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# Numerical modelling of the effects of fault slip on fluid flow around extensional faults: Discussion

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## INTRODUCTION

Zhang and Sanderson (1996) simulated joint dilation associated with normal faulting using the distinct element code UDEC (Itasca Consulting Group Inc., 1993). The idea was original and the problem was well proposed. Rupture along active fault zones in jointed rock mass may cause changes in joint aperture, which may alter hydraulic conductivity of the rock mass. We appreciate the authors' ideas because they have significant importance in effective isolation of radioactive nuclear waste at the proposed geological repository at Yucca Mountain, Nevada. The numerical simulation was well documented, which allows others to compare the results, but the modelling results are highly sensitive to the boundary conditions and modelling approaches. We suggest that the boundary conditions used in the paper may not be the most appropriate for the problem to be solved. The authors did not discuss the effects of boundary conditions and modelling approaches on their modelling results, and so resultant conclusions could be misleading.

## BOUNDARY CONDITIONS

The paper used fixed horizontal stresses that are equal to the horizontal stress component of the *in situ* stress along the vertical boundaries. These stress boundaries are inappropriate when they are close to the fault zone because stresses along the vertical boundaries may change due to fault slip. Since large displacement may occur along these boundaries to maintain the constant stress state, these stress boundaries do not necessarily simulate the confinement provided by an *in situ* rock mass.

Mechanically, grid points along these boundaries can move freely along both the horizontal and vertical directions without any physical confinement. As a result, joint aperture changes along the vertical–subvertical joint set may have been over-estimated due to lack of horizontal confinement.

To evaluate this hypothesis, we developed a simplified model based on model A of Zhang and Sanderson (1996). The modified model was analyzed using two different boundary conditions: stress boundaries (as in the original paper) and a boundary-element boundary. The boundary-element boundary is an artificial boundary that simulates the semi-infinite extent of isotropic, linear, elastic material and is, therefore, a more realistic simulation of the subsurface conditions. Figure 1(a&b) shows the geometry of the modified model and the distribution of joint aperture before fault slip, respectively. In Fig. 1(b), the line thicknesses are proportional to joint aperture. The simplified model differs from model A of Zhang and Sanderson only in terms of the joint pattern. In the simplified model, regular joint patterns were used, including a vertical joint set with 2.5 m spacing and a horizontal joint set with 5 m spacing. Figure 2(a&b) compares joint apertures after fault slip using stress boundaries and a boundary-element boundary, respectively. Joint apertures shown in Fig. 2(a) are similar to those obtained in the original paper: i.e. increases in joint aperture occur mainly in the hanging-wall block along vertical joints and also within the fault zone. Figure 2(b) shows that for the case of a boundary-element boundary, most significant changes occur along

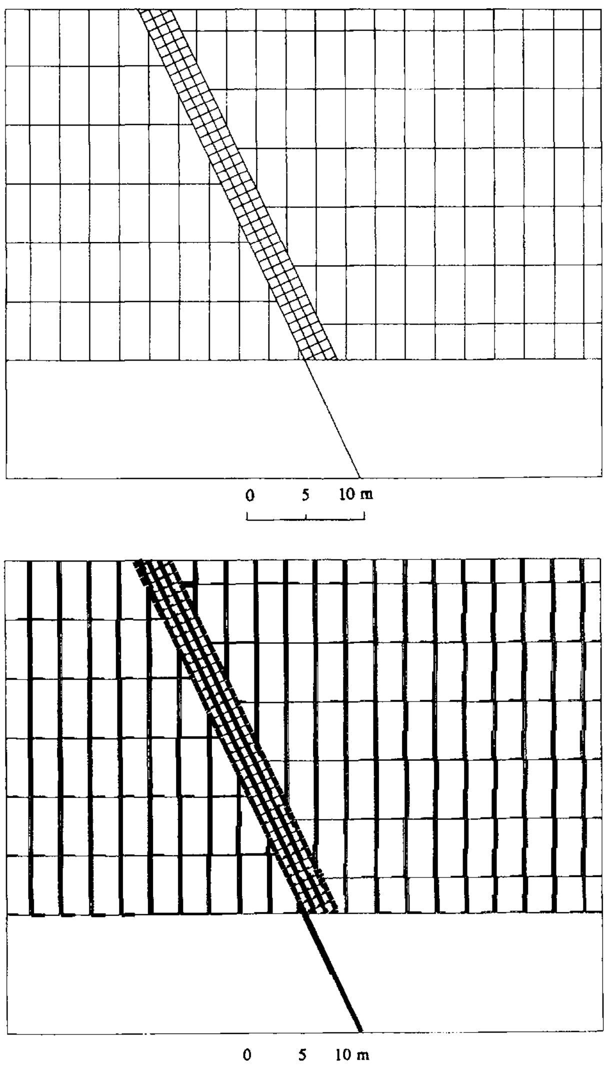


Fig. 1. (a) Model geometry modified based on model A in Zhang and Sanderson (1996). (b) Uniform distribution of joint aperture before fault slip. Line thickness is proportional to joint aperture.

