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A NUMERICAL STUDY OF WATER PERCOLATION THROUGH AN UNSATURATED VARIABLE APERTURE FRACTURE UNDER COUPLED THERMOMECHANICAL EFFECTS

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INTRODUCTION

In calculation of ground water travel times associated with performance assessment of a nuclear waste repository, the role of fractures may turn out to be very important. There are two aspects related to fracture flow that have not been fully resolved. The first is the effect of coupled thermomechanical impact on fracture apertures due to the thermal output of the nuclear waste repository. The second is the effect of the variable aperture nature of the fractures. The present paper is an exploratory study of the impact of these two effects on water percolation through unsaturated fractures.

The paper is divided into two main sections. The first section describes a calculation of the thermomechanical behavior of the geologic formation around a waste repository. In this exploratory study we assume two major fractures, one vertical and one horizontal through the repository center. Temperature and thermally induced stress fields are calculated. The second part of the paper considers the unsaturated case and describes a study of water infiltration from the land surface through the vertical fracture to the repository.

REGIONAL THERMO-MECHANICAL CALCULATIONS

Because of the radioactive decay of the stored waste, a nuclear waste repository in rock can be expected to release considerable energy over the thousands of years following its closure. This energy will give rise to mechanical stress changes and hydrologic buoyancy flow in the geologic formation. To be able to model such coupled thermo-hydro-mechanical (THM) processes in order to carry out repository performance assessment presents a considerable challenge (Tsang, 1987; 1991).

Coupled processes around a nuclear waste repository have been the subject of active research during the last few years. A far-field regional analysis was made, using the numerical code ROCMAS (Noorishad et al., 1984). This code is based on the finite element method solving the fully coupled thermal transfer, mechanical stress-strain and saturated fluid flow equations. It is thus capable of calculating the coupled THM process for the saturated system. It has been verified against a number of known solutions. In the present application, the emphasis is on the thermomechanical behavior around the waste repository.

A repository is assumed to be located at a depth of 600 m, with a length and width of 3 km. The analysis of the coupled processes is performed on a two-dimensional vertical cross section of the repository system, which is capable of simulating a worst case scenario. The modeled section has a vertical dimension of 2.2 km and a horizontal dimension of 18 km. Figure 1 shows the cross section with the vertical scale exaggerated fivefold. We include two major fractures in this section; one fracture intercepts the repository (represented by a thin disk) in its horizontal plane, and the other fracture cuts through the repository along a vertical plane of symmetry. Both fractures extend to the model boundaries. A geothermal gradient of 30°C/km is assumed to exist in the model. Material properties assumed are shown in Table 1. The repository is assumed to possess a decaying thermal power output; the power decay curve is adapted from Wang and Tsang (1980), with a 10-year cooled down power output of 14.4 W/m^2 gross thermal loading for the spent fuel. This selected power is chosen in some level of conformity with one of the scenarios of the Atomic Energy of Canada (Acres, 1978).

The nonlinearity introduced in the model is that of the two extensive fractures that pass through the model. The results reveal significant effects. We present here an example of the thermal and stress patterns 1000 years after repository closure. Figure 2 gives the temperature contours. Far away from the repository, the temperature field follows the initial geothermal gradient. The presence of the repository is accompanied by a local high-temperature region. The principal stresses at 1000 years are shown in Figure 3. Originally they are parallel to the x and z directions and increase in magnitude as a function of depth. The influence of heating from the repository and of the presence of the major horizontal and vertical fracture can be seen in this figure. The normal stress changes along the vertical fracture from the repository to the land surface range over two orders of magnitude, resulting in aperture increases near the surface and aperture decreases near the repository. This is shown in Figure 4 where is plotted the change in the aperture of the major vertical fracture as a function of depth from the surface to the repository. Thus the aperture change due to the thermomechanical effect is not uniform over the fracture. This may have certain implications to water percolation through such an unsaturated fracture.

