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# FRACTURE NETWORK MODELING OF HIJIORI HOT DRY ROCK RESERVOIR BY DETERMINISTIC AND STOCHASTIC CRACK NETWORK SIMULATOR (D/SC)

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## ABSTRACT

D/SC (Deterministic / Stochastic Crack network simulator) is a fracture network modeling system with a new technique for building a fracture network by using combined deterministic and stochastic information for the fractures. The basic concept is to put fractures into the model directly if their features have been determined, and to interpolate the space in between by stochastic fractures which follow the statistical properties of the reservoir. The model with a number of discrete fractures is then converted to a continuum mesh whose elements have equivalent permeability to the fracture network. Finally, the pressure and flow vector at every element is calculated. The advantage of this approach is that the various kinds of data obtained from the reservoir can be utilized in describing the characteristics of the reservoir.

In this paper, fracture network models for the Hijiori HDR reservoir are investigated by using the D/SC simulator. A comparison of the three types of models gave us several valuable understandings of the D/SC simulator and the Hijiori HDR reservoir.

## 1. INTRODUCTION

Since 1984 the New Energy and Industrial Technology Development Organization (NEDO) has been conducting a Hot Dry Rock (HDR) Geothermal Project at the Hijiori test site, Yamagata, Japan. One of the required tasks for HDR development is to characterize the reservoir and to predict its future hydraulic and thermal performance. For this, modeling of the reservoir is necessary. Various kinds of borehole measurements and hydraulic experiments have shown that the flow paths and reservoir volume in the HDR reservoir consists of a fracture network. The integrated interpretation using the accumulated data sets, such as oriented cores, BHTV, PTS logs and microseismic events, led to the idea that the growth of the reservoir was strongly controlled by the distribution of favorably oriented fractures, i.e.; critically stressed fractures (Tezuka and Niitsuma, 1997). However, it is still difficult to build a reliable fracture network model by using only the fracture information obtained by field measurements, because the detected fractures lie mostly along the borehole. For these reasons, a stochastic approach for filling in the rock volume with reasonable fractures was proposed (Watanabe, 1995).

D/SC (Deterministic / Stochastic Crack modeling system) is a fracture network model simulator with a new technique for building a fracture network by using combined deterministic and stochastic information for the fractures. An advantage of this approach is that the various kinds of data obtained from the reservoir can be utilized in describing the characteristics of the reservoir. Another advantage is the flexibility for including various conditioning factors such as the mechanical properties of the rock and the surrounding stress state (Willis-Richards et al., 1996).

In this paper, we first overview the concept and the basic flow of D/SC modeling, then apply the D/SC simulator to the Hijiori HDR reservoir.

## 2. D/SC

### 2.1 Concept and Basic Flow

Fig. 1(a) shows the basic flow of the D/SC modeling. The first step is to extract the deterministic and stochastic features of fractures from the field data set. Next, using the evaluated features a fracture network is generated. The fracture network model is then converted to a continuum mesh whose elements have equivalent permeabilities to the discrete fractures. Finally, the pressure and flow vectors at every element are calculated. For the stochastic model, a number of realizations are necessary to process the results in statistical a manner. The final outputs from this modeling are also provided in a statistical format as probability distribution functions. Of most significance is building the fracture network. The detailed flow of the builder part is shown in Fig. 1(b). The basic concept is to put fractures into the model directly if their features can be determined and otherwise to interpolate the volume by stochastic fractures which follow the statistical rules derived from the fracture system. In the Hijiori case, borehole televiewer (BHTV) and PTS log data are used to determine the deterministic fractures. For the stochastic fractures, core, BHTV, neutron/density log and microseismic events are used. From these data, four types of stochastic fracture parameters are extracted. Those are an aperture distribution, an orientation distribution, an averaged porosity (eventually this becomes matrix permeability) and a spatial distribution. In addition to these stochastic parameters, a size distribution is necessary. However, it is difficult to get the size of the subsurface fractures by direct measurement. Thus, we made the assumption that there was a relationship between the fracture aperture and the fracture size. Then we adopted the following equation proposed by Vermilye and Scholz (1995).

$$a = \alpha \sqrt{r} \tag{1}$$

where $a$ is the fracture aperture, $r$ is the fracture radius, and $\alpha$ is the factor which controls the relationship between the aperture and the radius. $\alpha$ is the field dependent factor and requires a careful choice for the value. In the Hijiori case, the value is evaluated by a parameter study that will be described later.

