Embedment Depth Effect on the Shallow Foundation - Fault Rupture Interaction

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SUMMARY:
The 1999 earthquakes in Turkey and Taiwan as well as the 2008 earthquake in China have increased the interest of engineering community on the structure behaviours subjected to surface fault ruptures. The field investigations represent which many structures have been constructed and/or are under construction in Iran and other places of the world which may be crossed by the surface fault rupture. Due to the uncertainties in predicting the exact fault traces, discover of the fault rupture propagations is difficult. Nevertheless, to find the main mechanism of fault rupture-shallow foundations interaction, there are several studies that discussed the interaction between fault rupture and foundations on ground surface without considering the depth of embedment. In reality, the foundations are found into ground and they have the embedment depth. Hence, in this paper, the numerical modelling by FLAC^{2D} software conducted to take in account the effect of the embedment depth in the shallow foundation-fault rupture interaction.

Keywords: Fault rupture, Shallow foundation, Embedment depth, Numerical modelling, FLAC^{2D}

1. INTRODUCTION

After the 1999 earthquakes in Turkey (Kocaeli and Duzce earthquakes) and Taiwan (Chi–Chi earthquake) as well as the 2008 earthquake in China (Wenchuan earthquake), which induced severe damages to building and infrastructures, detailed studies were performed to characterize the behaviour of structure when meet to surface fault rupture and identify the foundation-soil-fault rupture mechanism based on: interpretation of field investigations (Anastasopoulos and Gazetas, 2007; Faccioli et al, 2008), analytical methods (Yilmaz and Paolucci, 2007; Paolucci and Yilmaz, 2008), centrifuge experiments (Ahmed and Bransby, 2009; Loli et al, 2011) and numerical analyses (Anastasopoulos et al, 2007, 2009, 2010).

Several numerical studies, similar in their main features to these, have investigated the shallow foundation and dip slip fault rupture interaction (e.g. Anastasopoulos et al, 2007, 2009, 2010; Loli et al, 2011), and have led to realize the affecting parameters e.g. bearing pressure, foundation position and rigidity of foundation. These studies had focused on the interaction between fault rupture and shallow foundations on ground surface without considering the depth of embedment.

This paper is an investigation of shallow foundation embedment effect on the interaction between 60° dip-slip fault and shallow foundation by FLAC^{2D} Finite-Difference (FD) software. Fig. 1 shows a typical illustration of interaction between shallow foundation and reverse fault rupture. The reverse dip-slip fault propagates in 60° dip angle relative to horizontal. In the free-field condition, when the movable part of the split box (Hanging wall) moves up sufficiently, the failure surface completely develops through the entire height of the soil, as it can be seen in Fig. 1. The free-field fault rupture is as an indicator in numerical models to define the different position of foundation relative to fault rupture outcropping on the soil surface, s. A shallow foundation of breadth B and bearing pressure, q rests near the surface at depth, D. When the embedment depth, D is 0 (i.e. D=0), the foundation is surface footing.

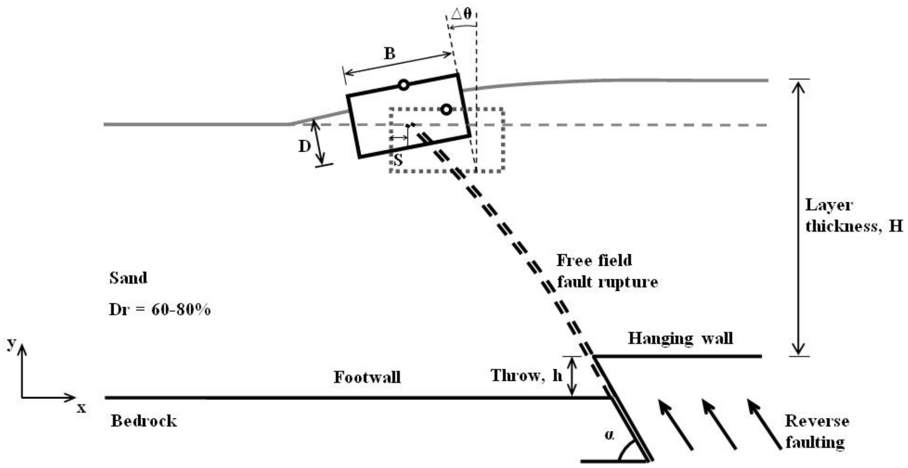


Figure 1. Schematic illustration of interaction between shallow foundation and reverse fault rupture

2. FINITE-DIFFERENCE MODELING METHODOLOGY

One of the first studies about the propagation of a fault rupture through soil has been reported by Bray et al. (1994). Afterwards, the studies performed by Cole & Lade (1984), Lade et al. (1984) and Anastasopoulos et al. (2007 and 2009) showed that the fault rupture propagation is highly dependent to the response in the yielding state, as well as in the post-yielding of the soil. Therefore, Mohr-Coulomb's elastoplastic constitutive model with the strain softening built-in FLAC software is capable of predicting successfully development of shear localisation in soil layer and is used in this numerical modelling. Furthermore, it should be mentioned that the large strain formulation is used in the simulation of faulting.