WATER PERCOLATION THROUGH A VARIABLE APERTURE FRACTURE

The next stage of the calculations then assumes an aperture change in the vertical fractures such as that in Figure 4 and the effect of water percolating through this fracture is studied under the effect of thermomechanical processes. In the above calculation a major fracture is assumed. In actual conditions, this may represent a vertical fracture zone including a large number of narrow fractures. In what follows, let us consider one of these narrow fractures (with smaller apertures and changes). A typical section of a fracture has apertures which are varying and is here represented by a grid which is 40 x 40 (Figure 5). At each mesh element, the apertures are of a different value, which are generated geostatistically based on a log normal distribution of aperture values. The physical phenomena involve gravity, capillary force at each aperture values, and the permeability to the water flow. A numerical method is adopted which calculates water percolation step by step without going through the complete solution of differential equations. Assuming that the water percolation would take the step that represents the maximum flow effects due to both the gravity and capillary potentials, we calculate step by step the flow of water through the system. An example of such a percolation from the top of the fracture to the bottom is shown in Figure 6. The shadings over the fracture area represent the magnitude of fracture apertures. This could vary by one or more orders of magnitude. The white areas represent the water that has percolated downward. It is seen that the water does not fill the whole fracture, but rather, it tends to seek out the path of the smallest aperture where the capillary effect is the largest. In the next step of calculation we take the result from the coupled thermomechanical modeling giving the change in aperture of the fractures. Assuming that the fracture is opened near the top, the flow pattern of the fluid percolation is calculated. In some of the cases studied, it is found that the flow pattern is strongly affected even when the change is no more than 25 micrometers in a fracture with a mean aperture of 50 micrometers. Thus initially before thermomechanical effect is significant (say at early years after waste emplacement in the repository), water may percolate along paths shown in Figure 6. After the thermomechanically induced aperture changes, percolation may seek out new paths. One consequence is that new fracture surfaces are coming into contact with the water and become available for chemical interactions with solutes carried by the water.

CONCLUDING REMARKS

A series of scoping exploratory simulations were made. These calculations show that the thermomechanical effect due to the repository on the fractures is an important consideration. The induced changes of apertures will give rise to alternative flow paths for the percolation of water. This will have a significant effect on surface sorption phenomena because fresh fracture surfaces are now in contact with the percolated water. Analysis is continuing and we will study the total effect of such phenomena on the travel times of flow and of solute transport.

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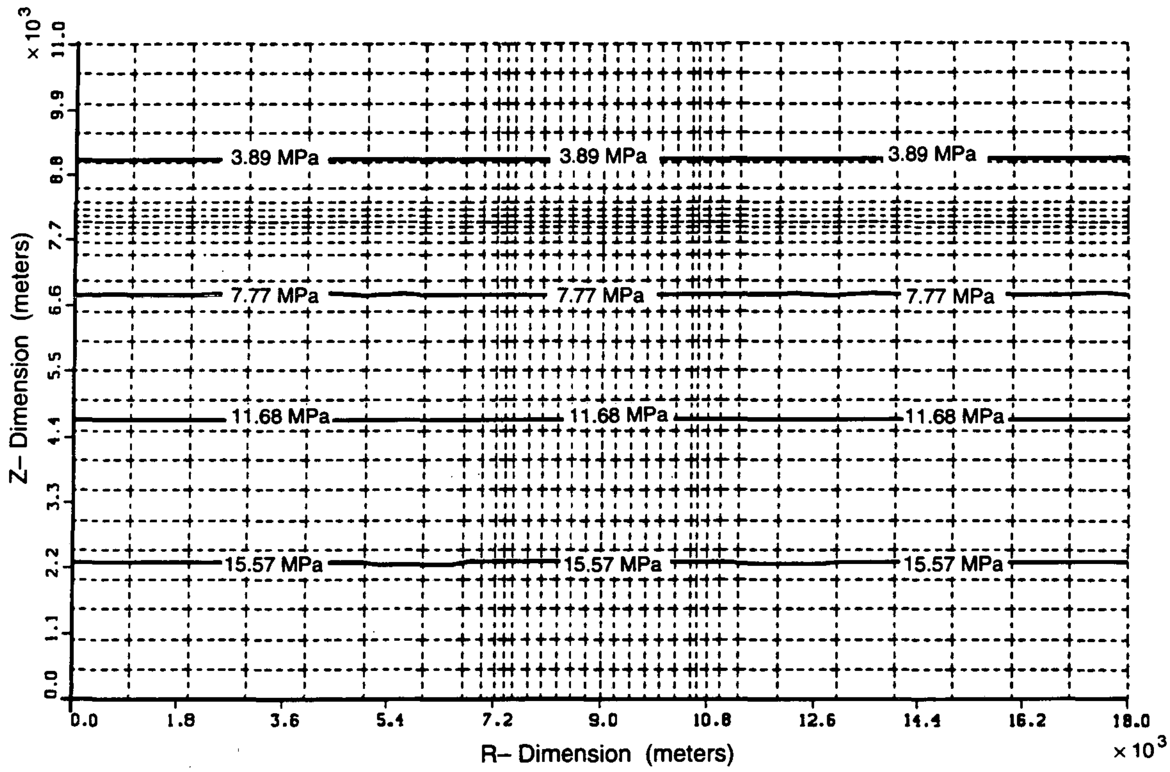

