

Fault Rupture Propagation through Level Ground and Sloping Sand Layers

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SUMMARY:

The study of fault rupture propagation from base rock to the surface has long been the concern of many researches. In this paper the problem of propagation of reverse dip-slip fault rupture is examined through the use of Finite Element Method. The numerical modeling is verified through physical simulations. The focus is to find real soil responses to dip-slip faulting during its propagation through soil deposit and study effect of ground surface slope on fault outcrop. Special attention is given to the near surface distortion which is of practical importance in engineering. Therefore, the angle of rupture path while approaching the surface is measured in different cases of fault dip angle for different soil types and found to be correlated with soil characteristics and ground surface slope and mostly independent of fault dip angle.

Keywords: Fault rupture, Numerical method, FEM, Surface distortion

1. INTRODUCTION

The phenomenon of fault rupture propagation through soil layers has been the subject of many numerical analyses as well as physical modeling and field studies. Field studies have focused on evidences from surface observations and trenches (Bray et al., 1990; Bonilla and Lienkaemper, 1990). Along with these findings, other researchers tried to model soil layer behavior in laboratory tests, (Cole and Lade, 1984; Bray et al., 1990; Lazarte, 1996; Johansson and Konagai, 2006; Lin et al., 2006) and in numerical simulations (Bray et al., 1994; Lazarte, 1996; Johansson and Konagai, 2007; Lin et al., 2006; Anastasopoulos et al., 2007; Loukidis et al., 2009).

Through these efforts, many aspects of fault rupture propagation have been established. In this paper numerical modeling is employed and verified for analyses of the problem. The emphasis is on the effect of fault dip angle, soil characteristics and ground surface slope on fault rupture pattern and fault outcrop. The characteristics of soil and ground slope have a serious impact on the out coming surface distortions of fault rupture.

2. PROBLEM DESCRIPTION

The problem of fault rupture propagation through a soil deposit is simplified to the model of horizontal and sloping soil layer with uniform material lying on a base bedrock. The present study is limited to the case of dip-slip reverse faults. For the simulation of fault movement the right side of the layer is assumed to be fixed (foot wall) and an upward movement with angle of α is applied to the left boundary (hanging wall). Fig. 2.1 shows the typical geometry and boundary conditions.

2.1. NUMERICAL ANALYSIS

The numerical analyses are static and do not account for potential effects of strong ground motion. Finite element method with Abaqus code is employed as a numerical tool for the analyses. The problem is two dimensional and in plane strain conditions.

For the numerical simulation of 10 meter high horizontal and sloping soil deposits a rectangular area of 10×50 m with 40×200 elements and a triangular area with 2894 elements are modeled (Fig. 2.2).