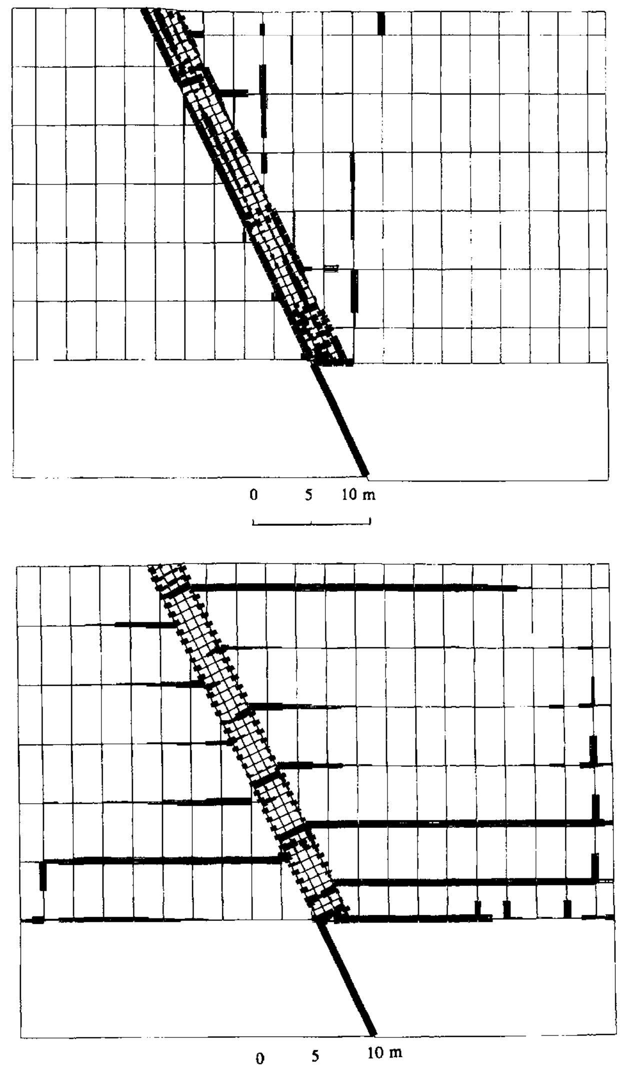


Fig. 2. (a) Joint aperture after 0.4 m fault slip for model shown in Fig. 1(a), using stress boundary conditions. Line thickness is proportional to joint aperture. Apertures less than 1.5 mm or greater than 10 mm are not included for clarity. (b) Joint aperture after 0.4 m fault slip for model shown in Fig. 1(a), using boundary-element boundary condition. Line thickness is proportional to joint aperture. Aperture less than 1.5 mm or greater than 10 mm are not included for clarity.

the horizontal joint set, although aperture changes mainly occur in the hangingwall, which is consistent with the case of using stress boundary conditions. These two figures show that the applied boundary conditions have significant impact on joint deformation.

## MODELLING APPROACH

Zhang and Sanderson (1996 p. 112) state "faulting was simulated by allowing movement of the basement beneath the hangingwall region to a total throw of 0.4 m. This subsidence was achieved in 1 s and was monitored for a further second". This modelling approach has two fundamental problems. First, the model should be run to a new equilibrium for as long as necessary after applying fault displacement, otherwise the solutions are not equilibrium solutions. From our experience, one second is not enough to bring the model to equilibrium. Unbalanced force and block velocities should be monitored during a simulation to determine the state of equilibrium. Second, modelling fault slip by applying uniform displacement along the bottom boundary of the hangingwall (i.e. dragging down the hangingwall) may only be appropriate for the extreme case when the source of fault rupture is very deep and far away from the area of interest, so that the effect of fault slip on the region of interest can be simulated as a uniformly distributed boundary displacement. Otherwise, fault slip should be simulated as shear displacement along the entire fault zone or portion of the fault zone, depending on the problems to be solved. Our analyses show that these approaches result in different solutions.

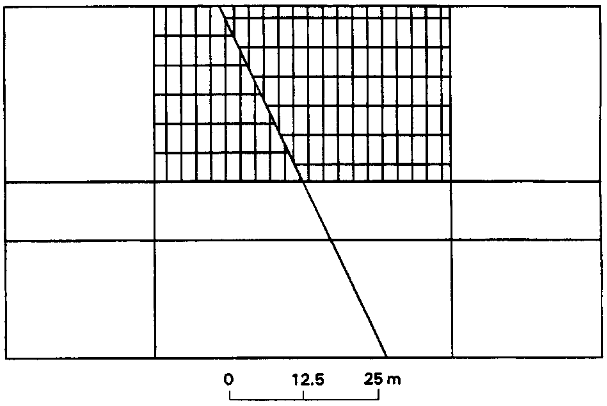


Fig. 3. Geometry of the model modified to simulate fault slip by applying shear displacement along the fault zone.

