on local horizontal and vertical spatial variability of hydraulic properties. Long-term pumping tests are planned to assess the existence of a scale-dependent permeability structure, taking advantage of the well arrays with radially increasing spacing.

Conservative tracer tests will be carried out in much the same way by creating a convergent flow field into an interval and releasing various tracers from other intervals. Groundwater flow paths will be estimated by analyzing the tracer arrivals from the various release points. Both organic and inorganic tracers are planned for use, and the sampling and measurement methods are currently under development. The data from various tests will be used to construct a coherent hydrologic model of the site. Optimization algorithms such as simulated annealing will be used to invert both hydraulic and tracer-test data. Further experiments will then be conducted to test the accuracy and applicability of the model.

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6821

A Tool for Studying Two-Phase Flow in Fracture Networks

K. Karasaki, S. Segan, and K. Pruess

Problems concerning two-phase flow in fractured media are commonly encountered in oil fields, geothermal fields, groundwater reservoirs, and other geologic media of engineering interest. In recent years, considerable attention has been focused on the storage of radioactive wastes in fractured rock. In the United States, the site for the potential high-level nuclear waste repository is in the unsaturated, fractured welded tuff at Yucca Mountain, Nevada. One possible scenario by which radionuclides could reach the accessible environment is transport by groundwater through the unsaturated zone to the water table and then into the saturated zone. Therefore, accurate characterization of the two-phase flow behavior of the fractured rock mass is vital to the safety of such an operation. The most direct information regarding the two-phase flow characteristics can be obtained by conducting *in situ* cross-hole pneumatic tests. However, analysis of the test results is extremely difficult, because the two-phase flow phenomena in a fractured rock are not well understood and the initial saturation condition and the intrinsic rock properties, such as fracture and matrix permeability, are not known *a priori*.

A numerical model is an essential tool for assessing the performance of the potential repository for tens of thousands of years, during which the spent fuel remains highly radioactive. To model the volume of rock within the 5-km distance from the potential repository perimeter, given the current computational capability, a node would have to be as large as 200 m × 200 m × 20 m in order to be feasible. For each nodal volume the two-phase flow parameters, such as relative permeability and capillary pressure, are necessary inputs for a two-phase flow simulator. It is very important, therefore, to develop an understanding of how water and air flow in fractures and to accurately represent a volume of rock that contains a network of fractures for field test interpretation and reliable performance assessment modeling. Persoff et al. (1991) carried out a laboratory investigation of two-phase flow in transparent replicas of rock fractures. Pruess and Tsang (1990) and Kwicklis and Healy (1992) numerically studied two-phase flow in a single fracture. Kwicklis and Healy constructed a simple network using the parameters obtained from their single fracture simulation. In the present report, we outline a tool for studying two-phase flow in numerically generated networks, showing how networks are generated randomly and how the flow path for each phase is tracked rigorously using accessibility criteria based on the connection to the boundary and the different rules at the intersections. We then describe the assumptions involved, how the networks are generated, how the two-phase flow is simulated in them, and provide some sample results.

ASSUMPTIONS

For the particular case of air and water flowing through a fracture network embedded in an impermeable rock matrix, certain reasonable assumptions can be made that will allow this system to be studied systematically with computer-generated fracture networks. It is assumed that capillary pressure is the dominant driving force causing movement of the phases but that these pressures are in a range in which volume compressibility and changes of state can be ignored. The rock is assumed to be water-wet, which means that water preferentially occupies thinner fractures. With capillary pressure being the predominant force, one of the criteria for a given fracture element to be occupied by either fluid is established by the relationship between capillary pressure, P_c, and aperture size, b, given by

$$P_c = \frac{2\gamma}{b} , \tag{1}$$

where γ is the surface tension between water and air. It is assumed that the contact angle between water and air is zero. This capillary pressure criterion is called "allowability." The no-compressibility assumption, combined with the allowability criterion, implies that each element has only one phase in it and that this phase is present until a sufficient change in capillary pressure allows the other phase to occupy the element, at which point the initially present phase is considered to flow out smoothly.

Two assumptions are made regarding interaction of fluids at an intersection (Figure 1). In the first assumption, it is assumed that fluids do not "see" each other (no-blocking case); that is, the remainder of a water-filled fracture cut by a second fracture is considered accessible to water, even if the second fracture is filled with air (Figure 1a). In the second assumption, the remainder of a fracture cut by an air-filled fracture may be considered inaccessible until the latter gets filled with water (blocking case, Figure 1b); this assumption is probably more rigorous in a strictly two-dimensional geometry. However, the first assumption essentially makes the two-dimensional network pseudo-three-dimensional, which may be a better representation of the real situation, which is three-dimensional. Nonetheless, these two assumptions are believed to be the limiting cases.