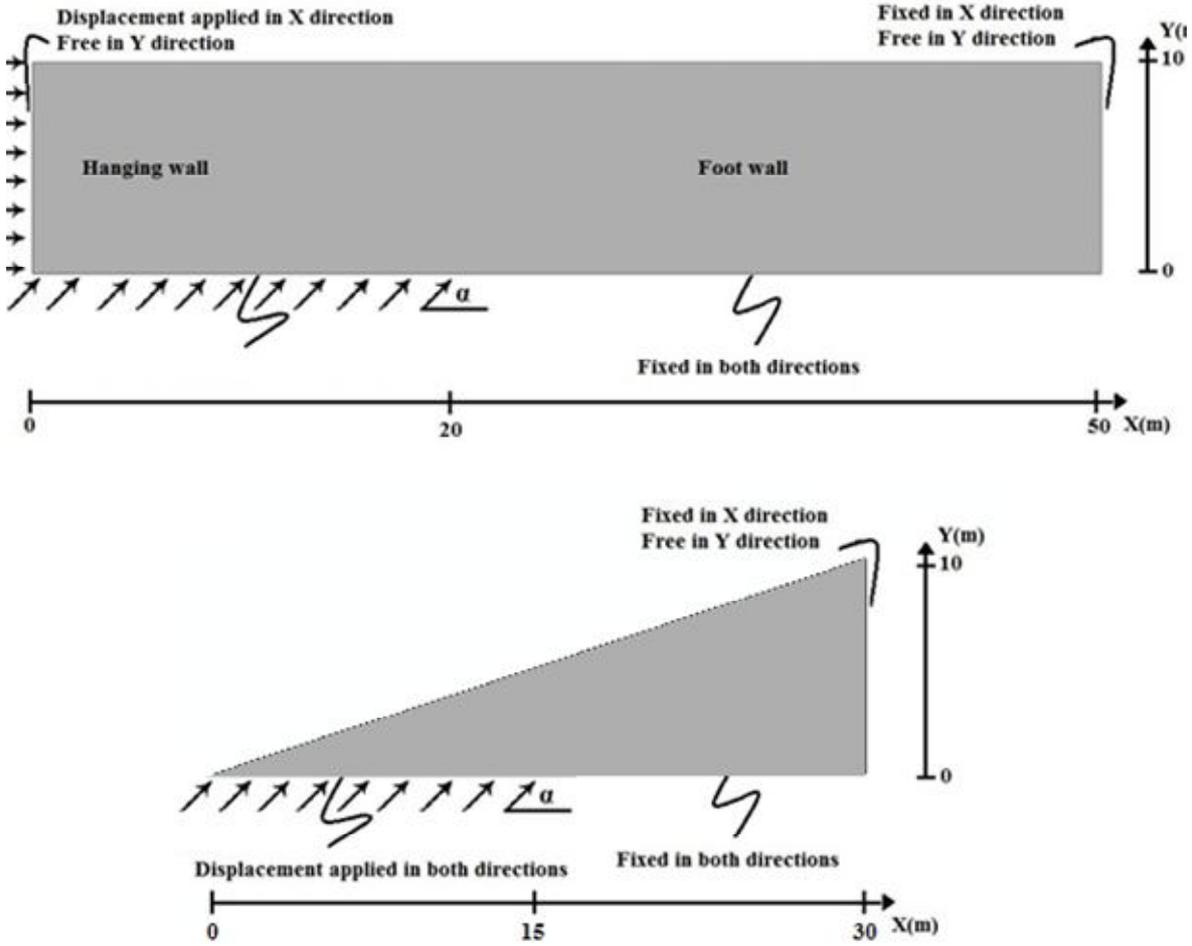


Figure 2.1. Horizontal soil model and boundary conditions

The soil layers are composed of uniform cohesionless materials. Soil behavior is modeled with Mohr-Coulomb elasto-plastic constitutive model and Menetrey-Willam flow potential to have a nonassociated flow rule for more realistic predictions of deformations.

Three soil types are considered and abbreviated to LS for Loose Sand, MS for Medium dense Sand and DS for Dense Sand. The values assigned to the input parameters of the constitutive model are shown in Tab. 2.1. According to the literature, a vertical base displacement of 2-6 percent of the height of the layer is needed for the rupture to reach the surface. Herein, a vertical base displacement of 4 percent of the height of the layer (which will be 40 cm) is employed. The dip angle (the angle of fault direction with horizon, α) is assumed 30°, 45°, 60° and 75°.

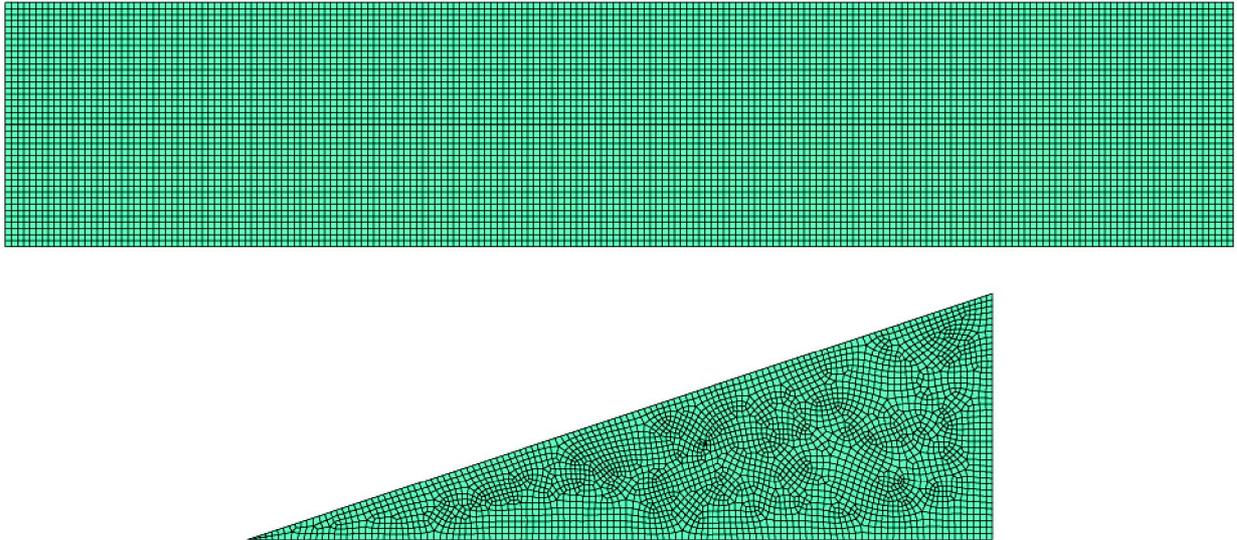


Figure 2.2. Meshing of the problem

Table 2.1. Soil parameters used in numerical simulation

Material	Abbreviation	$\gamma(kN / m^3)$	φ^0	ψ^0	ν	$c(kPa)$	$E(MPa)$
Loose Sand	LS	18	30	0	0.3	5	10
Medium Dense Sand	MS	19	38	8	0.3	5	20
Dense Sand	DS	20	46	16	0.3	5	40

