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Effects of the tip depth of a pre-existing fracture on surface fault ruptures in cemented clay

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ABSTRACT

Ground deformation due to faulting can cause serious damage to buildings and structures. Much attention has been devoted to understanding fault rupture propagation in uncemented soil. However, the effects of a pre-existing fracture in cemented soil on surface fault ruptures are not fully understood. This paper describes a numerical parametric study to investigate the mechanism of normal fault rupture propagation through cemented clay. Special attention was paid to the effect of the location (or tip depth) of a pre-existing fracture on the mechanism. The numerical model and model parameters adopted were verified through two centrifuge model tests. The results show that a zone of influence consisting of a tensile failure zone and a differential settlement zone was induced by normal faulting in cemented clay both with and without a pre-existing fracture. The width of this zone of influence increased with the tip depth of the pre-existing fracture. The effects of the tip depth of a pre-existing fracture on the width of the zone of influence were more significant when the tip was located at a shallow depth.

1. Introduction

Large earthquakes (e.g., the 1995 Kobe earthquake, the 1999 Jiji earthquake, the 1999 Kocaeli earthquake, and the 2008 Wenchuan earthquake) have resulted in the deaths of thousands of people and enormous economic losses. An important lesson from these disasters is that ground deformation due to faulting can cause serious damage to buildings and structures located within the active fault zone. Much attention has therefore been devoted to understanding fault rupture propagation in soil [19,20,2,21].

Experimental research [26,12,6] and numerical analyses [7,2,21] have shown that the location of a surface fault rupture depends not only on the type and magnitude of faulting but also on the geometry and material characteristics of the overlying soil. Fault propagation in clean dry sand [12,2] and saturated clay [6,18] has been extensively studied, but fault propagation in cemented soils is not fully understood.

Bonilla and Lienkaemper [4] give a state-of-the-art summary of the characteristics of fault strands exposed in trial trenches. They found that 45% of the strands either appeared to die out or actually died out within the soil. The presence of these pre-existing fractures in the soil could affect a newly developed surface fault rupture and its associated propagation [4,5]. Centrifuge tests conducted by Cai et al. [9] demonstrate that pre-existing fractures provided preferential paths for ground deformation in three uncemented soil strata. Ng et al. [23] investigated fault rupture propagation induced by normal faulting in uncemented clay and cemented clay with and without a pre-existing fracture in a centrifuge. In addition, preliminary numerical analyses of the centrifuge tests were carried out to study the mechanism of fault rupture propagation under these three ground conditions. The ground deformation was dominated by a shear mechanism in uncemented clay, and a shear zone developed along the projection of the bedrock fault plane. On the other hand, a bending deformation mechanism was identified at the ground surface in cemented clay with or without a pre-existing fracture. The presence of a pre-existing fracture in the cemented clay initiated fault rupture at the tip of the fracture. As far as the authors are aware, however, little is known about the effects of the tip depth of a pre-existing fracture in cemented soil.

The main objectives of this paper are to perform a series of numerical parametric analyses to study the mechanism of normal fault rupture propagation and to investigate the influence of the tip depth of a pre-existing fracture on fault propagation in cemented clay.

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2. Centrifuge modeling of normal faulting

Two centrifuge model tests were conducted in the beam centrifuge of the Hong Kong University of Science and Technology [22] at an operational acceleration of 100 g. Hence, a scale factor of $N = 100$ was applied to all dimensions of the experimental problem. Tests CCnF and CCmF were carried out in cemented clay without and with a pre-existing fracture, respectively.

2.1. Experimental set-up

Fig. 1 shows a cross-section of the experimental apparatus that was developed to simulate normal faulting in the centrifuge modeling. The apparatus was installed at the bottom of a plane-strain container with internal dimensions of 350 mm × 1244 mm × 851 mm (width × length × height). One side of the container was fitted with a 100 mm thick Perspex window to allow observation of soil deformation during testing. An oil valve (item 6 in Fig. 1) was utilized to transfer oil out of a hydraulic cylinder (item 3c) that acted as an actuator. This actuator pulled the hanging wall block (item 1) and the soil retaining wall (item 11) down to simulate normal faulting. The vertical soil retaining wall and the hanging wall block displace consistently during the modeling of normal faulting to provide a flexible boundary condition for the soil model. A similar boundary condition has also been adopted by other researchers in centrifuge models of fault propagation [13,2,8]. In addition to the guidance system (item 12) and the footwall block (item 9), roller bearings (item 2) were installed between the hanging wall block and the actuator to ensure that the displacement occurred at the desired dip angle (70° with respect to the horizontal).