Figure 1. Diagram of model with vertical scale exaggerated fivefold.

Table 1. Material properties used for various runs with ROCMAS.

Material	Parameter	Laboratory/field* data	Modeling data
Fluid:	Mass density, r_l		997 kg/m^3
	Compressibility, b_p		5.13×10^{-1} GPa^{-1}
	Dynamic viscosity at 20°C, n_l		1×10^{-3} N/m^2
	Thermal expansion coefficient		3.17×10^{-4}°C^{-1}
	Specific heat		1.0 kcal/kg
Rock:	Young's modulus, E_s	80 GPa	35 GPa
	Poisson's ratio, v_s	0.25	0.25
	Mass density, ρ_s	2.9×10^3 kg/m^2	2.9×10^3 kg/m^3
	Porosity, ε		0.015
	Intrinsic permeability, k		10^{-20} m^2
	Biot's constant, M		130 GPa
	Biot's constant, α		1.0
	Thermal expansion coefficient		1.1×10^{-5}°C^{-1}
	Specific heat		2×10^{-1} kcal/kg
	Solid-fluid thermal conductivity		6.9×10^{-4} kcal/m·s·°C
*Fracture:	Initial normal stiffness, K_n	1620 GPa/m	1620 GPa/m
	Initial tangential stiffness, K_s		3 GPa/m
	Initial aperture, b	17 microns	17 microns
	Porosity, ε		1.0
	Biot's constant, M		2 GPa
	Biot's constant, α		1.0
	Radius, r		1.2 m
	Initial normal stress, σ_0	10.2 MPa	8.6 mpa

*Energy transport in fractures presumed to be negligible.