Although applying shear displacement directly to a fault zone is not a straightforward process, it can be achieved by using the FISH functions available in UDEC revision 3.00 (Itasca Consulting Group Inc., 1996) or using artificial rigid slices parallel to the fault zone to apply velocity over a certain length of time that would accumulate the desired total shear displacement along the fault zone. Both these approaches were tested using the model shown in Fig. 3, and they resulted in similar solutions. The model shown in Fig. 3 was developed based on the modified model shown in Fig. 1. In Fig. 3, the model was extended to minimize boundary effects on the area of interest, and the fault zone was simplified to include only one single fault surface instead a fault zone. The boundary-element boundary condition was used. In the approach using the FISH functions, fault slip was simulated by applying velocity parallel to the fault zone to grid points along the fault zone. The direction of the velocity applied to grid points in the hangingwall has the opposite direction to that applied to the grid points in the footwall. Figure 4 shows the distribution of joint apertures after applying 0.4 m shear displacement along the entire fault zone. Increases in joint aperture mainly occur in the hangingwall, on vertical joints close to the fault zone and along the horizontal joints in the rest of the model. Since the fault displacements are specified, this approach cannot be used to study aperture changes within the fault zone. Nevertheless, it can be used to model aperture changes in the rest of the model.

## FLOW RESULTS

The title of Zhang and Sanderson's paper is misleading. The paper really discussed changes in joint aperture, not fluid flow, due to normal faulting. There should be no meaningful fluid flow in model A in this paper, since the fluid pressure was assumed hydrostatic and the hydraulic boundaries were selected to maintain a hydrostatic fluid pressure in the entire model at a steady-state condition. Although there may be localized flow in response to changes in joint apertures due to fault slip, such transient flow processes are not modelled by the steady-state flow algorithm of UDEC used in the paper. Once the model reaches an equilibrium (steady-state) condition, fluid pressure is hydrostatic and there is no flow in the model. The small amount of flow shown in Zhang and Sanderson (figs 6a and 7) was probably due to numerical "round off" and unbalanced boundary hydraulic pressure after applying fault slip; i.e. after moving the hangingwall downward for 0.4 m. Therefore, we believe the flows do not have any physical meaning.

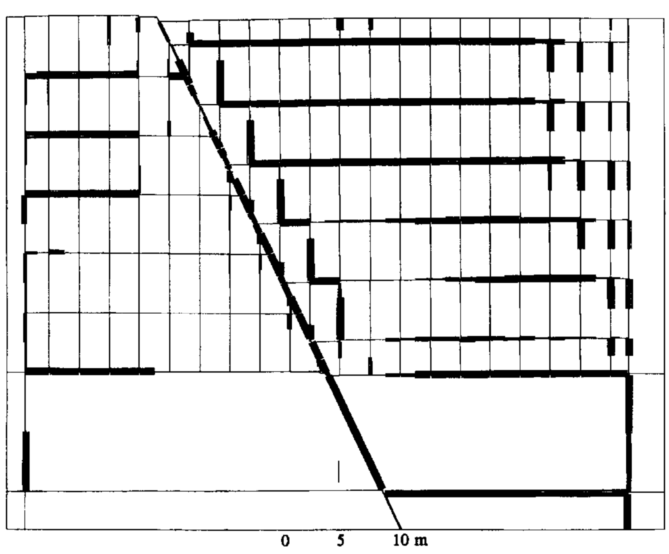


Fig. 4. Joint aperture after 0.4 m fault slip along the entire fault zone. Line thickness is proportional to joint aperture. Apertures less than 1.5 mm or greater than 10 mm are not included for clarity.

## CONCLUSIONS

A fundamental problem in modelling disturbances due to faulting is representation of the semi-infinite extent of the rock mass beneath the ground surface. Far-field boundary locations and descriptions must be chosen so that they do not significantly affect behavior near the fault. This selection is particularly important when joint aperture changes near the fault are of interest. We believe that use of a boundary-element boundary is the most appropriate way to represent the boundary for the problem described by the authors. Furthermore, we believe that enforcing fault displacement directly on the fault is more representative of actual behavior compared to displacement of the basement.

## REFERENCES

Itasca Consulting Group, Inc. (1993). *UDEC Version 2.0 User's Manual.* MN: Itasca Consulting Group, Minneapolis.
Itasca Consulting Group, Inc. (1996). *UDEC Version 3.0 User's Manual.* MN: Itasca Consulting Group, Minneapolis.
Zhang, Z. and Sanderson, D. J. (1996) Numerical modelling of the effects of fault slip on fluid flow around extensional faults. *Journal of Structural Geology* **18**, 109–119.