2.2. Material properties

The artificially cemented clay used in the centrifuge test was prepared by mixing dry sieved clay powder and water while adding Portland cement. The cement content ratio was 3% by weight of dry soil. It is well-known that the stress–strain behavior of cemented soils is influenced by the cementing agent [15,29]. For naturally cemented soils, brittle responses have been observed and were found to be dependent on the degree of cementation and soil density [11,28]. The use of Portland cement in this study is intended to produce a brittle stress–strain response of naturally cemented soil. The uncemented clay powder was obtained from the Chang Ping area north of Beijing, China. The grain size distribution was 14% sand, 73% silt and 13% clay, and the coefficient of uniformity (C_u) was 29. The mean particle size d_{50} was 32 μm.

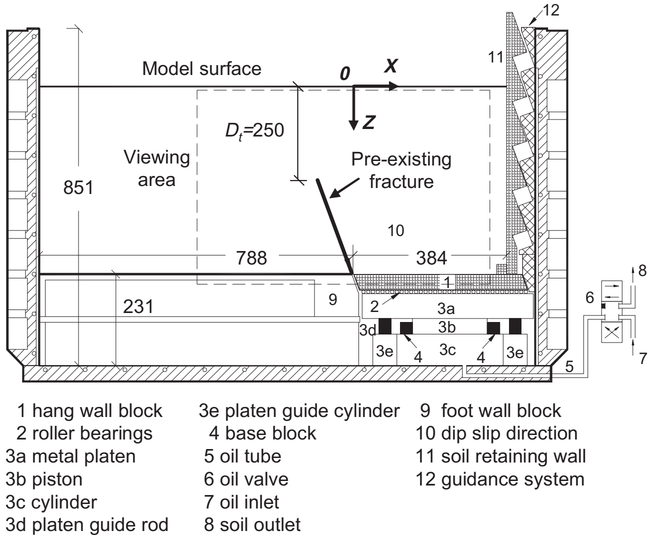

Fig. 1. Cross-section of the strong box and the bedrock fault system used in the centrifuge test (dimensions in mm).

To study the shearing behavior of cemented clay and to investigate the feasibility of modeling a pre-existing fracture with filter paper, two series of direct shear tests were performed in the laboratory, one on cemented clay specimens and the other on sandwiched cemented clay specimens. In the second series of tests, a piece of filter paper was sandwiched between the top and bottom halves of a soil specimen to prevent the formation of cement bonds between the soil particles. The laboratory test program is summarized in Table 1.

Fig. 2 shows the results of direct shear tests on the cemented clay and the sandwiched cemented clay. The direct shear tests were conducted at vertical effective stresses ranging from 100 kPa to 500 kPa, which are typical values for a slab of soil that is 50 m thick.

As shown in Fig. 2(a), the stress–strain behavior of the cemented clay is described as initially stiff and linear up to a peak, beyond which the stress ratio decreases with increasing shear strain until the ultimate state is reached at a shear displacement of approximately 7 mm. The measured softening behavior is consistent with the typical stress–strain behavior of cemented soil reported by other researchers (e.g., [14,28,29]. The stress–strain relationship after the peak states are reached can be described as bilinear with a well-defined post-peak state. The strength parameters at key stages of this series of direct shear tests are summarized in Table 1. Fig. 2(b) shows the dilative volumetric response observed in the cemented specimens. As expected, the dilation rate increases with decreasing vertical stress. The constant dilation rate at shear strains larger than 15% is most likely due to the inclined shear failure plane that formed within each soil specimen.

The tests on the sandwiched cemented clay show an initially linear stress–strain relationship similar to the tests on cemented clay. This indicates that the filter paper had insignificant effects on the initial stiffness of cemented clay. The stress ratio of the cemented clay embedded with a piece of filter paper approaches a constant value with increasing shear strain after reaching an ultimate state at a shear strain of 10%. Interestingly, none of the specimens embedded with a piece of filter paper had a volumetric response. This is most likely because that the shear plane coincided with the plane along which the filter paper was located. Distinctly different behaviors were observed between the cemented specimens with and without the filter paper (see Fig. 2). The cemented specimen exhibited a peak and stress–strain softening behavior during the shearing test. In contrast, no peak was observed in the test on the sandwiched specimen. The effectiveness of using the filter paper technique was verified [23].

2.3. Model preparation and instrumentation

Each centrifuge model was constructed by the moist tamping method that was used in the laboratory tests. It should be noted that the moist tamping method may not be the best way to simulate the formation of a natural clay deposit in terms of its stress history and uniformity. To verify the uniformity of the compacted clay deposit, soil deformation during each layer of compaction was monitored and captured by digital cameras. The digital images were then analyzed using the particle image velocimetry (PIV) technique developed by White et al. [31] to determine the variations of density of each compacted soil layer. The maximum difference between the dry densities of two compacted layers in the soil model was less than 1%.

The soil models were compacted in 27 layers to a dry unit weight of 16 kN/m^3 and a moisture content of 20%. Compaction