Another mechanism examined is the effect of trapping of one phase by the other. In one case, it is assumed that a phase can replace the other in any element as long as the element is accessible and allowable for the replacing phase (no-trapping case). In the other case, a phase is not permitted to replace the other unless there is a continuous exit path by which the replaced phase can reach the outflow boundary (trapping case, Figure 2); this assumption leads to a somewhat more rigorous treatment of the actual phenomena but does not fully account for the dynamics of the transient imbibition/drainage process. That process is treated as a succession of steady states with incremental change in capillary pressure. In total, four combinations of assumptions were examined: (1) no blocking and no trapping, (2) blocking and no trapping, (3) no blocking and trapping, and (4) blocking and trapping.

In this study, simple rules were applied to stochastically generated fracture networks of varying density. It is assumed throughout that the distribution of apertures is uniform and that the same holds true for length and orientation. Values for these quantities were chosen arbitrarily on the basis of intuitive arguments. For example, the average length of an element should be small compared with the length of the study region, and, in the absence of experimental data, distributions should be kept simple because they will probably be easier to analyze.

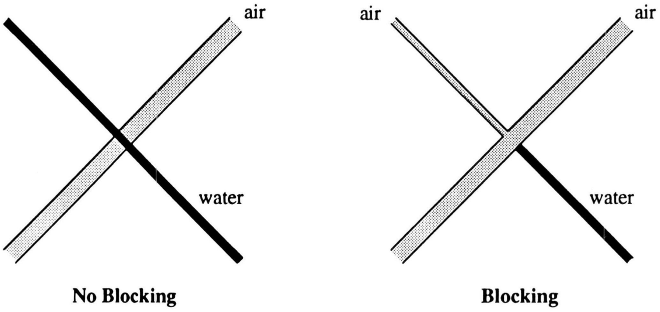

Figure 1. No-blocking and blocking assumption at a fracture intersection. [XBL 935-778]

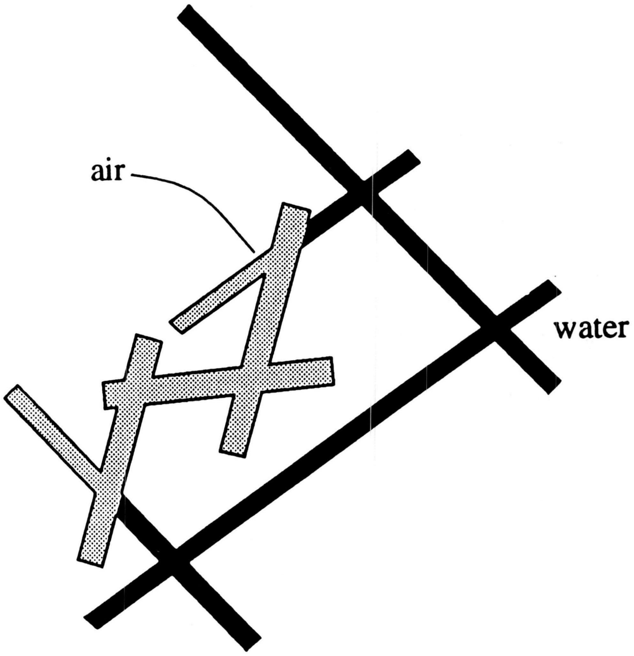

Figure 2. Trapping assumption. Air is trapped because there is no exit path for it. [XBL 935-779]

Our model ensures that flow takes place only along pathways that are geometrically connected to the inflow boundary. Among the important mechanisms represented are the blocking of a water-flow pathway by an air-filled path and the effect of trapping of either phase, leading to the phenomenon of irreducible residual saturation. In this regard, the present work goes significantly beyond previous work using percolation models that turn elements on and off without regard to physical connections while retaining the important feature of a percolation model, which is the ability to discuss a fracture network as a system of discrete objects and not as a continuum.

APPROACH

The random fracture network is generated using the fracture network generation program FMG (Billaux et al., 1989a,b). A path-tracking program, RENUM (Billaux et al., 1989a,b), is then used to trace flow paths for each phase from the boundary. RENUM was originally written to renumber the nodes of the random fracture network to minimize the bandwidth of the matrix for flow calculation and to identify and eliminate isolated clusters and dead-ends that do not contribute to flow. In the present study, some modifications were made to RENUM so that the original network can be divided into two subnetworks, one representing the elements that contribute to water permeability and water saturation and the other representing those elements that contribute to air permeability and air saturation. The assumption that only one phase may occupy a given element at a time guarantees that each element of the original fracture network is uniquely placed in one or the other of the two subnetworks. This implies that the combined saturation of the two subnetworks are exactly equal to the saturation of the original fracture network.

