2-D Numerical Simulations for the Deformation of Fault-related Folding: Case Studies for Coseismic Deformation of the Chi-Chi Earthquake at Chushan Trench

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Abstract

The fault-propagation folds are generally associated with blind faults and they have recently been recognized as extremely important for their seismic hazard potential. The Chi-Chi earthquake produced many monoclinal scarps by fault-propagation folding which caused great damage. The trishear kinematic model of fault-propagation folding appears to approximately represent the geometric development of some structures like monoclines, comparatively little is known of the mechanical controls on their development. Thus we construct a series of distinct-element models that consist of bounded assemblies of elastic particles that simulate the brittle deformation associated with fault-related folding over a rigid footwall. Here we attempt to predict the broad-scale features and basic characteristics of distributed deformation developed above blind contractional faults at depth. The initial rock mass is modeled by a series of discrete, non-uniform-sized circular, elastic, frictional particles, connected with each other by parallel bonds and capable of progressive fracturing during loading. The models reproduce the deformation patterns with an evolutionary slip of rigid the basement fault in different strength of parallel bond representing the cementation of granular particles. We conclude that weak cover strength promotes cover flowage, wide zone of deformation and limited fault propagation while strong cover reproduce a narrow zone of deformation and faster fault propagation in the same fault slip rate. The cracks develop at the fault tip area and free surface in the initial stage for the models with strong cover, and then the growth of cracks tend to link these two parts to produce a fracture zone propagating to surface. In addition, in this study, we use the geological profile of the Chushan trench as a case study to investigate the coseismic deformation due to the fault propagation by a series of 2-D discrete element modeling.

Introduction

The Chi-Chi earthquake (M_W = 7.6) was caused by rupture along the Chelungpu fault. Recently, extensive paleoseismological research has been performed along the Chelungpu fault to better characterize the paleoseismic history of the Chi-Chi earthquake. The Chushan site is located on a 3 m high river terrace; the Chi-Chi earthquake rupture was located between this terrace and the Western Foothills. Fault tip deformation in the south wall of the Chushan trench is exposed as a fault-bend folding with an asymmetric fold and a ramp-flat thrust. On the north wall of the trench, the folding style is more akin to a fault-propagation fold. Chen et al. (2006) indicated that there were five large paleoearthquake events causing the large offsets during the past 2 ka and the vertical slip rate is estimated to be at least 3.9±0.2 mm/yr. (Chen et al., 2001, 2006). We attempt to simulate the evolution of coseismic deformation due to the fault propagation in this area.

Method

We use discrete granular simulation to investigate the mechanics of coseismic fault-related folding induced by the Chi-Chi earthquake. The distinct element method (DEM) with bonded-particle model (BPM) facilitate to simulate the mechanical behavior of a collection of non-uniform-sized circular or spherical rigid particles that may be bonded together at their contact points (Cundal, 2004). The BPM is implemented in the two- and three- dimensional discontinuum programs PFC2D and PFC3D. The calculations performed in the DEM alternate between the application of Newton's second law to the particles and a force-displacement law at the contacts and the dynamic behavior is represented numerically by a time-stepping algorithm. The parallel bond model can be imaged a set of elastic springs at the bond periphery which could be assigned for the strength of cementation between particles. If the moment and force exceed its corresponding parallel bond strength, the parallel bond breaks.

We simulate a series of the biaxial and Brazilian tests, the microproperties are chosen to approach the mechanical properties from the laboratory test for sandstone with the parallel bond strength equals 40.25 MPa (Fig. 1). In addition, the parallel bond strength is reduced to 1/2 1/5, 1/10, 1/15 and 0 to simulate the weak sedimentary covers.

We use a random lattice of 24185 particles to define the cover sequence and the sedimentary cover is 160 m thick and 1km in length (Fig. 2). The footwall is fixed and the hanging wall moves upward along the basement fault of dip of 15°, 30°, 45°, 60° and 75°. The slip displacement is set to be 0.0001 m per time step. The cover is mechanically homogeneous and color layers are for visualization only.