### 2.2 Water Flow Analysis

For numerical calculations, the volume of interest is divided into a mesh of small elements as shown in Fig. 2. In the D/SC simulator, the equivalent local permeability caused by fractures is given between elements in the mesh where fractures intersect element interfaces as shown in Fig. 3. Although the apertures of natural fractures are not spatially uniform, it is assumed that water flow can be approximated as that in a parallel-sided fracture with some constant aperture. The quantity of water flowing between the elements can be expressed by the cubic law as illustrated in Fig. 3.

## 3. CASE STUDY

### 3.1 Fracture Information

Fracture information for the Hijiori HDR reservoir is summarized as follows.

Fracture Aperture

Fracture apertures and their populations are measured by using oriented cores obtained from well HDR-3. Fig.4 shows the relationship between the fracture aperture (*a*) and the cumulative number of fractures (*Nba*) whose apertures are larger than *a*. The plot shows a linear relationship in a log - log scale that means the distribution follows the fractal rule. We adopted this fractal characteristic for generating stochastic fractures in the modeling. The exponential constant (fractal dimension) derived from the slope is -1.43.

Fracture Orientation

An orientation distribution of fractures is investigated by using BHTV images obtained from wells HDR-2a and HDR-3. Fig.5 shows the stereo projection of fracture poles to the lower hemisphere. North dipping fractures are dominant in the Hijiori reservoir. These types of fractures are supposed to be critically stressed fractures. In other words, these fractures are favorably oriented to provide principal flow paths (Tezuka and Niitsuma, 1997). The probability distribution of the fracture orientations is derived from Fig.5 by taking into account the well crossing probability as a function of fracture dipping angle.

Producing Zones

PTS production logs provide the depth of producing zones, production rate (fraction), and reservoir pressure (Miyairi and Sorimachi, 1996). A combined interpretation of the producing zones and the BHTV fracture data has the potential to highlight the fractures that are possibly contributing to the fluid production, those are features of primary importance for the fracture network model. The observed feature, that the producing zones are located roughly every hundred meters in both wells HDR-2a and HDR-3, is also the important characteristics of the Hijiori reservoir.

Averaged Fracture Porosity

The neutron log and the density log in combination represent a measure of the fracture density in the case of the fractured reservoir in hard basement rock, rather than the formation porosity as in sediments. The reading can be used to map the fracture distribution in both deterministic and stochastic senses. The averaged porosity is a good constraint on the range of the fracture size distribution. Eventually, it defines the minimum size fracture and the equivalent matrix permeability. The averaged porosity around the Hijiori reservoir is estimated to be 3.6% from the neutron log and 3.4% from the density log.

### 3.2 Model Frame Setting and Boundary Conditions

The following is a summary of the assumptions we made for fracture network modeling of the Hijiori HDR reservoir.

- Fractures are circles.
- Fracture aperture follows the statistical distribution evaluated by the oriented core analysis.
- There is a relationship (eq. (1)) between the fracture radius and the aperture.
- Fracture orientation follows the statistical distribution evaluated from the BHTV analysis.
- Spatial distribution is random.