3. MESH AND BOUNDARY CONDITION

FD discretization of the numerical model relevant to reverse fault rupture propagation through soil layer is displayed in Fig. 2. It indicates a uniform soil layer of thickness H and at the base, the dip-slip fault is at angle α, ruptures and produces either downwards (normal fault) or upwards (reverse fault) displacement with a vertical component "h". The width of the numerical model is selected equal to L= 4H, following to Bray's recommendation (Bray, 1990), in order to minimize the undesirable effects of the boundaries. Meshing of the entire model is done with the 1m×1m quadrilateral elements. This selection is made as a result of the sensitivity analysis conducted by Anastasopoulos (2007). The non-uniform movement is applied to the right side of the model (Hanging-Wall) in small consecutive pseudo-static steps.

4. VALIDATION OF THE NUMERICAL MODELING RESULTS BY THE TEST RESULTS OF THE CENTRIFUGE

A set of centrifuge tests has been conducted at the University of Dundee, in order to study the interaction between dip-slip fault ruptures and shallow foundations (El Nahas et al., 2006). For more details about these tests see Bransby et al (2008a, b). In these tests, the interaction between 60° dip slip fault rupture and shallow foundation are being studied for two types of the normal and reverse faults. Also, Fontainebleau sand (Gaudin, 2002) has been used with 60% and 80% relative density (Dr). The soil parameters of the laboratory models calibrated by Anastasopoulos et al. (2009) are briefly shown in Table 1.

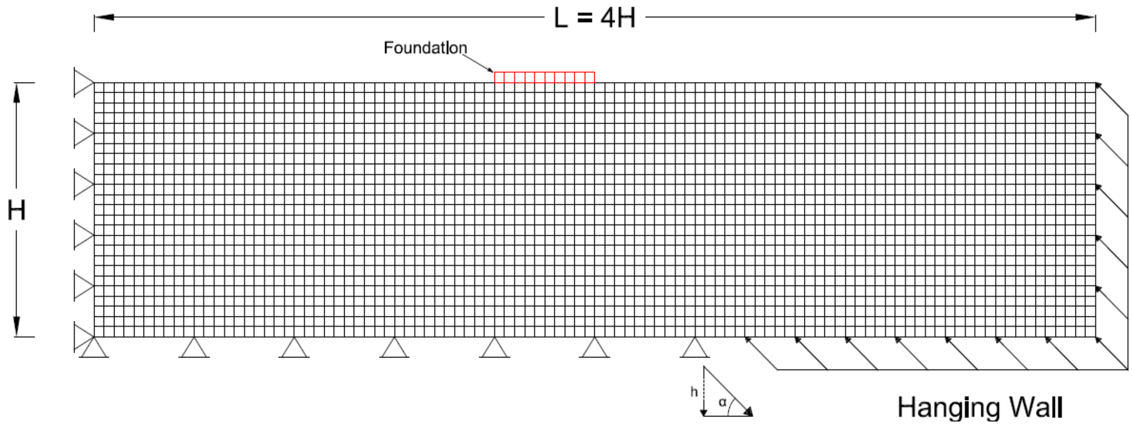


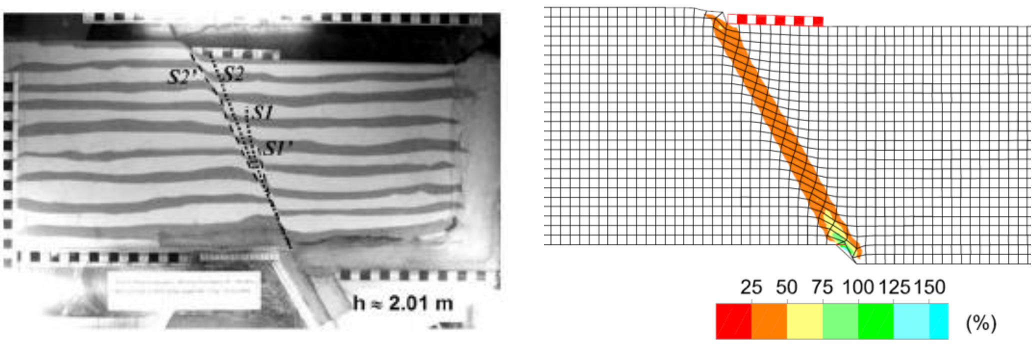
Figure 2. Problem geometry, finite-difference mesh and boundary condition of reverse faulting

Table 1. Calibrated Fontainebleau sand parameters (Anastasopoulos et al., 2009)

