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Study of fracture process of an earthquake fault

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ABSTRACT: Computer simulations using the Extended Distinct Element Method were made to study fracture behavior of the earth's crust. In one type of the numerical experiments, progressive development of cracks at a certain angle to the shear plane, dilatation and stick-slip type of forces were observed. In another type, it was possible to simulate propagation of rupture from a small region where it was incited. It was found that the rupture slowed down when the region ahead was made successively 10%, 20% and 30% stronger by increasing the shear strength parameters μ and c to simulate strength barriers. With a barrier having random shear strength parameters, however, the rupture velocities changed at various locations when the rupture propagated in the model–leaving few unbroken regions which were destroyed at later time stations–before it finally stopped.

1 COMPUTATIONAL METHOD

The Finite Element Method (FEM) and the Boundary Element Method (BEM) are more suitable when the objective medium undergoes small deformation without the occurrence of cracks. The Distinct Element Method (DEM) proposed by Cundall(1971), on the other hand, is applicable to only a perfect discrete granular assembly. The DEM is based on explicit integration of the equations of motion of every element in a granular assembly, and the force acting on every element from the surrounding elements is estimated from the law of action and reaction. For an element i, the equations of motion are

$$m_i \ddot{\underline{x}}_i = \underline{F}_i \tag{1}$$

and

$$I_i \ddot{\omega}_i = M_i, \tag{2}$$

where m_i is the mass of the element and vector $\underline{x}$ denotes its displacement components in the x and z co-ordinate directions (in the two dimensional case) respectively. The vector $\underline{F}$ represents force components in the respective co-ordinate directions and include the forces of interaction between elements and the damping forces. In the second equation, ω denotes rotation of the element i, I_i its rotational inertia and M_i is the resultant moment acting at its center.

Hakuno et al. (see for example, Meguro 1989) extended this method so as to include continuity. They introduced springs in both the normal and tangential directions between adjacent elements before the analysis and termed them as pore-springs or joint-springs. As criteria of destruction of these springs during the course of analysis, critical parameters–a critical tensile strain for the pore-spring in the normal direction and critical parameters of the cohesion and the coefficient of friction in Mohr-Coulomb's equation $\tau = c + \mu . \sigma$ in case of the pore-spring in the shear direction–were used. In this way, they simulated some phenomena like compression test of a concrete specimen from a continuous stage to a discontinuous stage following the total fracture process. The area of application of the conventional DEM was thus broadened and subsequent researchers improved the method and named it the Extended Distinct Element Method (EDEM) or the Modified Distinct Element Method (MDEM) in their contributions.

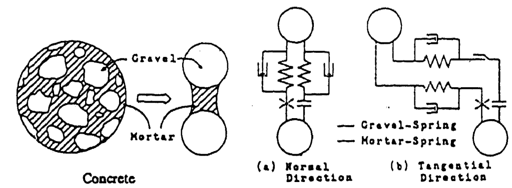


Figure 1 Modeling concrete by the EDEM

In case of the EDEM, use of pore-springs between elements enables one to simulate progressive development of cracks inside a medium in a natural way. Figure 1 shows modeling of concrete by the EDEM. The gravel and pore materials present in concrete are represented respectively by circular elements and non-linear pore-springs. Element springs exist between contacting elements only and the pore-springs are set in the beginning of the analysis in the normal and the tangential directions. Figure 2 shows elements i and j at contact along with the associated displacement increments (dx_i, dz_i)