The size of the model is 1 cubic km whose center is at 2km below the well head of HDR-1. The model is divided into a 50 by 50 by 50 mesh with elements of 20 cubic m. The boundary condition is the well head pressures of HDR-1, HDR-2a and HDR-3. The wellhead pressures of these wells, and the injection interval in HDR-1 and the openhole intervals of the production wells are set as follows,

| | | |
|---|---|---|
| -HDR-1: | 1.45MPa, | 2160m - 2200m (injection interval) |
| -HDR-2a: | 0MPa, | 1500m - 2200m (openhole interval) |
| -HDR-3: | 0MPa, | 1500m - 2200m (openhole interval) |

The surrounding outer boundaries of the model are treated as a drain by setting the pressure to be hydrostatic. The top and bottom outer boundaries are treated as non-permeable.

### 3.3 Effect of parameter $\alpha$ and $r_{\max}$

All parameters except for $\alpha$ and $r_{\max}$ can be assumed or estimated from field measurements. $\alpha$ is a field dependent value which relates the fracture aperture distribution to the fracture radius distribution. $r_{\max}$ is an upper bound of the fracture size distribution, which might be influential on the model characteristics. Thus, prior to building a realistic fracture network model, a sensitivity analysis for both parameters was done to find the appropriate values. For this study a purely stochastic fracture model, which does not include any deterministic fractures, is used. Parameter $\alpha$ eventually controls the number of fractures involved in the model. A small value of $\alpha$ gives a large number of fractures. Generally, small values of $\alpha$ and $r_{\max}$ generate a relatively homogeneous fracture network which shows a monotonous flow profile as shown in Fig.6(a). Conversely, larger values of $\alpha$ and $r_{\max}$ generate fracture networks in which some larger fractures dominate the flow. This type of model results in a flow profile with some discontinuous steps like a stair as shown in Fig.6 (b). The PTS logs in the production wells HDR-2a and HDR-3 show flow profiles with some discontinuous steps which correspond to producing zones located roughly every hundred meters. By comparing the simulated flow profiles and field profiles, the proper values for $\alpha$ and $r_{\max}$ are defined as follows,

$$\alpha = 4.0\times10\text{-}3$$

$$r_{\max} = 200\text{m}$$

### 3.4 Fracture Network Models

Three types of models are investigated. The first one is a purely stochastic model with the defined stochastic parameters. The second is the stochastic model with a single-major deterministic fracture whose radius is 200 m (MODEL2). The third one is the stochastic model with multi-medium deterministic fractures (MODEL3). The model configurations are shown in Fig.7. The single-major deterministic fracture in MODEL2 simulates the direct connection between the major injection zone of HDR-1 and the major producing zones of HDR-2a and HDR-3 in the deep reservoir. The multi-medium fractures in the deep reservoir in MODEL3 simulate the producing zones along HDR-2a and HDR-3 whose dip and azimuth angles are given by BHTV data. The radii of multi-medium fractures are set to 50 m so as not to intersect the other well directly. In addition to the deterministic fractures mentioned above, both models include three deterministic fractures in the shallow reservoir. They represent the producing fractures which have been evaluated by PTS logs during the 90-day-circulation test in 1992.

### 3.5 Results of flow simulations

One hundred simulations are performed for each model by changing the random series. The results are shown in Fig. 8 with the following three kinds of plots.

- Recovery rate of the production well, HDR-2a and HDR-3
- Flow profile of wells HDR-2a, five examples
- Flow profile of well HDR-3, five examples

In the recovery rate figures, the dark and light columns are for the contribution of well HDR-2a and HDR-3, respectively. The lower-most plots are the flow profiles along the production wells evaluated by PTS logs in the circulation test in 1995. The flow property for each model, inferred from the results, is as follows.

MODEL1

The hydraulic properties of the purely stochastic model such as recovery rate varies widely with different random series, even if the stochastic parameters of the models are the same. However, the average of 59.3% is not far from the actual recovery rate of 56% recorded during steady state operation during the circulation test in 1995. The flow profiles along the wells have some discontinuous steps corresponding to the major producing zones. The overall profiles are roughly consistent with the evaluated field flow profiles. This is because of the proper setting of parameters $\alpha$ and $r_{\max}$.