2.2. VERIFICATION

The results from numerical analyses are compared to the physical modeling results reported by Cole and Lade on sand (Cole and Lade, 1984). According to them, the testing apparatus consisted of a 142 cm long, 56 cm high and 15 cm wide glass-walled box. One half of the box was stationary and the other half moveable along various angles. The friction angle for sand was 58° and the angle of dilation was measured 30° . The average dry density of the sand was 1.627 g/cm^3 . The same dimensions and soil parameters are defined in the numerical model.

Fig. 2.3 displays the fault rupture surface for dip angle 60° in the physical model. In the numerical simulations, the rupture surface is as a shear band with a maximum shear strain at its center line representing the rupture path (Fig. 2.4). Fig. 2.5 compares fault rupture paths in numerical simulations with experimental results of Cole and Lade for 4 different dip angles. The results for 30° and 60° are similar. Fault trace location for 75° is close to the test result but fault path has lower curvature. The rupture path of physical tests for 45° is the same as 60° , it seems an unusual test result. but numerical modeling shows it between 30° and 60° , that is more reasonable.

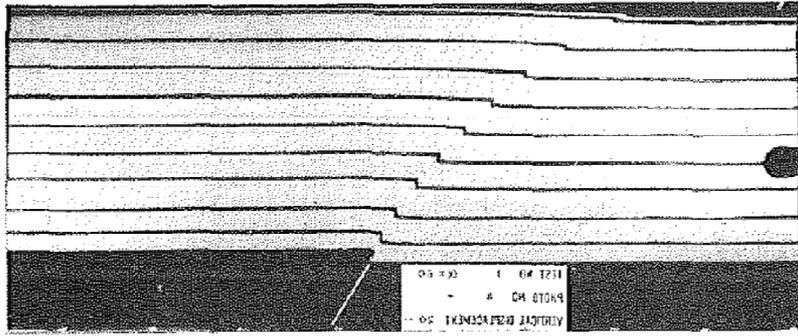


Figure 2.3. Developed failure surface in dense sand with dip angle 60° (Cole and Lade, 1984)

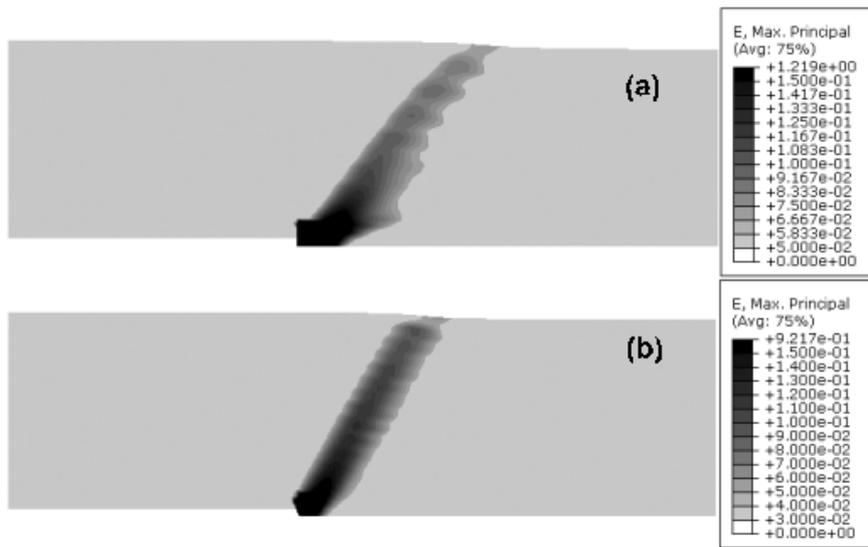


Figure 2.4. Fault rupture propagation in numerical modeling (a) Reverse fault 60° (b) Reverse fault 75° in dense sand