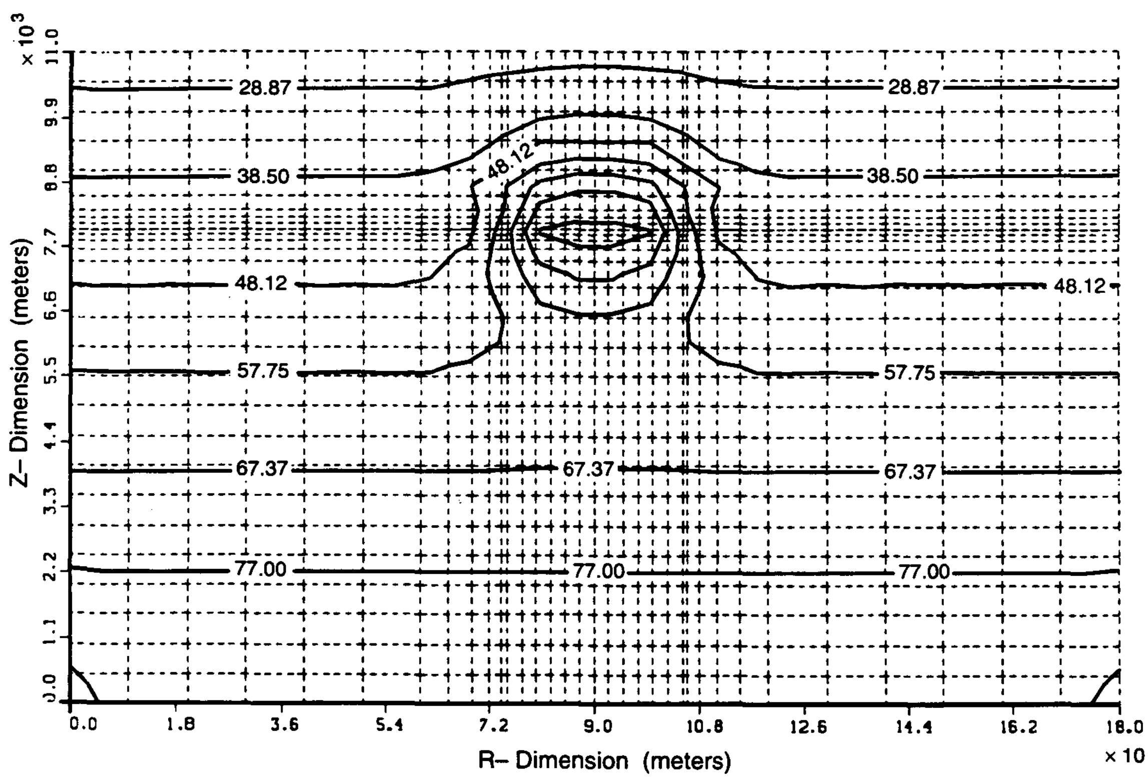

Figure 2. Temperature contours at 1000 yr.

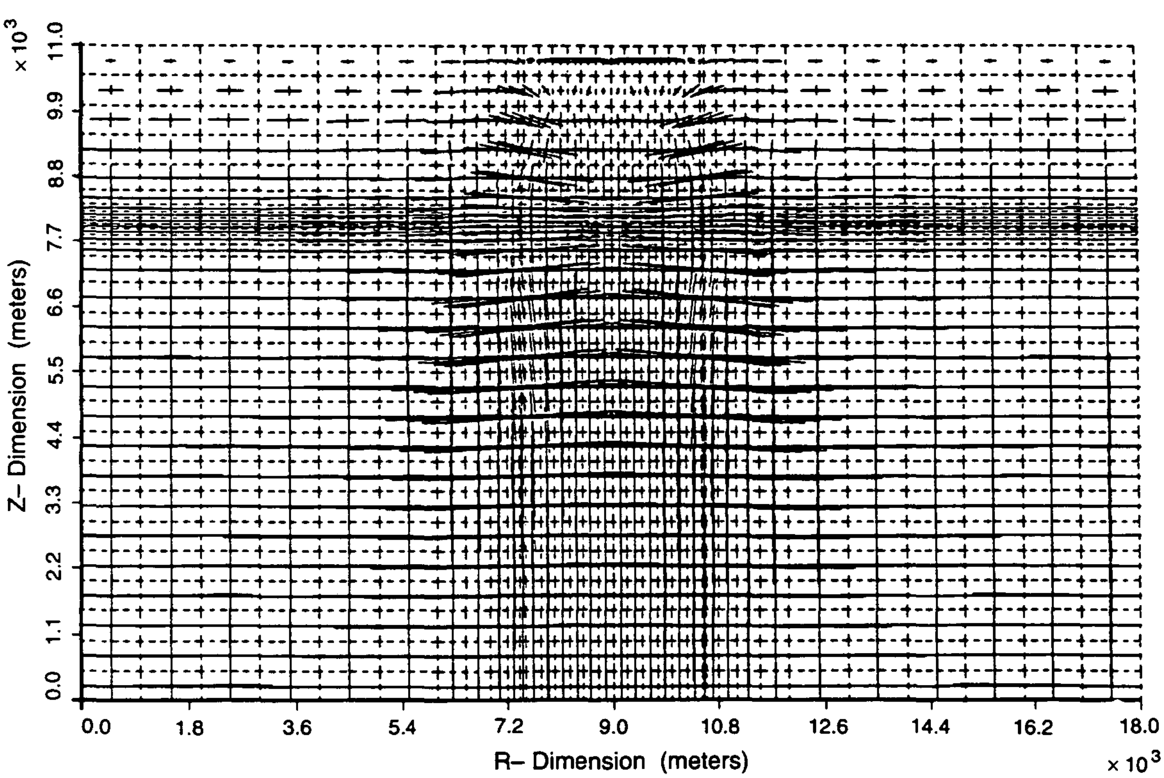

Figure 3. Principal stresses at 1000 yr.