Result and Discussion

In the model with unbonded particles, the width of the deformation zone decreases with the increasing of the dip angle of the fault. In spite of the difference fault dip, the monocline at the surface is broad and shallow, however bed dips in the cover increase progressively downwards and towards the basement fault dip, becoming subvertical. In the model with stronger cover, the pup-up structure resulted from thrust and back-thrust is frequently produced while the dip angle is less than 45°. However the models with dipping angle greater than 45^{o}, one dominated thrust plane is observed. Figure 3 shows the effect of the cementation strength of the particles with 30° fault dip angle. We conclude that weak cover strength promotes cover flowage, wide zone of deformation and limited fault propagation while strong cover reproduce a narrow zone of deformation and faster fault propagation in the same fault slip rate. Besides, the cracks develop at the fault tip area and free surface in the initial stage demonstrated by the models with strong sedimentary cover, the growth of cracks tend to link these two parts to produce a fracture zone propagating to surface.

References

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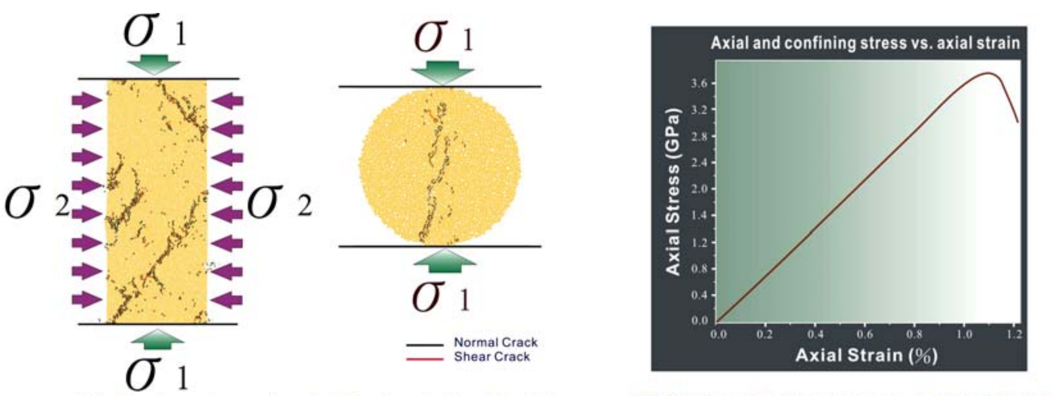

(a) Post-peak cracks distribution in the biaxial test and Brazilian test .

(b) Stress-strain response during biaxial test at unconfined condition.

Figure 1. Experimental set-up for two-dimensional biaxial test and Brazilian test.

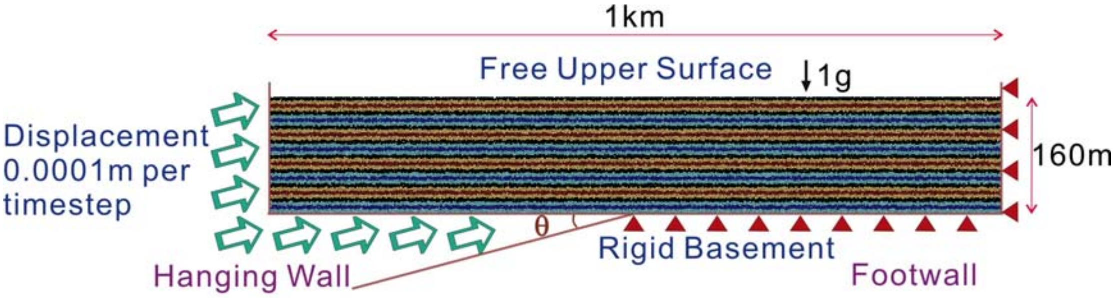

Figure 2. Model geometry and boundary conditions.