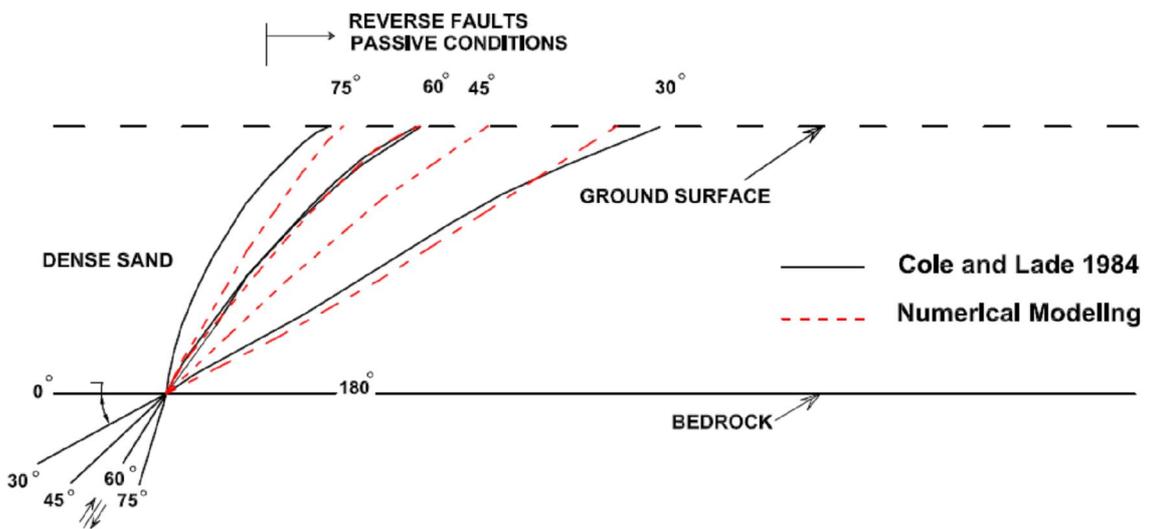


Figure 2.5. Comparison between numerical and experimental results

3. RESULTS

Soil response to base displacement for 4 different dip angles and for 3 different soil types are investigated. The results show some general aspects of fault rupture propagation together with new findings. The general trend of decreasing in dip is seen as the fault rupture propagates from the bedrock through the overlying soil toward the ground surface (Fig. 3.1). This was previously reported by many researchers (e.g. Bray et al., 1994; Lin et al., 2006).

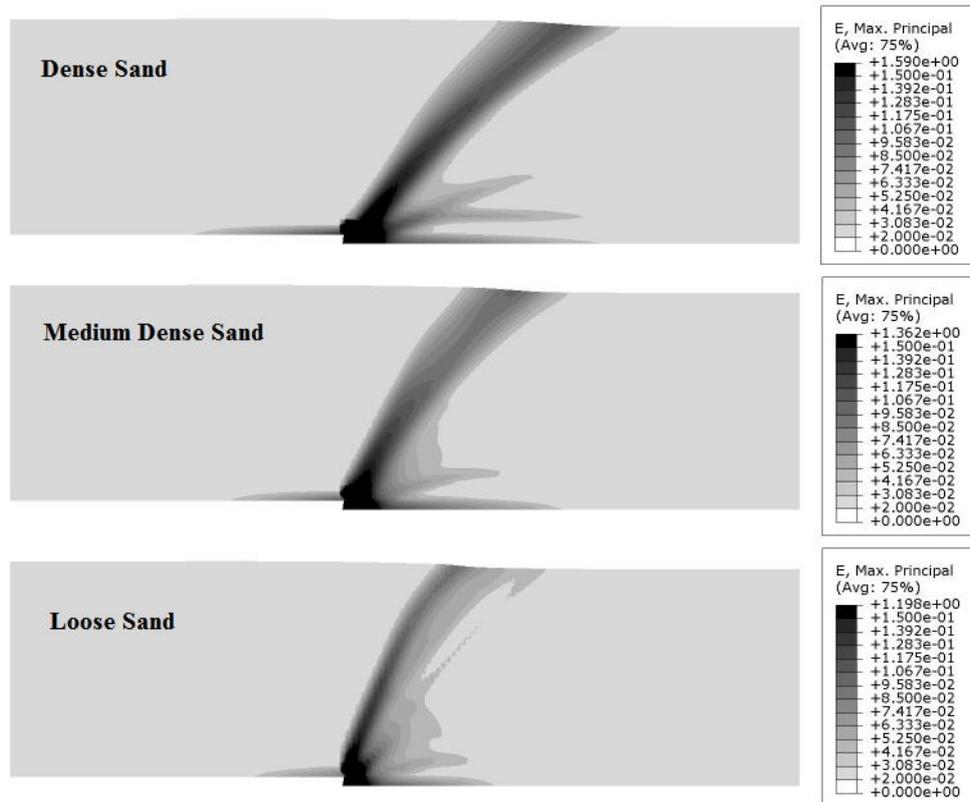


Figure 3.1. Fault rupture propagation for reverse 45° fault through three different sand types

One of the important discussions in geotechnical engineering is the direction of failure surfaces. According to Mohr-Coulomb failure criteria, failure surface has the angle of $45 - \phi/2$ in the passive case and $45 + \phi/2$ in the active case. In the classical approach, failure surfaces are of stress characteristics and related to ϕ . However, further studies have shown that the material behavior at failure is much related to dilation and thus to ψ . Reverse faulting is in analogy with the passive case of soil. In the base of the model, the surrounding boundary imposes failure plane which is almost in the continuation of dip angle. Near the surface, the effect of boundary is reduced and in horizontal layers failure surface is anticipated to incline at the angle of $45 - \psi/2$.