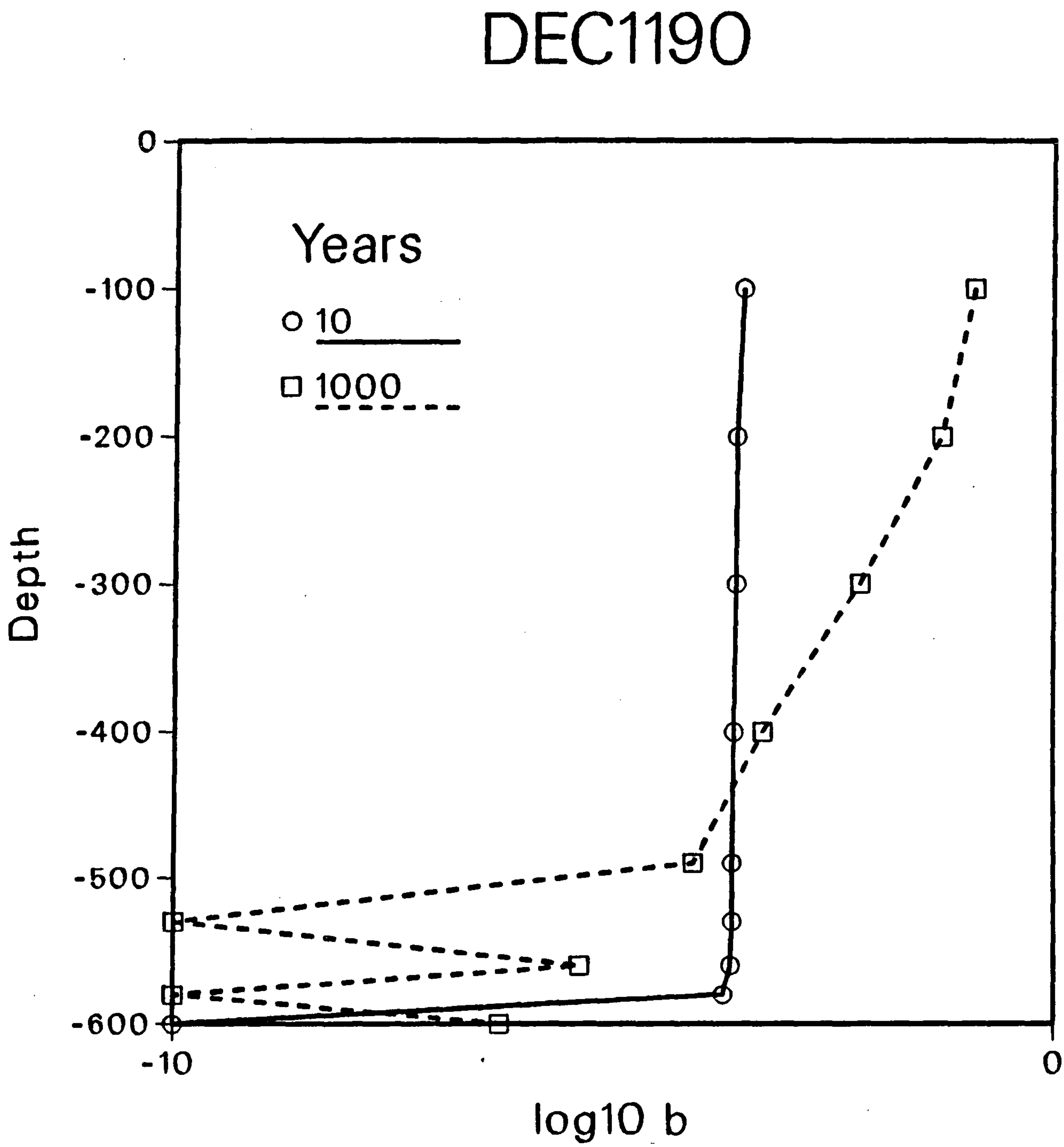

Figure 4. Change in aperture of a hypothetical major vertical fracture (or fracture zone) from the ground surface to the repository center due to thermomechanical effects.

