

The reliability of a stochastic fracture generator

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Abstract The use of the discrete modelling approach to simulate flow and transport processes in fractured porous media requires the discrete description of the fractures in space. Therefore, the fracture generator provides the geometric description of the fractures within the considered aquifer system. The description of the fractures is based on different types of data which are recorded in the field and approximated by theoretical distributions. In this paper, we present the development of a stochastic fracture generator to create fracture networks in three dimensions, where the fracture planes are represented by two-dimensional quadrilateral elements. We will investigate the use and the reliability of the stochastic generated fracture models with respect to the determination of effective parameters, e.g. the effective hydraulic conductivity.

INTRODUCTION

Fractured porous media combine fractures, fissures, and the surrounding rock matrix. Fractures have a high permeability and a low storage capacity. Conversely, the matrix has a lower permeability and a higher storage capacity. These differences lead to very complex behaviour of the system at different time and length scales. In order to characterize the system behaviour of a fractured porous medium with respect to a certain question formulation, one may use the powerful tool of numerical flow and transport models. The discrete modelling approach requires the description of the fractures by a geometric model. In a further step, a powerful net-generator has to be applied in order to produce a suitable mesh on which one can solve the flow and transport equations by applying numerical methods like the Finite Element or Finite Volume method (e.g. Helmig, 1997).

The fracture generating algorithm requires the geometric characteristics of the fractures; these are obtained by investigating core samples and outcrop sites (e.g. Hötzel, 1997; Teutsch *et al.*, 1997). The information which are gained from these samples and locations have a one- and two-dimensional (1-D and 2-D) character. One problem in generating a stochastic fracture field, particularly a three-dimensional (3-D) fracture field, is immediately obvious: the information content of the data does not allow for the strong 3-D behaviour of a fractured porous medium. The reliability of such stochastically generated geometric models strongly depends on the qualitative and quantitative description of the aquifer system. We focus on the question of how to combine different types of field information in a generating algorithm in order to provide geometric fracture models which reflect the real aquifer properties more realistically.

GEOMETRIC MODEL

There are three basic approaches to building a geometric model and these are briefly discussed here in the context of how to generate a reliable fracture network model. The first is the deterministic approach. The deterministic application requires exact information about, for example the fracture network and a single fault zone. A major problem with this approach is that one has to derive a 3-D system out of 1-D and 2-D information. Often this is not possible because of lack of information as mentioned previously. The second approach is the stochastic one. The field parameters are described by parameterized theoretical distributions such as the Fisher distribution for spherical orientation, or the exponential distribution for the trace lengths. These applied theoretical distributions are based on linear statistics. They do not include any information about the spatial variability of the data. The third approach, geostatistics, allows use of information about the spatial variability of the data.

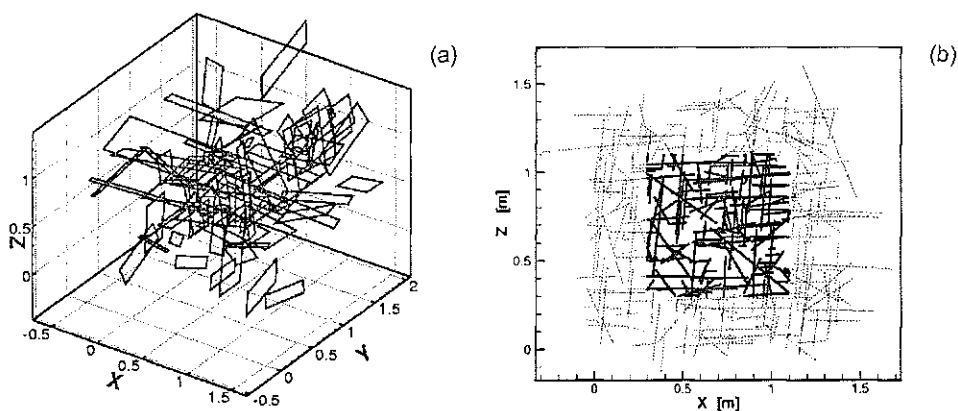


Fig. 1 Different fracture systems: (a) 3-D fracture network (fractures as 2-D quadrilateral elements in space); (b) 2-D fracture network (fractures as 1-D elements).