In this study, the angle of fault rupture near the surface is measured in horizontal layers with three soil types and for four dip angles (Fig. 3.2). The difference between ψ and ϕ is dominant in sandy soils. Therefore, the surface angles of rupture paths in sand is compared with $45 - \psi/2$ and $45 - \phi/2$. Fig. 3.3 shows the angle of fault rupture near surface for each soil. The corresponding values of $45 - \psi/2$ and $45 - \phi/2$ are presented in each graph.

It is seen that the surface angles are in good agreement with $45 - \psi/2$ values of the soils. It should be emphasized that the soil surface angles are independent of the dip angles. As an example, the surface

angles in the dense sand for 30 and 75 degrees reverse faults are the same. This new finding has an important practical and engineering meaning. Regardless of the dip angle of the fault, the surface outcrop angle is related to the soil specifications.

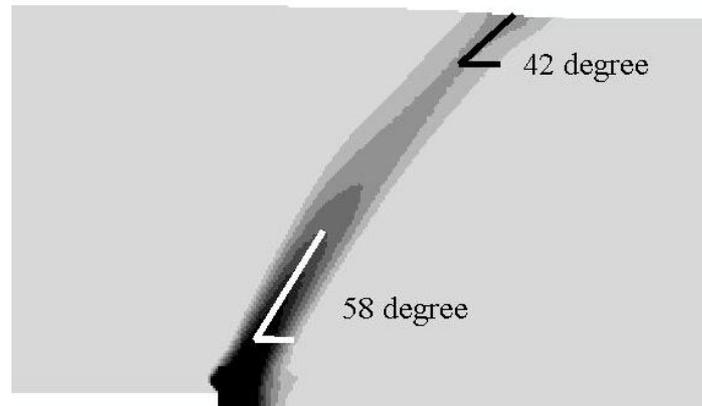


Figure 3.2. Fault rupture inclination for 60 degree reverse fault for dense sand for 4 percent vertical displacement

In sloping surfaces, the principle stresses are not in horizontal and vertical directions and usually the minor principle stress is in the direction of slope and the major principle stress is perpendicular to slope (Fig. 3.4).

The effect of slope on minimum and maximum stress directions changes the surface angle of rupture. Consequently the surface rupture angle in simulation of the sloping sand is $45 - \psi/2$ with respect to the direction of the minimum principle stress which is in the slope direction; on the other hand $45 - \psi/2 \pm \arctan(\text{slope})$ with horizon. Fig. 3.5 demonstrates the surface angle in the slope 1:3 for three sand types in different fault dip angles. Agreement between resulting angles and $45 - \psi/2 \pm \arctan(1/3)$ is observed.

The numerical simulations of fault rupture propagation shows steeper pattern in the loose sand in comparison with the same problem in the dense sand. Fig. 3.6 shows fault rupture propagation for 45 degree reverse fault in three different soils. The more bending rupture in dense sand and steeper pattern in loose sand is obvious in the results. Steeper path results in less horizontal distance between fault outcrop on ground surface and fault trace at bedrock.