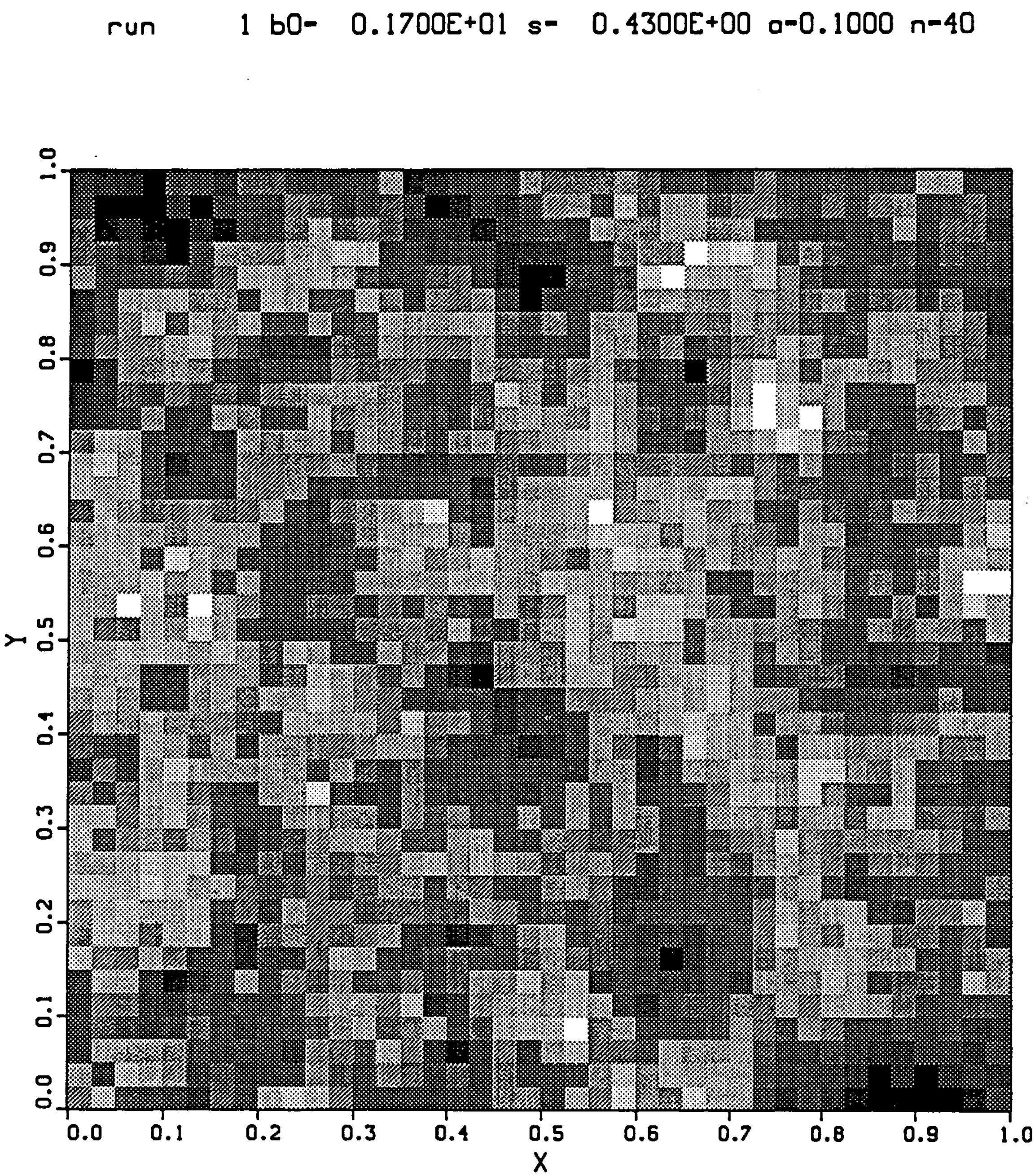

Figure 5. A hypothetical vertical fracture with variable apertures: the darker the shading, the smaller the apertures. The mean aperture is 50 μm.