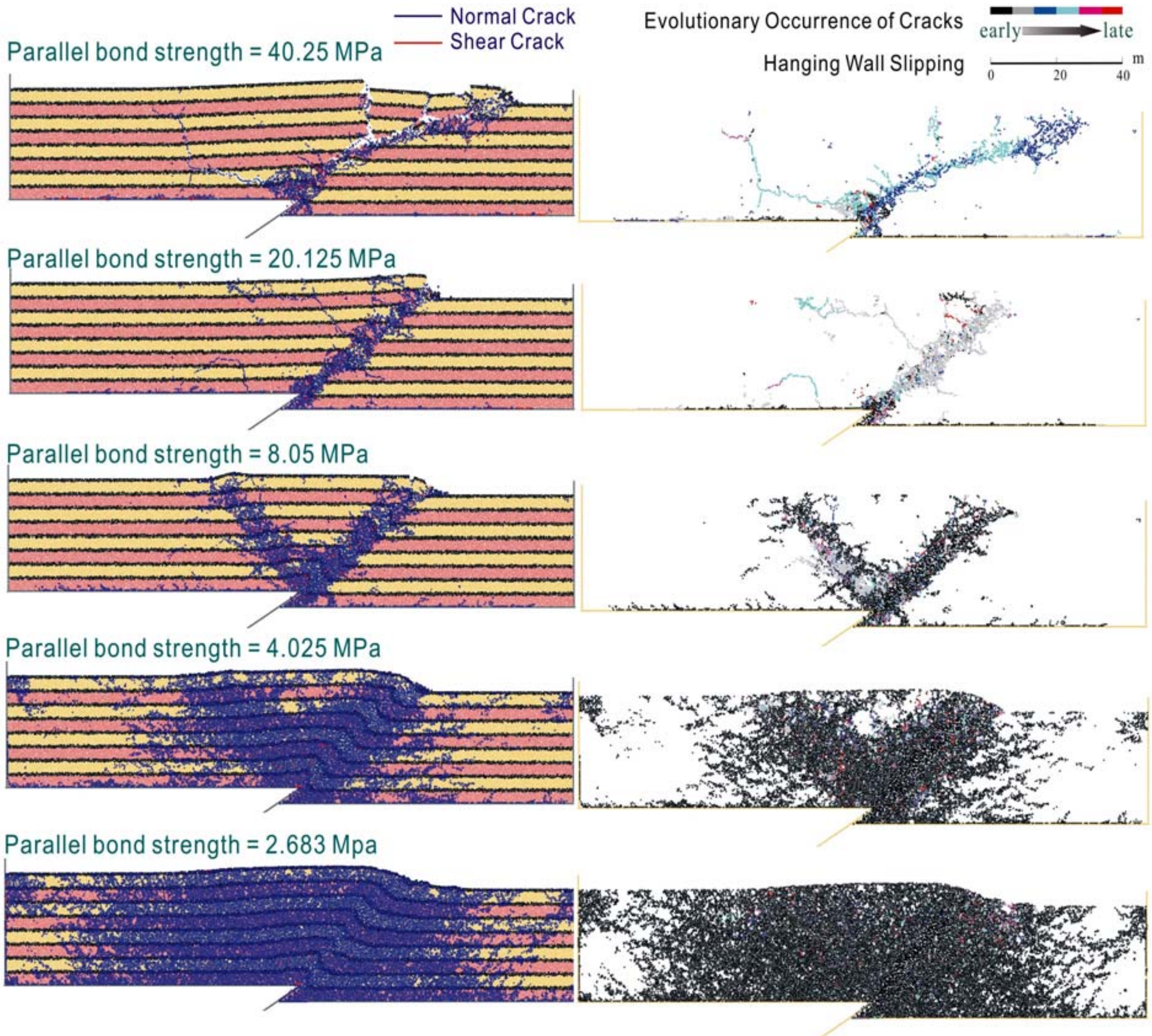

Figure 3. Numerical models with different strength of parallel bond and the evolution of crack growth. The total displacement is 40 m and the fault dip angle is 30°.