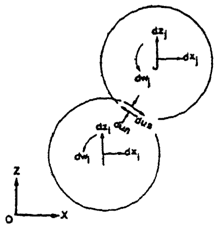


Figure 2 Elements i and j at contact

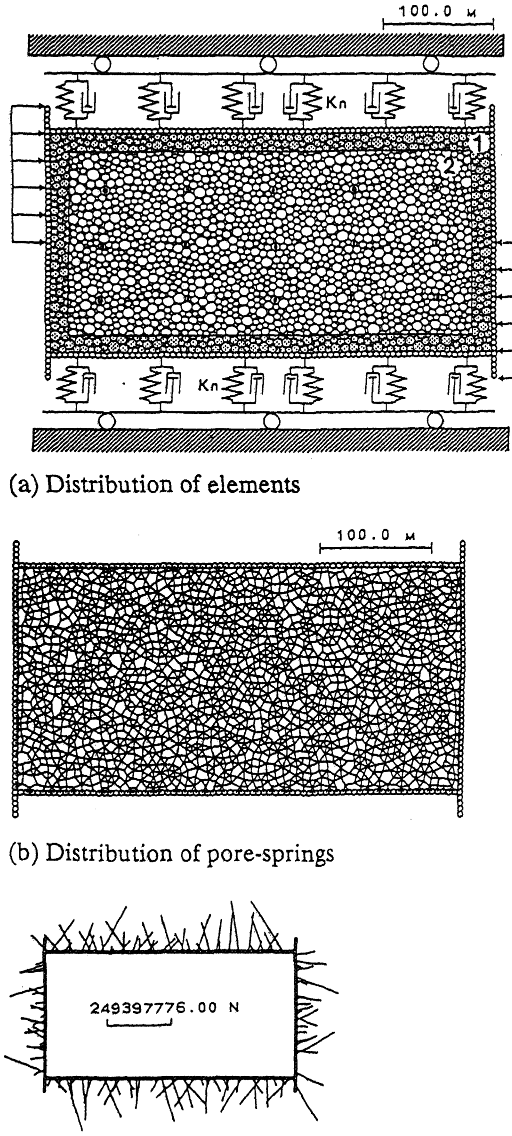
and (dx_j, dz_j) respectively during a small time step Δt in the respective co-ordinate directions. Incremental rotation of the element i during a small time step Δt is denoted by dw_i. These incremental displacement components are used to estimate the incremental displacements in the normal and tangential directions from which the forces of interaction between the elements are computed.

In case of the EDEM, the vector $\underline{F}$ in Equation (1) and the moment term M_i in Equation (2) should include the contribution from the pore-springs as well.

2 MODEL PREPARATION

With the EDEM, like with any other method, it is necessary to prepare a model before trying to simulate a phenomenon of interest. In this study, we have two types of models prepared for simulating fracture process of the earth's crust. In preparing the model designated in this paper as Model A, 1800 circular elements having a log-normal distribution of the element radius were packed and application of compressive all-round pressure was made to simulate a stressed crust. During the experiment conducted after the model became ready, the sides of the models were subjected to a constant rate shear displacement in the direction of the arrows shown in Figure 3. This is therefore a case of a displacement-controlled numerical experiment.

The model designated as Model B is prepared to simulate propagation of rupture from a small region where it is incited and to closely observe the results of inclusion of strength barriers ahead of the advancing rupture front. In preparing this model, 1500 circular elements all with a radius of 2.5m were placed in 5 rows as shown in Figure 4. The model has 894 inner elements and 606 boundary elements. The first step was to apply compressive stress to the model by bringing the top and the bottom walls close to each other. Use of viscous damping was made to bring the model to a practically at-rest condition. Next, the bottom row of elements was moved in the horizontal direction gradually in order to apply shear stress to the region. Again, viscous damping was used to bring the model to a practically at-rest condition. These steps were made to simulate the stressed state of the earth's crust prior to rupturing. In both models, the destruction of a pore-spring in the normal direction occurs by tensile fracture and the associated critical tensile strain parameter is denoted by β. In case of



(a) Distribution of elements

(b) Distribution of pore-springs

(c) Distribution of the force vector

Figure 3 Model A prepared after packing 1800 circular elements having lognormal distribution of the radii

the shear springs, failure occurs according to the Mohr-Coulomb's criterion and the critical parameters are the cohesion c and the coefficient of friction μ.

3 OBSERVATIONS AND DISCUSSION

Results of the numerical experiments conducted on Models A and B are described under separate headings in what follows.