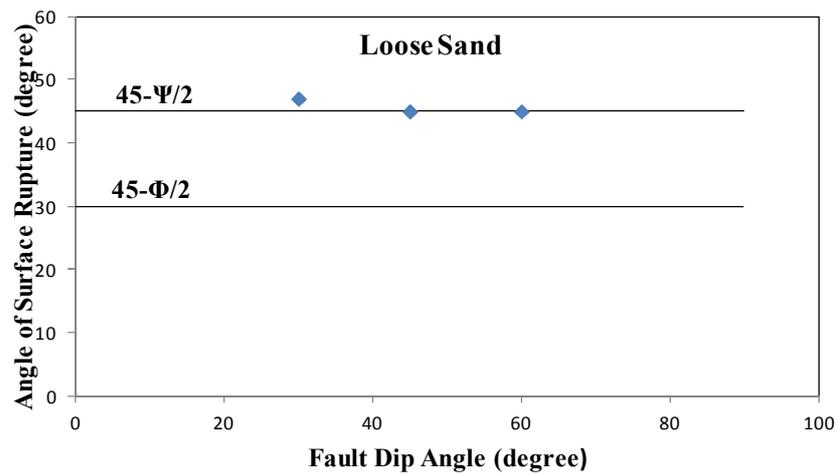
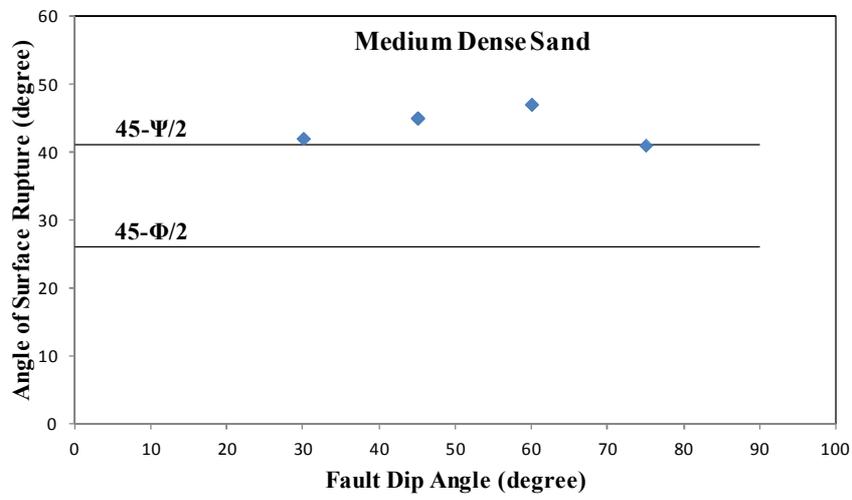
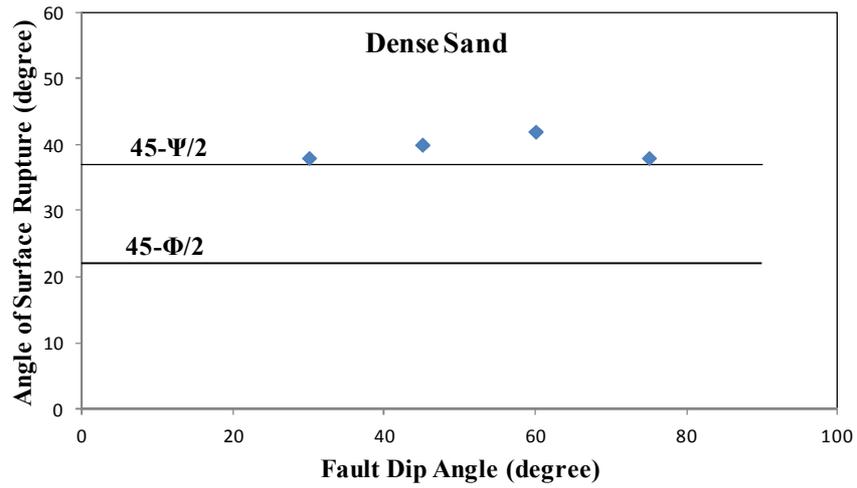


