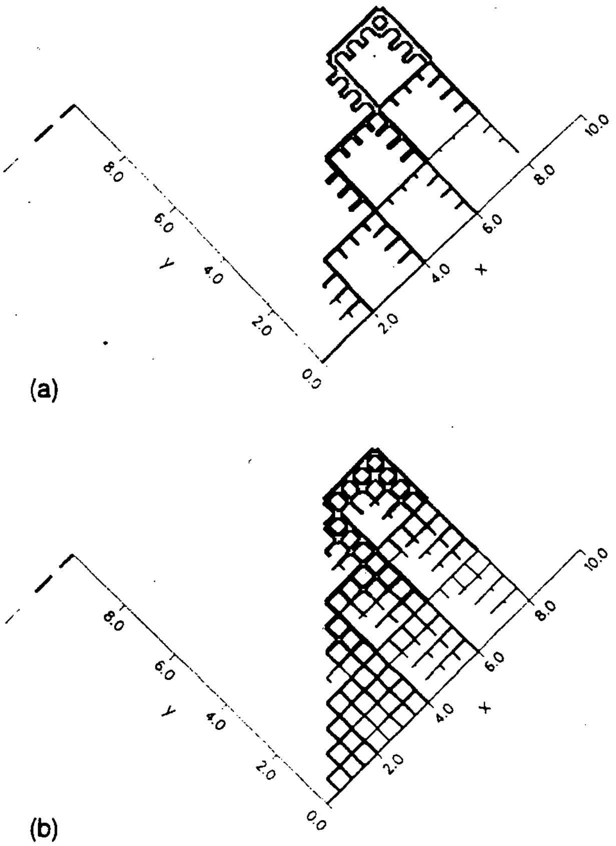


Figure 5 - Concentration distribution for Case B at a) 10,000 seconds, and b) 20,000 seconds.

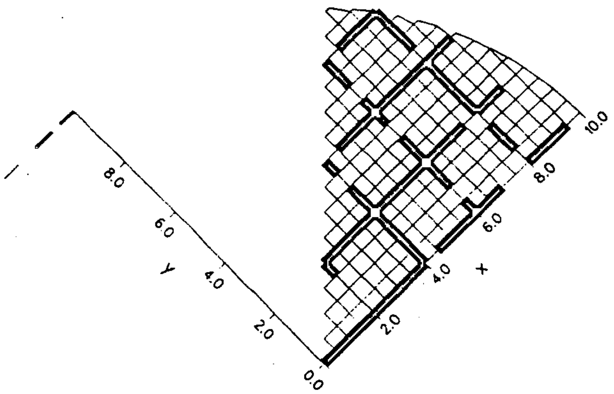


Figure 6 - A simplified hierarchical system with a discontinuous fault system.

three-dimensionally interconnected network of linear conduits. A numerical code based on Eulerian-Lagrangian scheme with moving grid technique is suitable for simulating flow and transport in such systems. The case study suggests that it is more appropriate to use the flow parameters of the large fracture system for predicting the first arrival time rather than using the bulk average parameters of the total system.

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