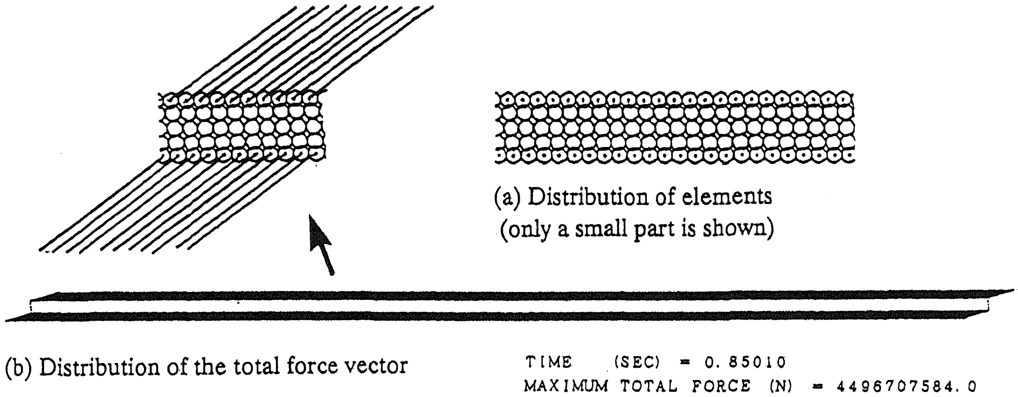


Figure 4 Model B having 1500 circular elements each of radius 2.5m arranged in 5 rows (Model Length = 1500m)

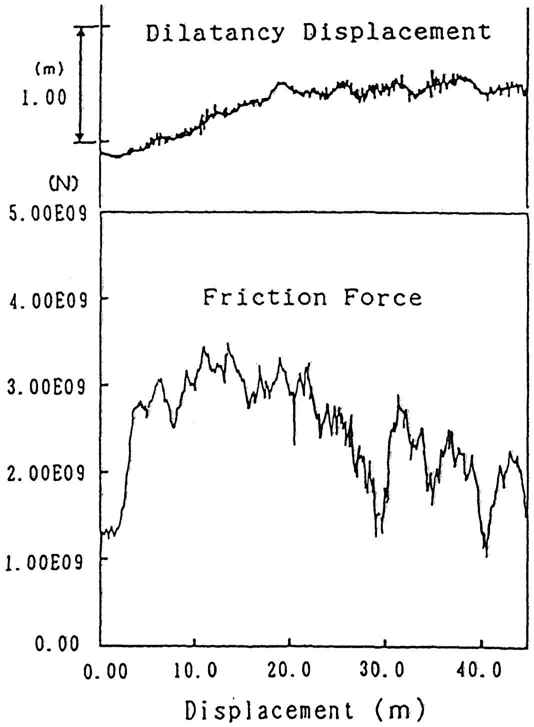


Figure 5 Dilatancy displacement and friction force distribution (Model A)

3.1 Model A

This corresponds to the model having circular elements with their radii following a log-normal distribution. The sides are moved with constant rate displacement during the fracture simulation (see Figure 3). The friction force distribution, the dilatation, and the progressive development of cracks are depicted in Figures 5 and 6 respectively. As can be seen from Figure 5, the dilatancy displacement decreases in the beginning and then increases. This observation has been made by experiments on rock samples in the field of rock mechanics. In Figure 6, cracks analogous to the echelon fissures are seen to have developed at a certain angle to the shear plane.

3.2 Model B

Critical parameters; β, μ, and c explained above; for which a pore-spring would break in the stressed model, were found after a few trials. This was done in order to determine a relevant set of parameters for simulating the rupture propagation. After this, one pore-spring at the left bottom corner of the model was destroyed by reducing the friction suddenly to zero in order to incite rupture. The critical parameters obtained were utilized in the subsequent analysis.

Figure 7 shows progress of cracks at different selected time stations. The rupture velocity in this case was measured to be approximately 2.67 km/s which is about 90% of the P-wave velocity assumed at the outset for determining spring-constants and other parameters of the model (see Meguro 1989 for estimation of different parameters). Figure 8 shows the total force vectors as the rupture advances from one corner of the model to the other. The point of stress concentration being moved with the rupture can be observed from this figure.

