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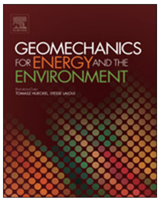

Experimental investigation of reverse fault rupture propagation through cohesive granular soils

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HIGHLIGHTS

- Fault rupture through cohesive soil was investigated using 1g physical models.
- Cohesive soil were modeled by adding different amount of clay to sand.
- Changes in cohesion affect all aspects of the faulting compared with dry soil.
- Fault displacement required for outcropping is increased by increase of clay content.

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ABSTRACT

Naturally occurring dry cohesionless soil is rarely found in urban areas; however, previous studies on surface fault rupture propagation using physical modeling has usually concentrated on dry cohesionless soil. In this investigation, the effects of cohesion on fault rupture propagation through granular soil were studied. Physical models were developed in which inherent cohesion was produced by adding different percentages of clay to the sand. A dry test also was conducted for comparison. The results show that changes in cohesion affect all aspects of the behavior of faulting, including fault rupture propagation, fault scarp at surface and required displacement at bedrock for outcropping. It was found that the vertical fault displacement required for outcropping (h_0/H) increased as the percentage of clay increased.

1. Introduction

Cohesive soil is a commonly observed constituent of sedimentary layers. Major cities are usually constructed on cohesive layers. The presence of clay minerals in the topsoil layers can affect surface fault rupture propagation by changing the geomechanical behavior of the soil. Research on fault rupture propagation that is limited to the investigation of cohesionless granular soil using physical modeling or numerical approaches cannot cover all situations in which fault rupture propagates through soil. Some studies have focused on dry cohesionless soil, especially by laboratory testing.[1–4] In others, water has been added to the soil for model construction, but the investigation has not focus on the effects of induced cohesion.[5–8] Still others have investigated wet and cohesive soil.[9–13] Less effort has been devoted to understanding the effect of cohesion on fault rupture propagation. This is could be related to difficulties in the preparation of laboratory models or problems relating to consolidation in fine materials.

An appropriate method for geotechnical studies is 1-g physical modeling. In this type of modeling, as the confining stress of soil decreases (with a decrease in the dimensions), the cohesion of the soil also should be reduced based on scaling laws. This reduced cohesion sometimes cannot be satisfied by modeling or presents difficulties. To overcome these difficulties, the current study added a small percentage of clay to granular soil (sand) to produce cohesive soil.

2. Physical modeling

The main purpose of modeling was to understand and recognize the response of cohesive soil to fault rupture propagation. The 1-g physical modeling approach was adopted in the present study, because it is economical and accessible.

2.1. Geometry of model and experimental apparatus

A split box was used to reproduce reverse faulting in this investigation. Faulting was applied to the model using an electromotor

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Table 1
Geomechanical properties of Firoozkooh no. 161 sand in dry condition.

G_s	$e_{\max}$	$e_{\min}$	d_{50} (mm)	Fine percent (%)	φ' (degree)	c' (kPa)	Uniformity Coefficient, U_c
2.65	0.943	0.548	0.27	1	37	0	1.87

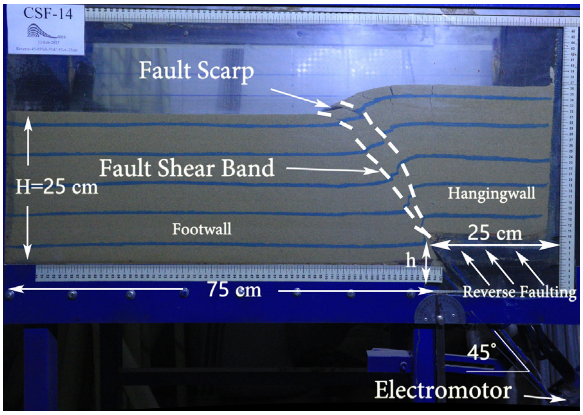

Fig. 1. Faulting box and geometry of model.

