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EXPERIMENTAL APPROACH FOR UNDERSTANDING OF FAULT RUPTURE PROPAGATION THROUGH AN ALLUVIAL SOIL

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This paper presents the results of experimental approaches to examine propagation of fault ruptures with particular concern on dip-slip fault. Based on the results from various cases of faulting tests under single gravity and centrifuge condition, some useful information to predict the location and the magnitude of surface rupture in sandy soil deposit has been provided. The variation of dip angle and the effect of soil density are appeared as major affecting factors to form the pattern of rupture propagation. Besides, it is confirmed that reproduction of fault rupture propagation in sandy soil deposit using physical model could be largely affected by its confining stresses from this research.

Key Words : *fault rupture propagation, earthquake surface fault, ,fault box test, centrifuge test*

1. INTRODUCTION

Recent large scaled earthquakes occurred at Kobe (Mw 7.2, 1995, Japan), Kocaeli (Mw 7.3, 1999, Turkey) and Jiji (Mw 7.9, 1999, Taiwan) invoked the necessity of further information about ground surface failures induced by fault rupture propagation during earthquake. These tragic events revealed that ground surface ruptures could cause severe damages to the major infrastructures located within the zone of faulting.

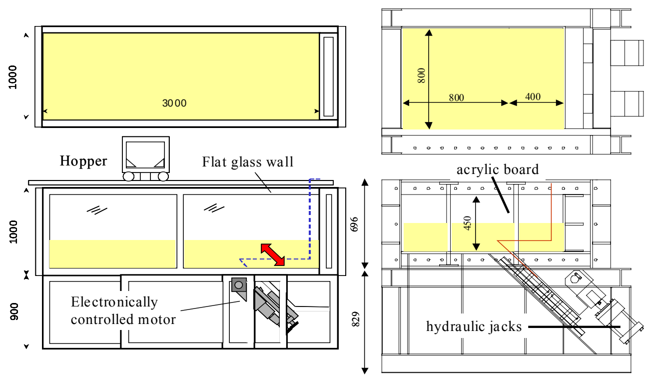
A few of studies on this subject using physical model have been continuously performed for past more than twenty years in Japan and US. Cole et al. (1984) presented a theoretical model to predict the location of surface rupture based on the results from a series of 1-g fault box tests of alluvial sand. Bray et al. (1994) released the experimental and analytical results of studies on the response of saturated clay soils to bed rock displacement. Several series of fault box tests under 1-g condition using Toyoura sand and silica sand in dry were carried out to investigate the effect of fault type on the required displacement to form shear rupture by Tani et al. (1994, 1999), who also suggested the modified analytical model to predict the behavior of rupture propagation based on their experimental studies. However, most of experimental studies seem to be conducted under low level of confining stresses, which may yield somewhat different trends from the actual behavior considering the thickness of deformable soil layers in real field.

In this study a series of physical model test under both of single gravity and centrifuge condition has been carried out to examine the rupture propagation in dry sand with particular concern on the relationship between the fault type and the affecting factors required to completely develop shear ruptures to the surface of ground. The effects of inclination of fault plane and fault types have been examined through the 1-g fault tests simultaneously considering the variation of density of sand deposit. The investigation into rupture patterns under various gravitational conditions shows that the prediction of location of the surface rupture in a sandy soil mass using a physical model under 1-g condition can be largely affected by the thickness of model itself and the results of which should be meaningfully verified with those from centrifuge tests.

2. OUTLINE OF PHISICAL MODELS FOR FAULT RUPTURE PROPAGATION

(1) Preparation of Testing Apparatus

Two kinds of testing devices have been introduced to conduct the dip-slip faulting tests under single gravity and centrifuge condition in this study. Both of the devices are not same in dimension and configuration but have been designed to function in the same way. The device for single gravity test (Apparatus I, Fig. 1 (a)) was built up with steel frame and glass-walled box of which in-plane dimension is 2.0m-0.5m-1.0m in length, width and depth. The adjustable rolling hopper was assembled to place the dry sand in the testing box at a uniform density. On the other hand, the testing apparatus for centrifuge tests, Apparatus II (Fig. 1 (b)), was constructed with a steel frame consisted of 30mm thick steel plates and an acrylic board with thickness of 50mm on one side of the box. The dimension of the in-plane apparatus is 1.2m-0.8m-0.45m in length, width and depth. One-third of the testing box could be moved up along a fixed dip angle - 45° in this study - to relative to the fixed part using double 200tonf-capacity hydraulic jacks. To minimize the influence of wall friction that is somewhat larger than that of glass wall on the tests, Teflon was attached on each inner side of wall before starting to put sand into the box. Fig. 1 and Fig. 2 explain the details of the testing devices.