In order to study the effect of a strength barrier when it is encountered by an advancing rupture front, a region starting nearly from the middle to the right end of the model, was made stronger. This was done by increasing the shear strength parameters c and μ successively by 10%, 20% and 30% in three different cases. The results of the simulations are shown in Figure 9 which plots the location versus time of crack occurrence in the model in different cases. It was observed in each case that the rupture slowed down when it encountered a stronger region ahead. As can be noted from Figure 9, the rupture velocities became smaller and smaller and the cracks could not penetrate the barrier in the 30% strong case. However, for

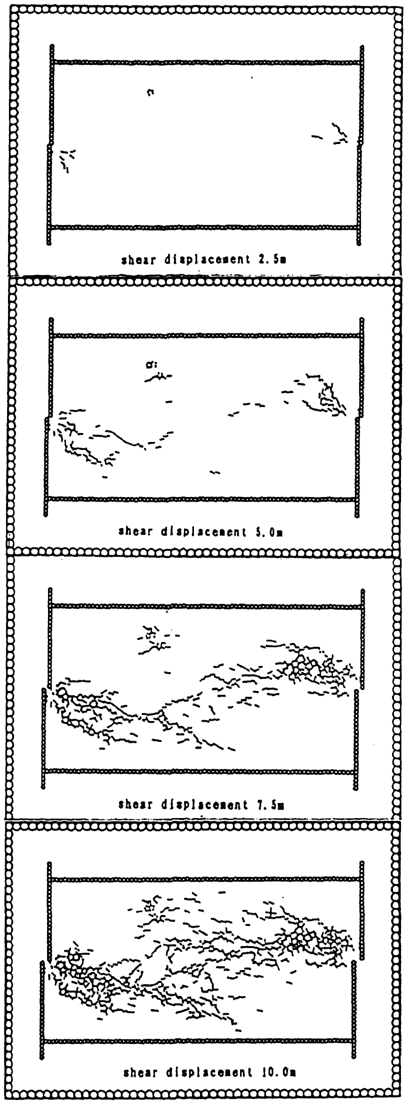


Figure 6 Progressive development of cracks (Model A)

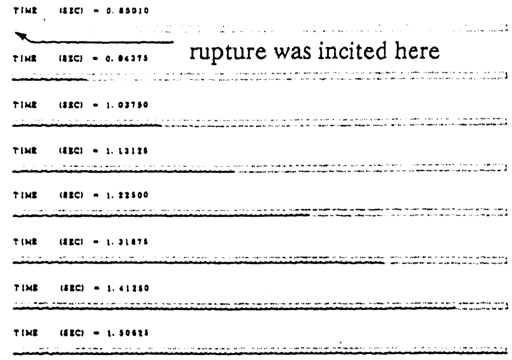


Figure 7 Propagation of cracks from the left bottom corner of the Model B towards right

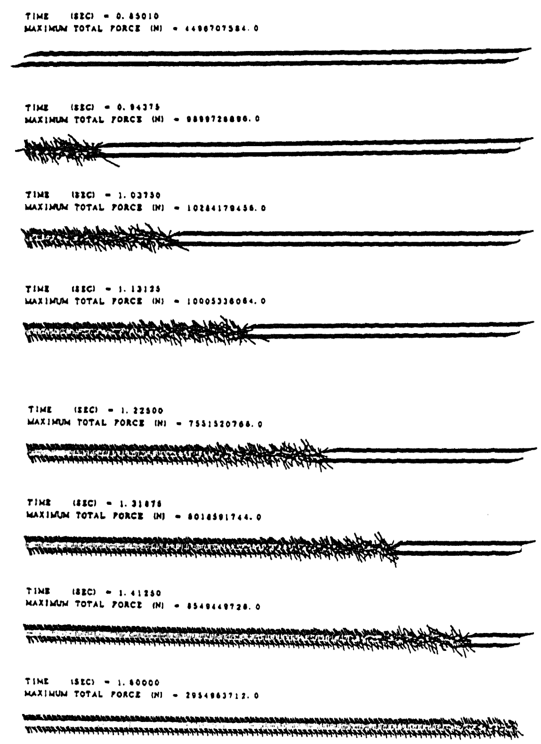


Figure 8 Distribution of total force vectors at different times when the rupture advances from the left bottom corner of the Model towards right

this case, one can see that the total force has been transmitted toward the right as shown in Figure 10. Next, the same region was taken as a random strength barrier with the shear strength parameters varying in the range 0%-50% in excess of the standard values. This case resulted in a few interesting results: the rupture speed varied at different locations giving a zigzag-type plot of the crack location and the time of occurrence; the rupture stopped to propagate after some time which might be attributed to the existence of a stronger barrier, and it was seen that only a few initially unbroken pore-springs were ruptured at later time steps (see Figure 11). The last result is analogous to the case of real earthquakes in that the unbroken patches of a fault are believed to be the future locations of aftershocks.