Based on the stochastic approach, we developed a fracture generator which creates fracture networks in 3-D, where the fracture planes are represented by 2-D quadrilateral elements and as 1-D elements in a 2-D clipping plane. A 3-D realization and a 2-D clipping plane can be seen in Fig. 1. The figure shows that in order to avoid generating errors at the outer domain boundaries, a subdomain is cut out of the 3-D and 2-D domain. The generating algorithm requires the following input parameters: fracture density, spatial orientation (Fisher distribution), trace length (exponential or Erlang2 distribution), fracture aperture (lognormal distribution). Single known fracture planes or fracture trace lines can be added to the generated fracture system. Information on the trace distance (exponential distribution) is not yet included. However, it has been shown that the connectivity of a fracture network strongly depends on the density, fracture length, and, additionally, on the distance between the fractures. These parameters control the percolation threshold at which local fracture clusters form a global fracture cluster. Further work will also include the important information on the distance between fractures in the generating algorithm.

In addition to the stochastic application, one can use major parts of the source code to build fracture network systems according to the deterministic approach. An example is shown in Fig. 2. Here, we try to reconstruct a fracture network system out of a core sample. The shell of the core sample serves as input data.

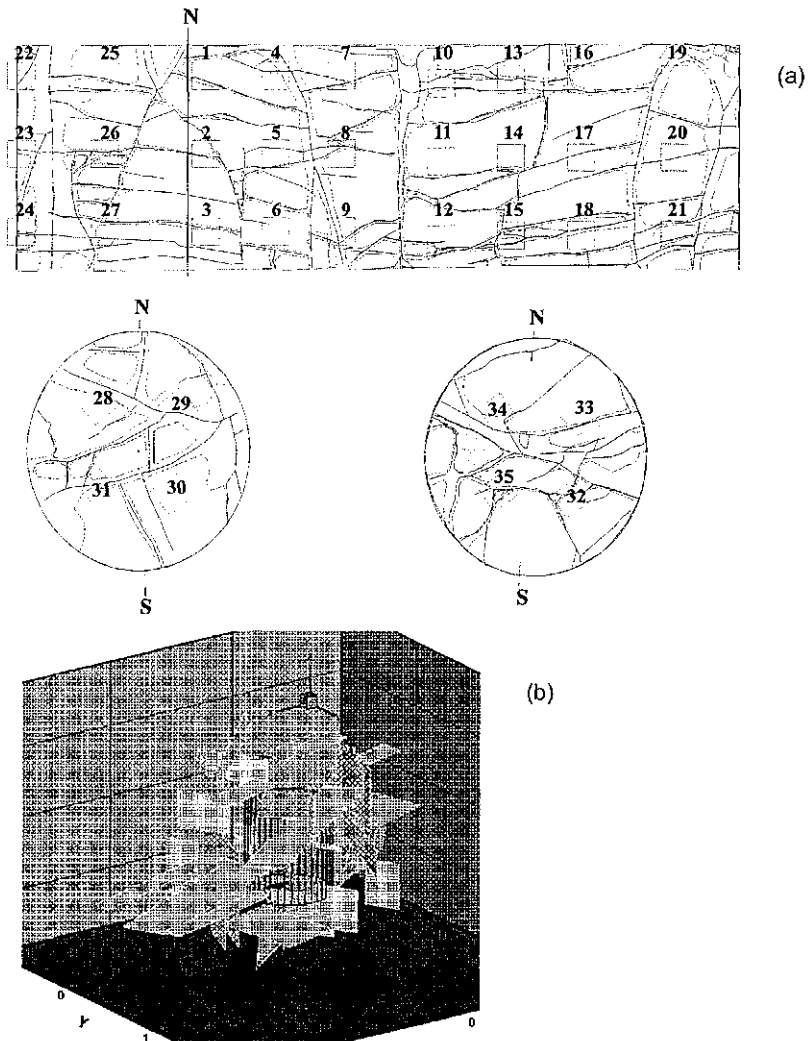


Fig. 2 (a) Shell of a core sample (McDermott, 1999). (b) Generated fracture model: combination of the deterministic and stochastic approach

GEOMETRIC MODEL vs REALITY

In comparisons of a stochastic geometric model with the real system on which the stochastic model was based, one never sees the exact system. It is possible to create different realizations, which are similar in regard to their statistical description. But a realization can not exactly predict the system behaviour at a certain point. Therefore,

one has to focus on a lot of realizations. Based on them, system properties including the effective conductivity and the effective dispersion of the system can be investigated and calculated (Hemminger *et al.*, 1998). However, one has to be aware that single fractures sometimes can control a whole fracture network. They can connect different independent fracture clusters. If such dominating fractures are known and can be described by their orientation and dimensions, a combination of the deterministic and the stochastic approach would improve the reliability of the generated fracture system.