The capillary pressure criterion discussed previously is employed to determine which elements are eligible to belong in which subnetwork. For a given aperture size distribution, there exists a range of corresponding capillary pressure, which may be divided into a specified number of intervals (e.g., 32). For a given interval, each element with a corresponding capillary pressure that falls below the maximum capillary pressure is allowable to the air phase and any element with a capillary pressure larger than the maximum of the interval is allowable to the water phase. This implies that air will preferentially occupy the larger-aperture elements and water the smaller, which is consistent with the assumption that water is the wetting fluid in this configuration. As stated previously, allowability is not the only criterion that determines phase occupancy. Also considered is the accessibility criterion, which is determined by path connections using different assumptions regarding blocking and trapping as well as the direction of flow in the sense of imbibition and drainage. At each capillary pressure interval, two subnetworks are constructed on the basis of the above criteria. The total flow across each network is calculated using a single-phase fracture flow and transport code, TRINET (Karasaki, 1987). The corresponding saturation for either phase at each capillary pressure is calculated by summing the volume of elements occupied by the phase and dividing that by the volume of the total network. Relative permeability and capillary pressure curves are calculated by stepping through a range of capillary pressure in either the imbibition or the drainage direction. Resaturation and redrainage processes can also be simulated.

SAMPLE RESULTS

Using the computational tools described above, a detailed study of two-phase flow in fracture networks can be made. The effect of blocking and trapping on relative permeability and saturation can be examined. Figure 3 shows a sample of simulation results. The example shown is the case of blocking with no trapping under an imbibition process. It is interesting to note that the saturation changes

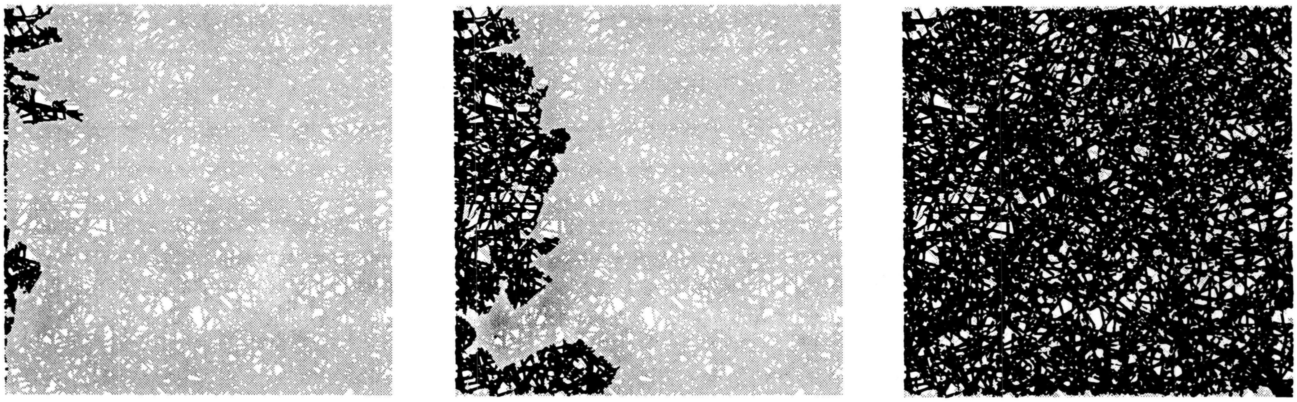

Figure 3. Imbibition from left-hand side with blocking and no-trapping assumption. [**a**, XBL 935-775; **b**, XBL 935-776; **c**, XBL 935-777]

dramatically between parts b and c of Figure 3, although there is only a very small capillary pressure increment. The relative permeability for water changes almost like a step-function, and for a wide range of saturation the relative permeability for both phases is zero (not shown). This is the result of a few bottleneck fractures with large apertures that obstruct the advancement of the imbibition front due to the blocking assumption.

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6822

A Numerical Study of the Structure of Two-Phase Geothermal Reservoirs

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Major two-phase vapor-dominated geothermal reservoirs have been exploited at The Geysers, California; Larderello, Italy; Matsukawa, Japan; and Kamojang, Indonesia. These reservoirs produce only steam and have nearly vapor-static pressure gradients at corresponding saturation temperatures. High observed upward heat transport in these reservoirs results from counterflows of vapor and liquid.

White et al. (1971) proposed a model involving counterflow of ascending steam and descending condensate that was elaborated upon by many investigators. In these models, boiling at a deep brine "water table" was assumed, with steam moving upward in large fractures along the pressure gradient produced by boiling and then condensing at the top of the reservoir because of conductive heat loss to the surface. The condensate flowed downward by gravity in the rock matrix and small fractures. However, recent discoveries in the northern part of The Geysers and some evidence from Larderello suggest that dry high-temperature rock underlies the vapor-dominated reservoir. Some wells in the Coldwater Creek field of The Geysers encounter a high-temperature zone (up to 347°C) only 200 m below the 245°C vapor-dominated reservoir. At Larderello, a number of deep wells show temperatures above 350°C.

The objectives of the present study are (1) to characterize possible thermodynamic states as well as flow structures and heat-transfer processes in typical vapor-dominated geothermal reservoirs and (2) to explain the thermodynamic conditions encountered in the high-temperature reservoirs observed in The Geysers and Larderello.

DESCRIPTION OF THE PROBLEM

A numerical study of steady-state two-phase geothermal reservoirs was performed using a two-dimensional vertical cross section of porous medium. The cross section is heated locally from below, reflecting situations where localized magmatic intrusion occurs beneath the reservoir. Figure 1 shows a schematic representation of the right half of the physical problem considered in the study. The cross