(a) Apparatus I (b) Apparatus II

Figure 1 Setup of testing apparatus used in fault tests

(2) Testing Procedure

The procedure for each fault test in this study is summarized as bellows;

i) Preparation of uniform sand layer using hopper with installation of black sand grid and target, ii) Activation of up/down movement of deck to the every incremental displacement with constant speed of 2mm/min., iii) Taking photos of both sides of deformed specimen and surface of soil mass at every increment of vertical displacement, iv) Repetition of processes described as ii) and iii) to required offset to form complete shear ruptures to surface of model.

(3) Specimen for Test

The silica No. 7 was commonly used in both of the 1-g tests and the centrifuge tests. As for the 1g-tests, the effect of soil density was considered but for the centrifuge tests only dense sand was included as the specimen for the tests The parameters related to soil deposit are summarized in Table 1.

TABLE 1: SOIL PARAMETERS USED IN TESTS

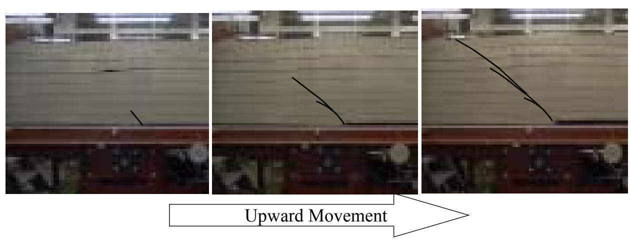
Material Type	Silica Sand No. 7
Average Grain size (D_{50})	0.157mm
Uniformity Coeff. (Uc)	1.55
Coeff. of Curvature (Uc')	0.946
Relative Density (Dr)	Loose : 59±4%(1-g) Dense : 83±4%(1-g), 74±6.58%(centrifuge)
Dry density (γ)	1.401tonf/m³≤ γ ≤1.452tonf/m³

3. OBSERVED BEHAVIOR FROM TESTS

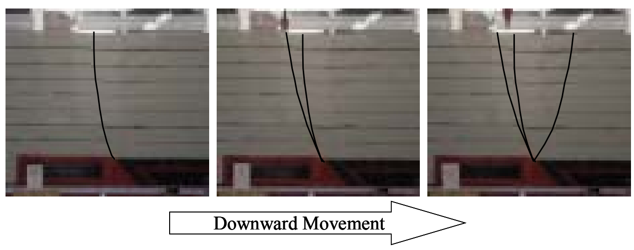
(1) Rupture patterns from fault box tests

Propagation of shear failure through sand layer in accordance with faulting movements at the bottom of the model can be obviously seen as the successive three photographs captured in Fig. 3. As shown in Fig 3 (a), the failure surfaces essentially shaped the curve that could be represented by logarithmic spiral. The failure surfaces with respect to different dip angles in this study also appeared in similar pattern. Meanwhile, as for the failure surfaces developed by normal faults, three lines of failure surfaces were taken place sequentially as the fault displacement continued as shown in Fig. 3 (b).

The deformed ground surface due to reverse fault formed a slope from the surface rupture to some extent so called "flexure" while the three rupture plnes due to normal fault configured a settled area so called "graben" between the second and third failure lines.



(a) Reverse fault - side view, H=40cm



(b) Normal fault - side view, H=40cm

Figure 2 Selected photos corresponding to three stages in reverse/normal faulting test on dense sand with dip angle=45°

Besides, the shape of fault rupture appeared in the centrifuge models appeared to be similar to those from the 1-g tests with 45° in dip angle as shown in **Figure 3**. However, comparing between the results from the 1-g tests and the centrifuge tests, the rather unique rupture surface with somewhat thicker band than that of 1-g test could be founded in case of the centrifuge tests whereas the rupture surfaces from 1-g tests appeared to frequently form plural numbers of failure lines with increase of the thickness of model.

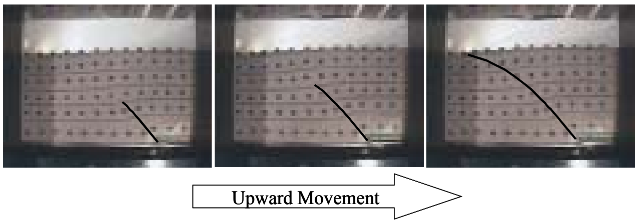
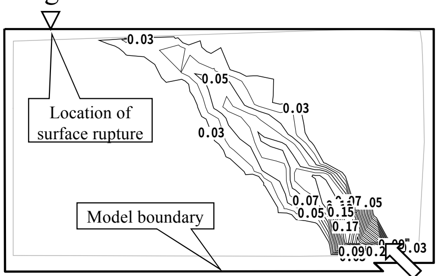