MODEL2

The hydraulic performance of the stochastic fracture network model becomes stable by putting in some deterministic fractures. Especially, the fracture intersecting the injection interval has a significant effect. But, the averaged recovery rate of 73% is much higher than that for the field experiment. This is because of the highly conductive single-major fracture that produces up to 70% of the total production. The simulated flow profiles of HDR-2a look very similar to the field flow profile.

MODEL3

The stability of the hydraulic performance of this model ranges between MODEL1 and MODEL2. The averaged recovery rate is 68.9%, approximately 5% smaller than for MODEL2. This is because of the reduction of transitivity between the injection well and the production wells due to the lack of the direct connection provided by the deterministic fracture. The flow profiles along the wells show discontinuous steps similar to MODEL1. However, the variation of profiles is converged more than MODEL1, due to the deterministic multi-medium fractures. The flow profiles of HDR-3 look very similar to the field flow profile.

### 3.6 Discussions

The following understanding of the D/SC simulator and the Hijiori fracture network models was revealed through studies of the three types of proposed fracture network models.

- A purely stochastic model has a wide variation in its hydraulic properties with different random series, even if the stochastic parameters are constant.
- Deterministic fractures have an effect on stabilizing the variations of hydraulic properties. Especially, the fracture crossing the injection interval has a significant effect.
- The single-major deterministic fracture model (MODEL2), shows very similar flow profiles to the field flow profile of the well HDR-2a, and the multi-medium deterministic fractures model (MODEL3) shows similar flow profiles with those of HDR-3. This implies that a direct connection by the single-major fracture occurs between the injection well and HDR-2a, but not between the injection well and HDR-3.
- The models with deterministic fracture (MODEL2 and MODEL3) show higher recovery rates than the field experiments. This fact suggests that other flow paths are necessary that lead the water outside the reservoir.
- The simulated contributions of wells HDR-2a and HDR-3 to the total production are between 7:3 to 6:4 for all models. This range is roughly consistent with the field experiment. This fact suggests that the flow contributions may not be controlled as much by the heterogeneity of transmisivity between the injection well and each production wells, as by the relative spatial positions of the three wells.

## 4. CONCLUSION

We propose a technique to build a fracture network model by using stochastic and deterministic information on fractures obtained by field measurements. The simulator called “D/SC” has realized this technique. D/SC has the advantage that most of the various kinds of measured data obtained from cores, BHTV, PTS logs, Neutron / Density logs, and microseismic signals, can be utilized for describing the characteristics of the reservoir. We applied this technique to the Hijiori HDR reservoir. By studying three types of models, one pure stochastic fracture network model and two models with deterministic fracture sets in the stochastic fracture network, several helpful understandings about the Hijiori reservoir are obtained as described in the discussion. Those understandings are also helpful to improve D/SC modeling and to reach a more reliable fracture network model for the Hijiori HDR reservoir.