We use the stochastic fracture models to investigate and calculate effective parameters, e.g. effective hydraulic conductivity (see e.g. Long, 1983; Cacas *et al.*, 1990), which are included in multicontinua models (Köngeter *et al.*, 1997). Effective parameters enable the description of processes and effects which occur on a smaller scale. The small scale property which is responsible for these effects can not be included in a higher scale model, because the information degree is too high or the equations applied in the higher scale model, can not use the information about the small scale properties. Hence, averaged model parameters are applied in order to describe small scale processes in a higher scale model.

Figure 3 shows a 2-D fracture network model with a fracture density of 100 (fracture m^{-2}) and the calculated effective hydraulic conductivity of this network system. On the right of the figure, the thin lines indicate different realization results and the thick lines depict the averaged value of the hydraulic conductivity. In this study, we vary the fracture aperture b_i for each fracture i . In the first case, a constant aperture for all fractures is assumed. In the second case, we generate a lognormal distributed aperture field. It can be observed that the shape of the two best fill ellipses are quite similar. But the effective hydraulic conductivity of the lognormal distributed aperture field is smaller than that of the constant aperture field. The results on the right side show, that in terms of calculating the effective hydraulic conductivity, it is important to know whether a more constant fracture aperture for the whole system can be assumed. Or, in the case of very rough fracture planes, a variation of the aperture has to be applied.

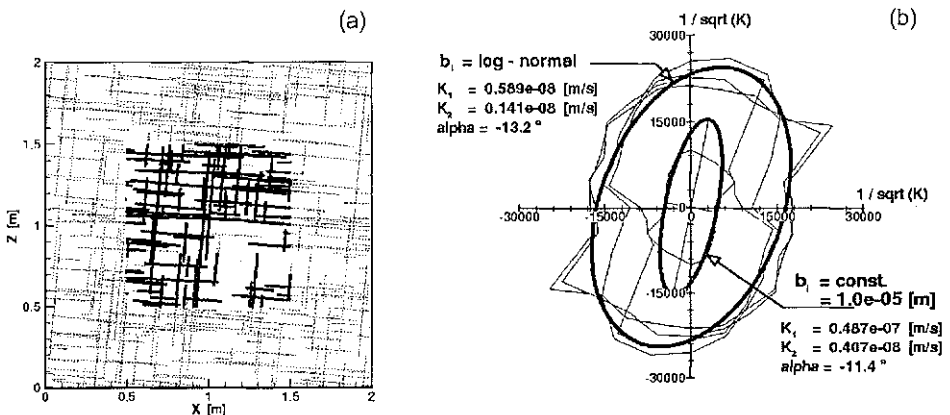


Fig. 3 2-D fracture network (a) with a variation of the fracture aperture b and the calculated effective hydraulic conductivity (b) from different realizations.

The next example (Fig. 4) shows the influence of the fracture density with respect to the calculation of the effective hydraulic conductivity.

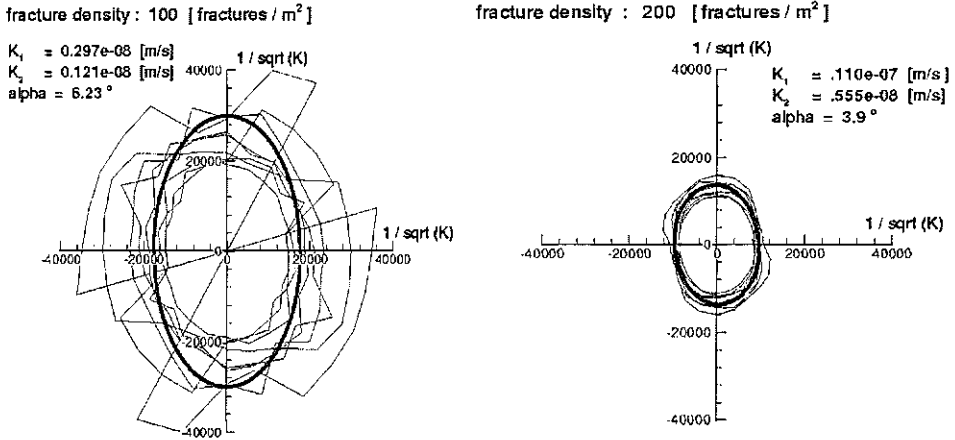


Fig. 4 Effective hydraulic conductivity calculated for fracture network systems with varying fracture density.