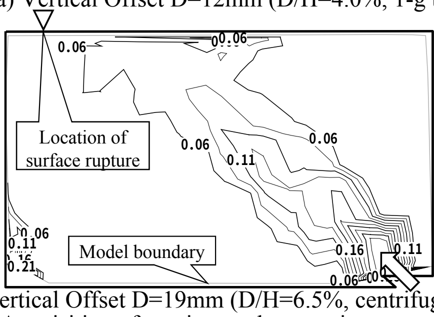
Figure 3 Selected photos corresponding to three stages in fault test on dense sand under centrifuge condition

(2) Shear strain distribution in soil mass

To figure out the development of maximum shearing strains in soil mass during fault rupture propagation, the contours of maximum shear strain in the model were calculated using the measured displacement vector during an experiment. As shown in the Fig. 8, the calculated contours of maximum shear strains corresponding to 4.0% of the normalized vertical offset show that the region of concentrated shear strains developed extending to the free surface of ground model as the observed failure surface during the test reached the model surface. At the same time, the value of maximum shear strain contour that appeared to approximately coincide with the observed failure surface was analyzed as ranging 0.03~0.04 for dense sand in 1-g tests and 0.05~0.06 for centrifuge tests.



(a) Vertical Offset D=12mm (D/H=4.0%, 1-g test)



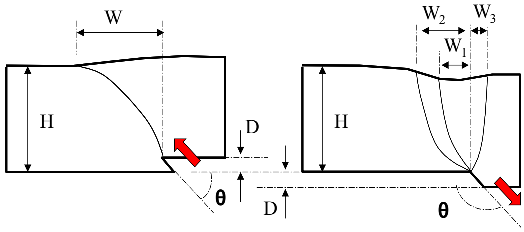
(b) Vertical Offset D=19mm (D/H=6.5%, centrifuge test)

Figure 4 Acquisition of maximum shear strain contour

4. DISCUSSIONS

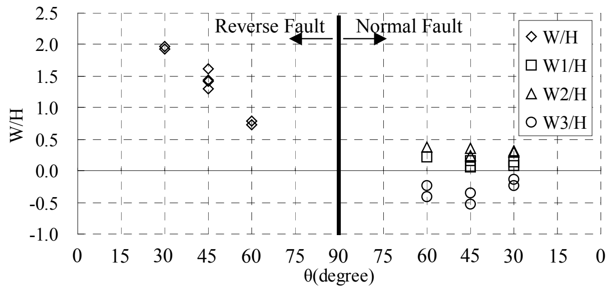
(1) Rupture patterns and its affecting factors

Based on the rupture patterns observed from the testing results, a model for examination of rupture pattern is depicted as Figure 5.

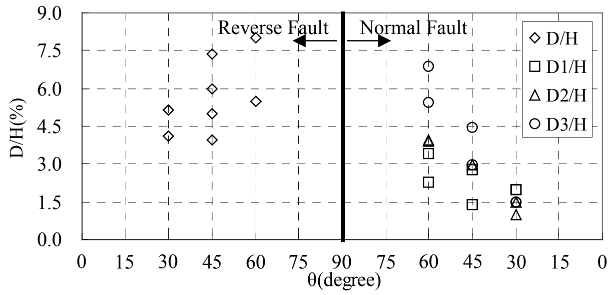


(a) Reverse fault (b) Normal fault

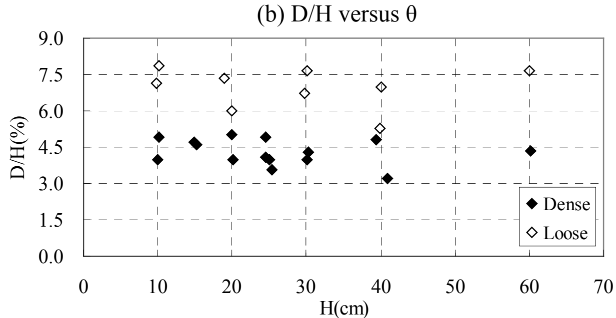
Figure 5 Model for the evaluation of rupture patterns



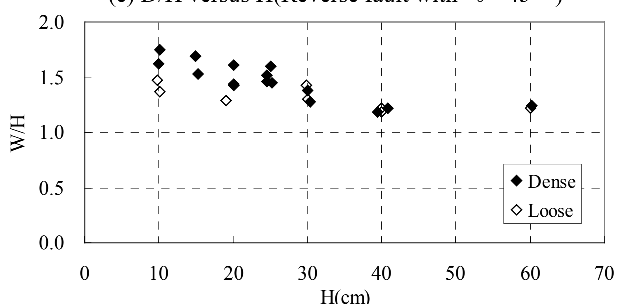
(a) W/H versus θ



(b) D/H versus θ



(c) D/H versus H(Reverse fault with θ =45°)