## ACKNOWLEDGMENT

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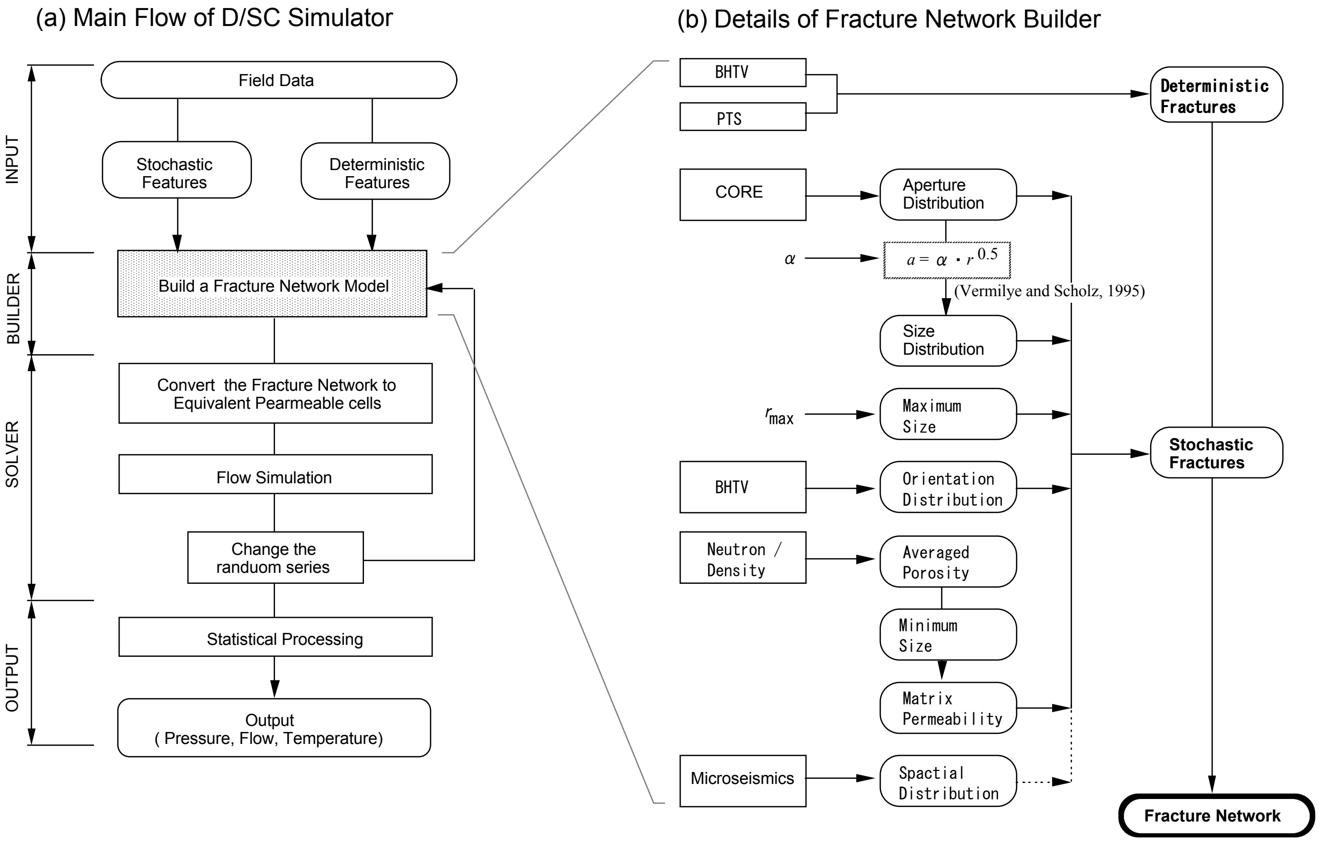


Fig.1: Flow Chart of fracture network modeling by D/SC(Left: Main flow, Right: Detail of fracture network builder)

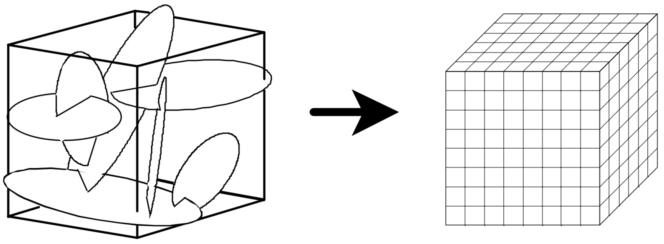
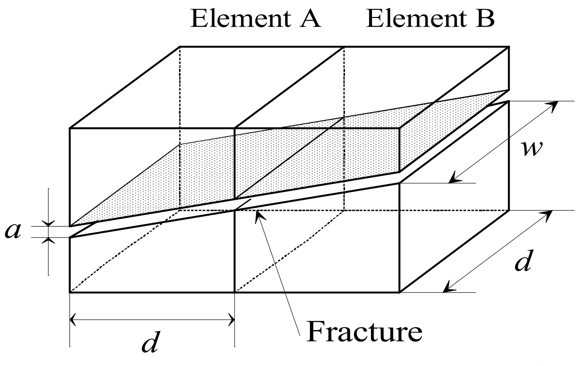