Figure 3.3. Angle of fault rupture near surface in horizontal layer

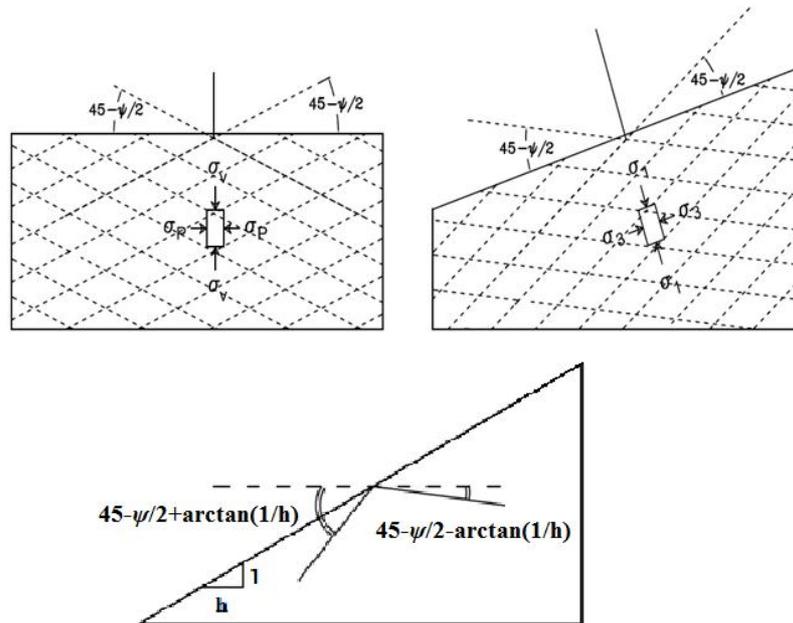


Figure 3.4. Direction of failure surface in sloping and horizontal layers

4. CONCLUSIONS

Numerical simulations of the rupture propagation of dip-slip faults (reverse) through a uniform horizontal and sloping soil layer were conducted using finite elements method. The Mohr-Coulomb constitutive model is used in this study to represent behavior of soil. The non-associated flow rule is employed to have realistic deformations. The numerical finite element simulation is proven to be a useful tool in fault rupture propagation estimation through comparison of numerical predictions with small-scale 1g tests.

The analyses were performed for three soil types (dense sand, medium dense sand, loose sand) and various fault dip angles. Studies depict general aspects of fault rupture propagation and peculiar surficial patterns of it. Bending of fault rupture toward the footwall is detected. It is shown that the angle of fault rupture near the surface is independent of dip angle and a function of soil type and ground surface slope. As a general finding, the importance of soil type and ground slope has been emphasized through investigation of the results.

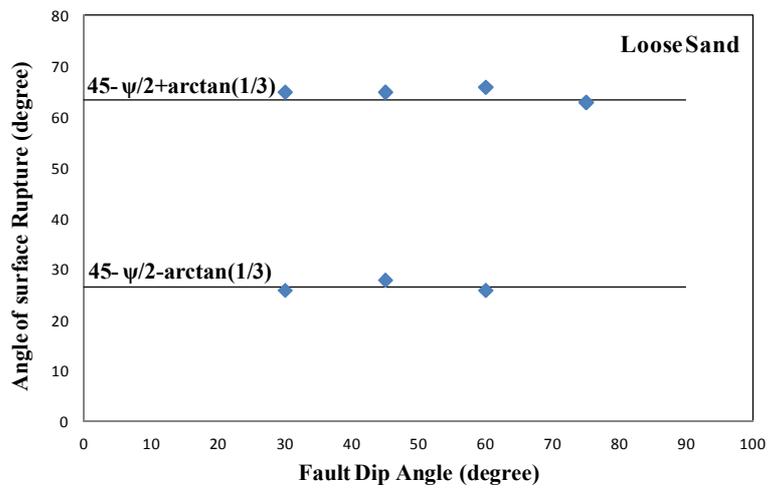
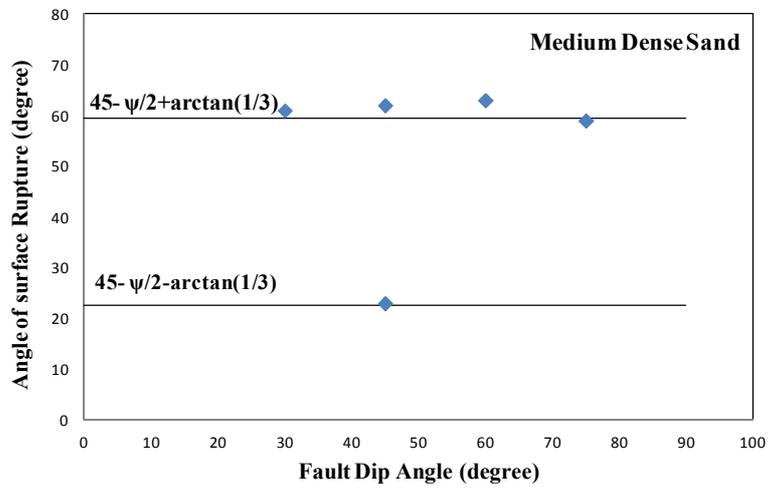
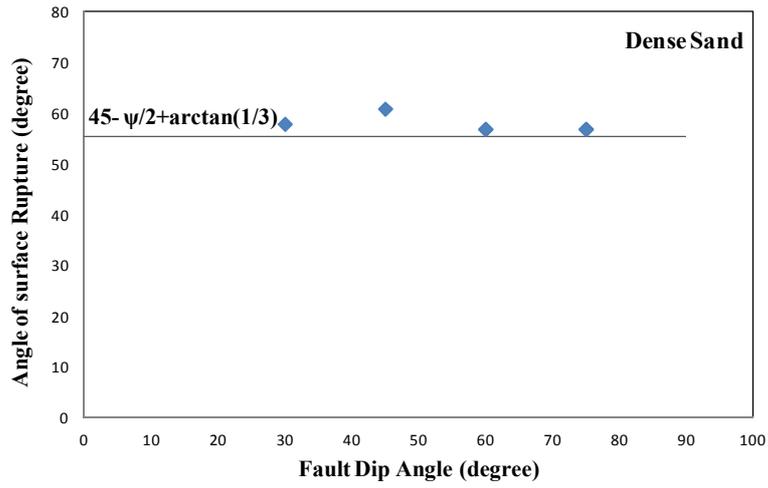