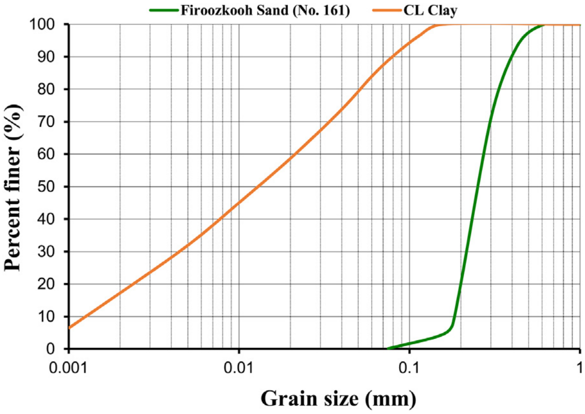

Fig. 2. Gradation curve of Firoozkooh no. 161 sand and CL clay.

Table 2
Test programs and characteristics.

Test No.	CSF-10	CSF-14	CSF-15	CSF-16
Water Content (%)	0 (dry)	5	5	5
Sand (%)	100	95	90	85
Clay (%)	0	5	10	15

in quasi-static mode to reproduce what occurs during a real fault rupture.[14] Free field conditions were studied in this research. The model simulated a soil layer with a height of 25 cm that was subjected to reverse faulting at a dip angle of 45°. The maximum vertical fault displacement was limited to 5 cm in all models. Fig. 1 shows the faulting box used and the geometry of the model. The total height of the soil layer, vertical fault displacement during faulting and the vertical fault displacement at which the fault rupture reaches the surface are denoted by H, h and h_0, respectively.

Particle image velocimetry (PIV) was used to recognize shear band formation and its propagation upward to the surface during faulting. The software used was Vision Strain Gauge (VSG) developed by IIEES.[15] To capture the propagation of faulting, an 18 MP camera (Canon EOS 650D) was mounted in front of the Plexiglas side to record high-resolution photographs for image processing.

2.2. Soil

Firoozkooh #161 sand was used in all tests as the main component of the soil and cohesion was implemented by adding different percentages of clay. Table 1 lists the geomechanical properties of the Firoozkooh sand. Fig. 2 shows the gradation curves for the different specimens. CL clay was added to pure sand for preparation of cohesive soil such that the cohesion of the mixed soil can be controlled according to the percentage of fine material. Liquid limit (LL), plastic limit (PL) and plastic index (PI) of CL clay (commercially named as Kaolinite ZMK2) are 29%, 17% and 12%, respectively.

Soil having a value of $D_r = 50\%$ was used in all tests. The wet tamping method was employed to construct the model. First, clay and sand were mixed precisely and then 5% water was added to produce homogeneous soil. The soil was poured in layers 2.5 cm in height and tamped to achieve the desired level of density. The density of the layers was controlled by its height after compaction. The number of tamps was determined in pilot tests. Under-compaction was employed to ensure a homogeneous soil layer. Tamping was increased on the top layer to assess the effect of compaction energy.

2.3. Physical modeling programs

In this study, four models were conducted. In three, the percentage of clay in the soil was varied to investigate the cohesiveness of the granular soil. To compare the response of cohesive and non-cohesive soil against faulting, one dry test using pure sand was also carried out. The characteristics of each test are listed in Table 2.

3. Results and discussion

3.1. Fault rupture propagation

Fig. 3 shows the results of cohesive testing with 5% clay at $h/H = 4\%$, at the initiation of faulting, microshear bands were produced from the fault tip at bedrock to the surface. Some of these microshear bands reached the surface and deform the surface slightly. Before vertical fault displacement at $h/H = 4\%$, the main fault rupture shear band reached the surface and a distinctive scarp was created. In this situation, development of other microshear bands that did not run through the main fault trace appears to have ceased. At $h/H = 8\%$, localization of shear strain occurred and the overall width of the shear band tended to decrease. Slight bifurcation or branching of the fault occurred in the upper half of the soil layer.

At the end of faulting, at $h/H = 20\%$, a new shear band formed from the tip of fault and began to propagate upward. This bifurcation indicates that the amount of relative displacement is likely the most important parameter when determining how a fault rupture can become hazardous. This shows the importance of the prediction of fault relative displacement before the design of a structure when a known fault exists at the construction site.

The main difference between the results of cohesive testing with the 10% and 15% clay model with the 5% model was diffusion of the shear bands in the upper layer of soil. An increase of more than 10% in the percentage of clay significantly increased the required fault displacement at bedrock for outcropping. Fig. 3 shows the 10% and 15% clay tests at $h/H = 4\%$ in which shear band localization formed above the fault tip at bedrock, but only microshear bands were created and reached the surface over a

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