Fig:2 Conversion of fractures to continuum mesh



$$Q\ (m^3/s) = w \cdot \frac{a^3}{\mu} \cdot \frac{\Delta P}{d}$$

Fig. 3: Equivalent permeability between elements

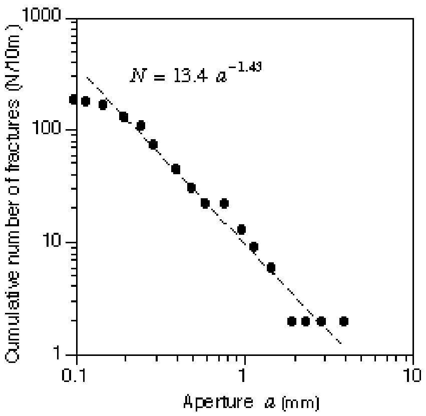


Fig. 4: Fracture aperture and its cumulative number

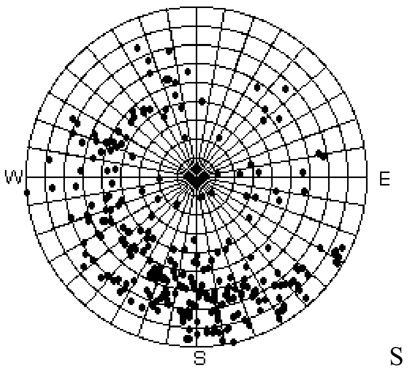
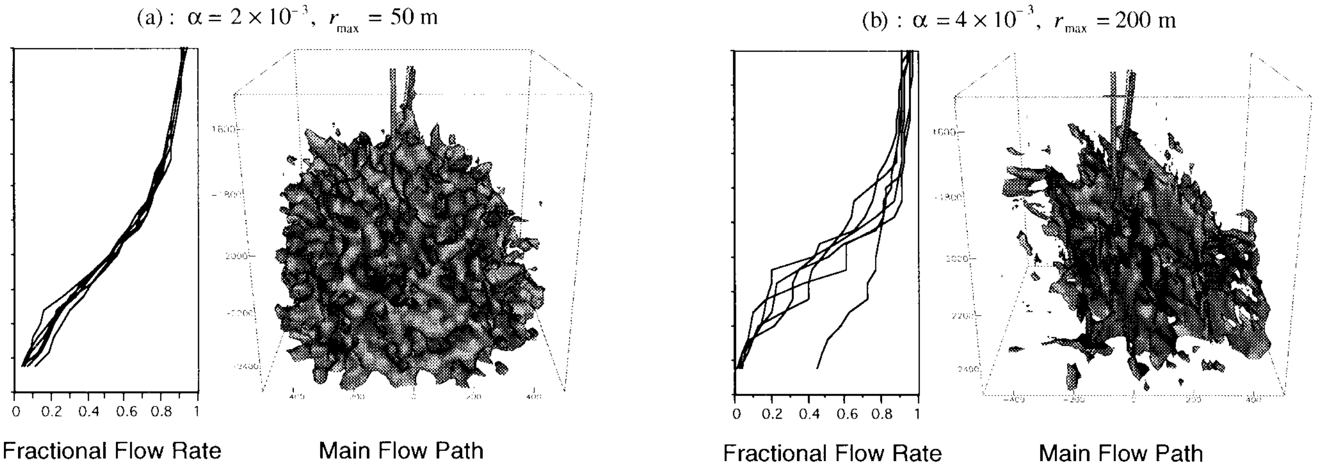