(d) W/H versus H(Reverse fault with θ =45°)

Figure 6 Variation of W/H and D/H as a function of θ and a function of H

Figure 6 shows the relationship between the location of surface rupture and its relating factors from 1-g tests. As shown in **Figure 6 (a)** and **(b),** as for the reverse faults, there appeared a definite inclination of the value of W/H to down with increase of the dip angle whereas there was only a little change in value for the normal faults. However, it appeared to be a reverse tendency in the variation of D/H. Besides, it can be seen in **Figure 6 (c)** that the required vertical offset to form a complete fault rupture in sand mass mainly depends on the density of soil itself but appears to be independent of the thickness of model. **Figure 6 (d)** indicates from the 1-g fault tests that the distance W is apparently associated with the thickness of model and coming closer to the point the fault intersects with increase of the height of soil mass. This implies that the rupture pattern could change as the thickness of the soil mass is varied under low confining pressure.

(2) Effect of confining pressure on rupture

The thickness dependent variation of surface rupture at 1-g model accordingly invoked the employment of centrifuge test to this study to investigate the fault rupture propagation under high confining pressure condition. The centrifuge model hardly provided so much distinct change of the location of surface rupture at higher confining stresses as plotted in **Figure 7**.

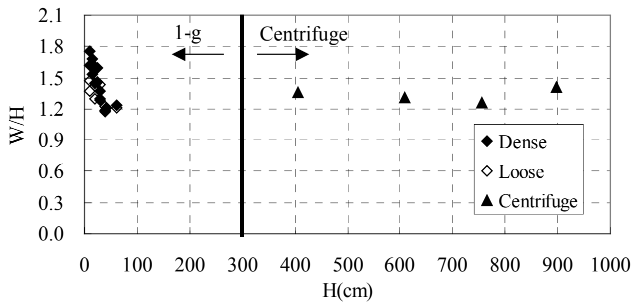


Figure 7 Variation of W/H as a function of H under 1-g and centrifuge tests

This stress dependent characteristic of fault rupture propagation can be understood by taking the dilatant behavior of granular soil into consideration. Similar to Stone et al(1992)'s achievement, the author's experiments provided an abrupt transformation of localized shearing deformation within a granular soil mass that was owing to the change of the dilation angle for the soil during process of shearing deformation as illustrated in **Figure 8**. This implies that relatively large displacement in higher thickness of models required to forming a complete surface rupture caused greater change of the dilation angle during the course of tests so that the initial surface failure could encounter kinematic incompatibility and might create a new localized shear region(noted as 1st and 2nd failures in **Figure 8**). Hence, provided that a significant value of dilation angle and its variation during shearing process for a isotropic dry sand at low confining pressure are validly expected, it can be understood reasonably that the shear zone patterns in the soil change with a definite tendency at low confining pressure under which the 1-g tests were implemented.

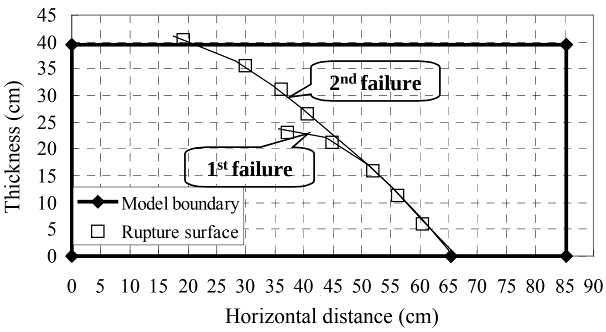


Figure 8 Twofold failure surfaces within a 40cm high model

5. CONCLUSION AND FUTURE STUDIES

The relationship of the location of surface rupture and its affecting factors such as the type of faults, the density of soil and the dip angle of fault plane were evaluated from 1-g and centrifuge fault box tests. It is founded that changing the angle of fault plane with reverse fault could greatly affect the location of surface fault rupture. And the results from 1-g model tests with change of its thickness indicate that the location of surface rupture might be definitely influenced by model thickness at low confining pressure. By comparison with the results form centrifuge models, it is confirmed from this study that the physical models at 1-g condition for fault rupture propagation might provide a properly simulating method to approximately understand the response of sandy soil over the various types of bedrock fault movement. However, for further understanding of the phenomenon to consider a mitigation method against hazards in real fields, an adequate centrifuge model should be taken into reproduction of fault rupture propagation to predict that behavior as close to real phenomenon as possible.

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