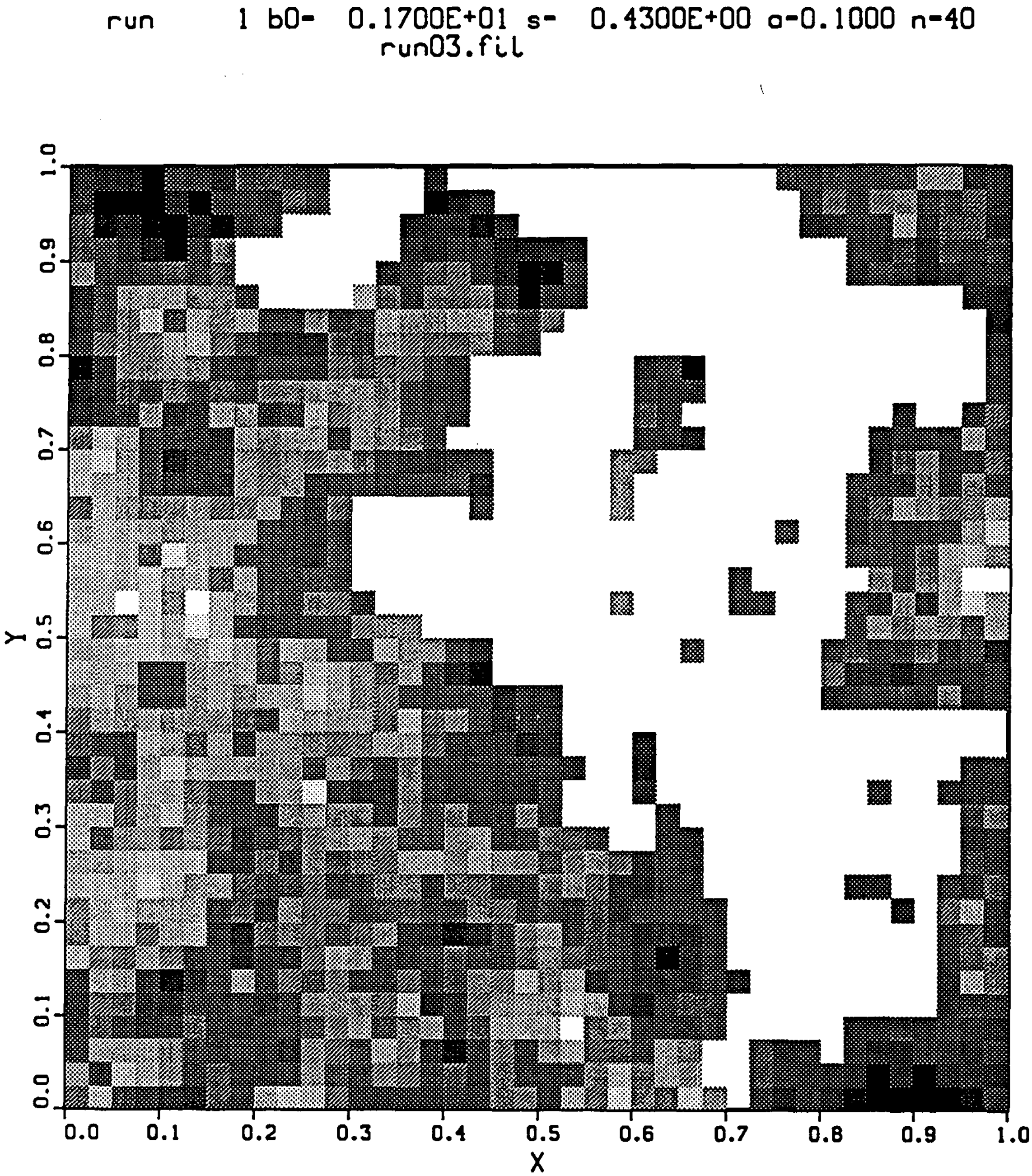

Figure 6. Water percolation through the variable-aperture vertical fracture shown in Figure 5 under gravity.

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