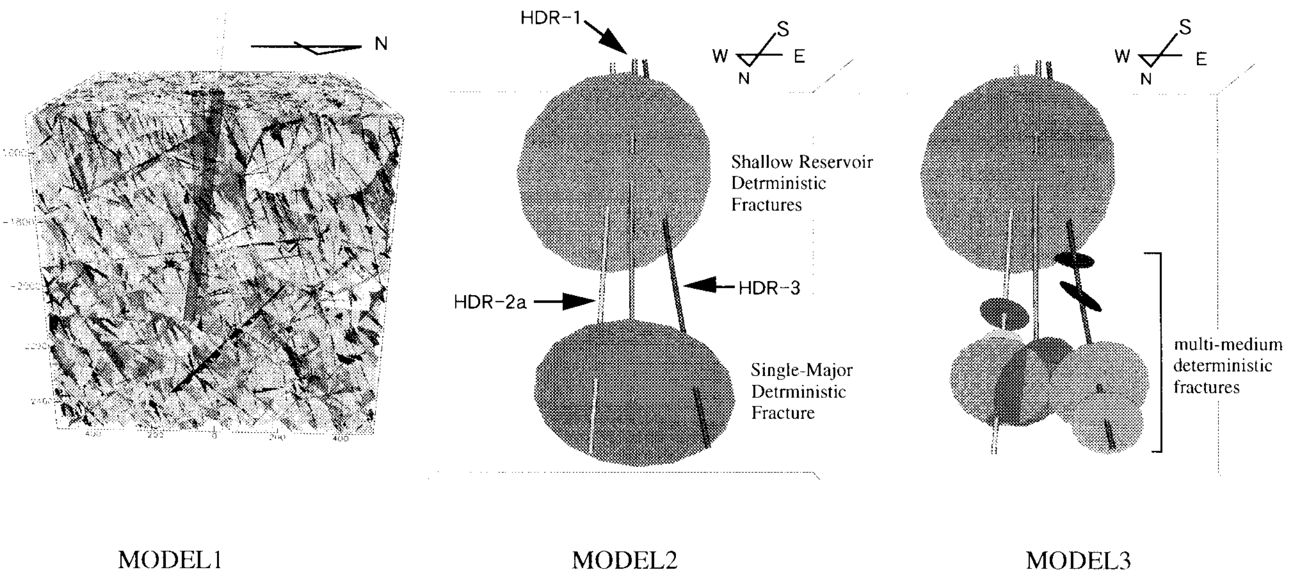
Fig. 5: BHTV fracture poles (lower projection)