4 CONCLUSIONS

The Extended Distinct Element Method (EDEM) was used to simulate fracture of the earth's crust and in one type of experiment with displacement control, progressive development of cracks at a certain angle to the shear plane–like echelon type of fissures–were seen to have developed. Also dilatation and stick-slip type of forces were observed in this experiment. In another type of experiment, rupture was incited at a

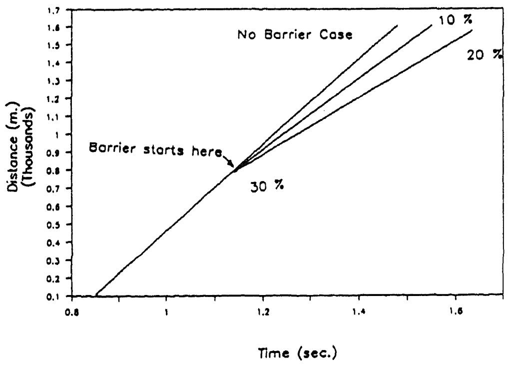


Figure 9 Plot of location versus time of crack occurrence in Model B (standard case as well as different cases of strength barriers)

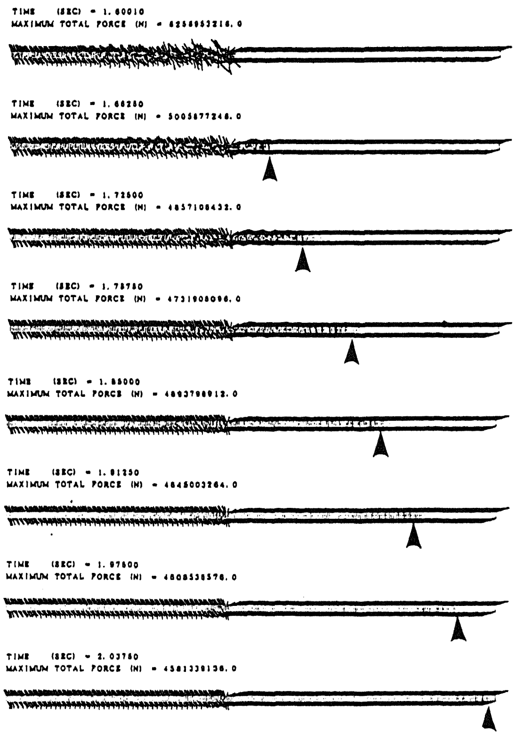


Figure 10 Distribution of total force vectors in case of 30% strong barrier (the propagation of total force can be seen from this figure although cracks could not penetrate this barrier region)

location after having simulated a stressed crust and rupture propagation, and effect of inclusion of different types of strength barriers ahead of the rupture front were studied. The results obtained in this study were very encouraging in that they were obtained in a very simple way. The EDEM, in the authors' view, should prove to be an important tool to explain some of the complicated mechanisms in the field of seismology.

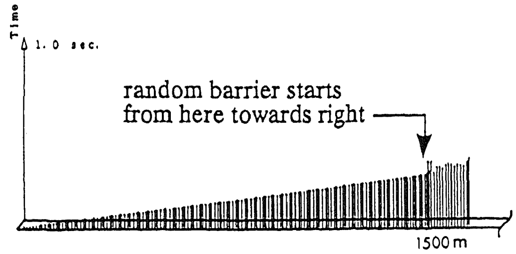


Figure 11 Location versus time of crack occurrence in Model B (case of barriers having random shear strength parameters). The cracks propagated in the barrier region in a zigzag manner and stopped finally.

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