The following points can be observed. First, the averaged best-fit ellipse, the thick line, on the left side, has a higher standard deviation than that on the right side. Because of the smaller fracture density, the uncertainties within these fracture networks are higher than in those with the larger fracture density. Second, the fracture network with the fracture density 200 (fracture m^{-2}) has a larger effective hydraulic conductivity than that with the smaller fracture density.

This is due to the higher connectivity associated with the higher fracture frequency. The system is more permeable. The fracture network with the higher fracture density could be well approximated as a porous medium with the calculated effective hydraulic conductivity. In addition the left of Fig. 4 shows one result which looks like an 8. The zero value in the plot, the restriction, is due to a fracture network which has no connected flow path between its input and output boundary.

Finally, one has to be aware that it is an effort to gain the different information which indicate a fractured porous media. Although they are described by parameterized theoretical distributions and by scalar values like the density, they are associated with considerable and often not neglectable uncertainties.

CONCLUSIONS

A 3-D fracture generator which can handle different kinds of input data and provides the data structure for the mesh generating process has been developed. The different approaches to creating geometric fracture models have been presented. We applied the stochastic approach to create different realizations of stochastic fracture models. The use and the reliability of these fracture models has been investigated with respect to the calculation of effective parameters, e.g. the hydraulic conductivity, from these models.

It was observed that, in addition to information on the fracture density, the trace length and the orientation, information on the distances between fractures is an important attribute which has to be included in the generating algorithm. Further work will investigate the sensitivity of the generating input data in more detail, particularly with respect to calculating effective parameters. Comparisons between numerical simulations based on such geometric models, and field experiments, are also planned. The results will lead to a better understanding of how the geometric model and the flow and transport behaviour are linked to each other, and how reliable a stochastic fracture model is.

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REFERENCES

- Cacas, M. C., Ledoux, E., de Marsily, G. & Tillie, B. (1990) Modeling fracture flow with a stochastic discrete fracture network: calibration and validation. 1. The flow model. *Wat. Resour. Res.* 26(3), 479–489.
- Helmig, R. (1997) *Multiphase Flow and Transport Processes in the Subsurface*. Springer-Verlag, Berlin, Germany.
- Hemminger, A., Neunhäuserer, L., Bardossy, A. & Helmig, R. (1998) Identification of equivalent parameters on different scales in fractured-porous media. In: *Advances in Hydro-Science and -Engineering* (ed. by K. P. Holz, W. Bechteler, S. S. Y. Wang, & M. Kawahara) (Third International Conference on Hydroscience and Engineering), 205. Center for Computational Hydroscience and Engineering, University of Mississippi, Mississippi, USA.
- Hötzel, H. (1997) Festgestein-Aquiferanalog: Experimente und Modellierung. Feldexperimente zur Wasser- und Stoffausbreitung in Abhängigkeit von Kluft- und Gesteinsdurchlässigkeit (Rock aquifer analogue: experiments and modelling. Field experiments to water and concentration spreading depending on fracture and matrix permeability) *Report 1, DFG, 1–18, Karlsruhe, Germany*.
- Königter, J., Jansen, D. & Legendijk, V. (1997) Festgestein-Aquiferanalog: Experimente und Modellierung; Einsatz von äquivalenten Modellansätzen (Rock aquifer analogue: experiments and modelling. Use of equivalent modelling concepts) *Report 1, DFG, 1–45, Aachen, Germany*.
- Long, J. C. S. (1983) Investigation of equivalent porous medium permeability in networks of discontinuous fractures. PhD Thesis, LBL, University of California, Berkeley, California, USA.
- McDermott, C. (1999) New experimental and modelling techniques to investigate the fractured porous system. PhD Thesis, University of Tübingen, Tübingen, Germany (submitted 1999).
- Teutsch, G., Sauter, M., Liedl, R., Baraka-Lokmane, S. & McDermott, C. (1997) Festgestein-Aquiferanalog: Experimente und Modellierung; Laborexperimente und Entwicklung neuer Untersuchungsmethoden (Rock aquifer analogue: experiments and modelling; laboratory experiments and development of new investigation methods). *Report 1, DFG, 1–39, Tübingen, Germany*.