(a) : $\alpha = 2 \times 10^{-3}$, $r_{\max} = 50$ m

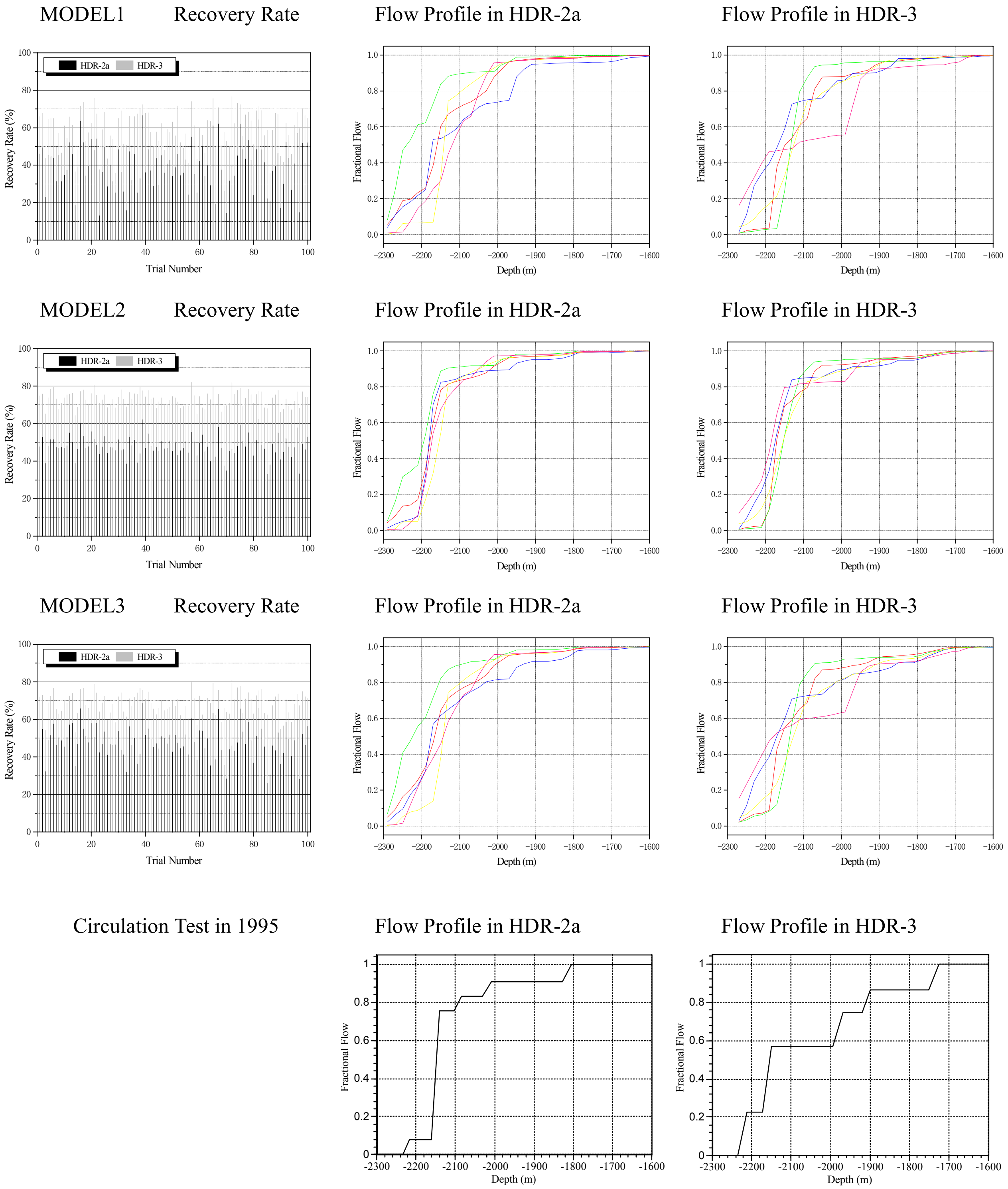
(b) : $\alpha = 4 \times 10^{-3}$, $r_{\max} = 200$ m

Fig. 6: Effects of parameter $\alpha$ and $r_{\max}$. Generally, small values of $\alpha$ and $r_{\max}$ generate relatively homogeneous fracture network which shows monotonous flow profile (a). Conversely, bigger values of $\alpha$ and $r_{\max}$ generate fracture networks in which some larger fractures dominate the flow (b). This type of model results in a flow profile with some discontinuous steps like a stair. Simulated major flowpaths for the stochastic fracture network models with various $\alpha$ and $r_{\max}$.
It is obvious that the flow pattern changes with different $\alpha$ and $r_{\max}$ values.



MODEL1 MODEL2 MODEL3

Fig. 7: Three types of fracture network models used in this study. MODEL1 is the purely stochastic fracture network model, MODEL2 is the stochastic fracture with Single-Major deterministic fracture, MODEL3 is the stochastic fracture with Multi-medium deterministic fractures.



MODEL1 Recovery Rate

Flow Profile in HDR-2a

Flow Profile in HDR-3

MODEL2 Recovery Rate

Flow Profile in HDR-2a

Flow Profile in HDR-3

MODEL3 Recovery Rate

Flow Profile in HDR-2a

Flow Profile in HDR-3

Circulation Test in 1995

Flow Profile in HDR-2a

Flow Profile in HDR-3

Fig.8: Results of flow simulation for MODEL1 to MODEL3. Recovery rates, flow profiles in HDR-2a and HDR-3 are presented for each model. The bottom plots are the flow profiles evaluated by PTS logs in the circulation test in 1995.