Figure 3.5. Angle of fault rupture near surface in sloping layer

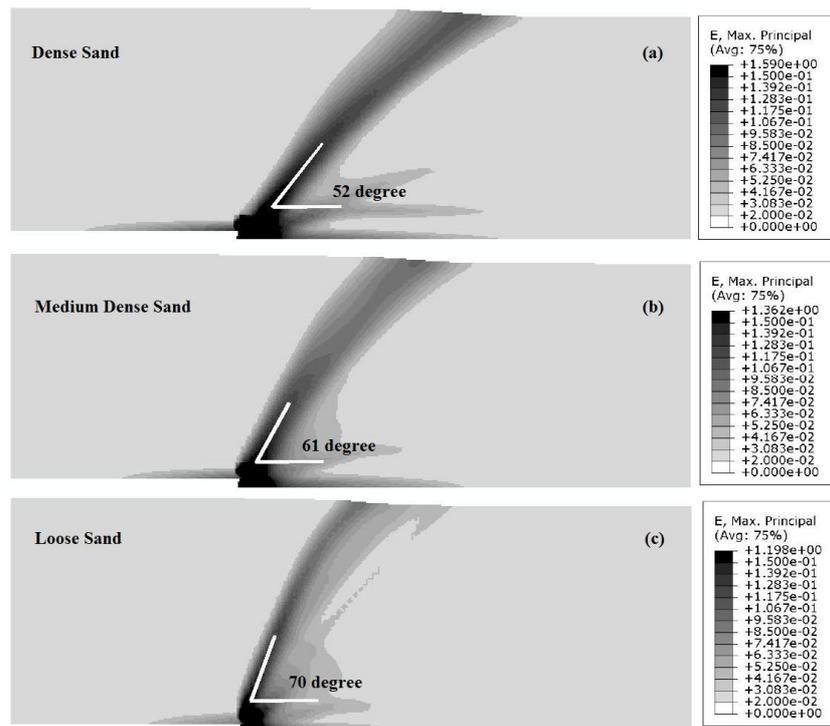


Figure 3.6. Fault rupture propagation for reverse 45° fault in a) DS, b) MS, and c) LS

REFERENCES

- Anastasopoulos, I., Gazetas, G., Bransby, M.F., Davies, M.C.R., Nahas, A.El.: Fault Rupture Propagation through Sand: Finite-Element Analysis and Validation through Centrifuge Experiments, *Journal of Geotechnical and Geoenvironmental Engineering*, 2007, 133(8), 943-958.
- Bonilla, M. G., Lienkaemper, J. J.: Visibility of fault strands in exploratory trenches and timing of rupture events, *Geology*, 1990, 18, 153-156.
- Bray, J.D., Seed, R.B., and Seed, H.B.: The effect of tectonic movements on stresses and deformations in earth embankments, Earthquake Engineering Research Center, University of California at Berkeley, Report No. UCB/EERC-90/13, 1990.
- Bray, J.D., Seed, R.B., Seed, H.B.: Analysis of earthquake fault rupture propagation through cohesive soil, *Journal of Geotechnical Engineering Division, ASCE*, 1994, 120(3), 562-580.
- Cole, D. A. Jr., Lade, P. V.: Influence zones in alluvium over dip-slip Faults, *Journal of Geotechnical Engineering Division, ASCE*, 1984, 110(5), 599-615.
- Johansson, J., Konagai, K.: Fault induced permanent ground deformations—an experimental comparison of wet and dry soil and implications for buried structure, *Soil Dynamics and Earthquake Engineering*, 2006, 26, 45–53.
- Johansson, J., Konagai, K.: Fault induced permanent ground deformations: Experimental verification of wet and dry soil, numerical findings' relation to field observations of tunnel damage and implications for design, *Soil Dynamics and Earthquake Engineering*, 2007, 27, 938–956.
- Lazarte, C.A.: The response of Earth structures to surface fault rupture, Ph.D. Thesis, Department of Civil Engineering, Univ. of California, Berkeley, 1996.
- Lin, M.L., Chung, C.F., Jeng, F.S.: Deformation of overburden soil induced by thrust fault slip, *Engineering Geology*, 2006, 88, 70–89.
- Loukidis, D., Bouckovalas, G.D., Papadimitriou, A.G.: Analysis of fault rupture propagation through uniform soil cover, *Soil Dynamics and Earthquake Engineering*, 2009, 29, 1389-1404.