Relative density, Dr (%)	Peak friction angle, φ_p (°)	Residual friction angle, φ_{res} (°)	Peak dilatancy angle, ψ_p (°)	Residual dilatancy angle, Ψ_{res} (°)	Plastic shear strain, γ^P (%)	Density, γ (kg/m^3)
80	39	30	11	0	0.215	1700
60	34	30	6	0	0.244	1570

4.1. The interaction of rigid B=10m foundation with surcharge load q=90kPa in s=2.9m subjected to normal 60° faulting

In this test, the foundation of width B=10m and distributed load q=90kPa, subjected to normal 60° faulting through a soil layer of thickness H=25m and relative density of Dr=60% (Bransby et al., 2008a). The foundation is positioned on the soil surface at distance from the free-field emergence s=2.9m (see Fig. 1). The shear strain contours is schematically compared at the centrifuge model test and FD numerical analysis in Fig. 3. As it can be expressed, the numerical model almost correctly shows the location of fault emergence adjacent to the foundation and the main rupture. But as it is seen in Fig. 3.a, a set of secondary ruptures exists in the centrifuge model test, where the numerical model (Fig. 3.b) couldn't display these ruptures.



(a) (b)

Figure 4. Interaction of rigid 10 m foundation, subjected to surcharge load q=90kPa and distance s=2.9 m relative to free field rupture (a) centrifuge model test image, (b) Finite-Difference deformed mesh with shear strain contours, for h=2.01 m

Also, the vertical displacement profile of soil surface subjected to normal faulting shows the results of the numerical model and the centrifuge model test have good agreement (Fig. 4.a). Besides, the foundation rotation Δθ with respect to the fault movements is depicted in Fig. 4.b. The results also show the good agreement between the numerical model and centrifuge model tests in prediction of foundation rotation Δθ.

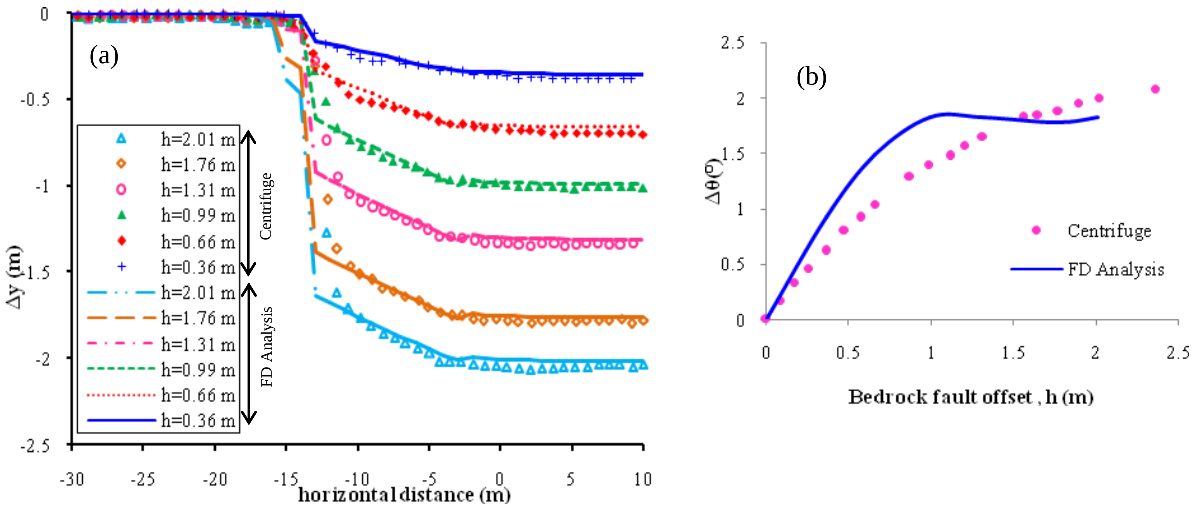


Figure 5. Interaction of rigid 10 m foundation, subjected to surcharge load 90 kPa and left side distance s=2.9 m relative to free field rupture with normal fault (a) surface vertical displacement profile, (b) foundation rotation Δθ

4.2. The interaction of rigid B=10m foundation with surcharge load q=37kPa in s=5.9m subjected to reverse 60° faulting

In this test, the foundation of width B=10m and distributed load q=37kPa, subjected to reverse 60° faulting through a soil layer of thickness H=25m and relative density of Dr=70% (Bransby et al., 2008b). The foundation is positioned on the soil surface at distance from the free-field outcropping on soil surface, s=5.9m.

The investigation of vertical displacement profile of soil surface subjected to reverse faulting shows some discrepancies between the numerical model and the centrifuge model test (Fig. 5.a). Also, the foundation rotation Δθ with respect to the fault movements is depicted in Fig. 5.b. However, the results show the good agreement between the numerical model and centrifuge model tests in prediction of foundation rotation Δθ.

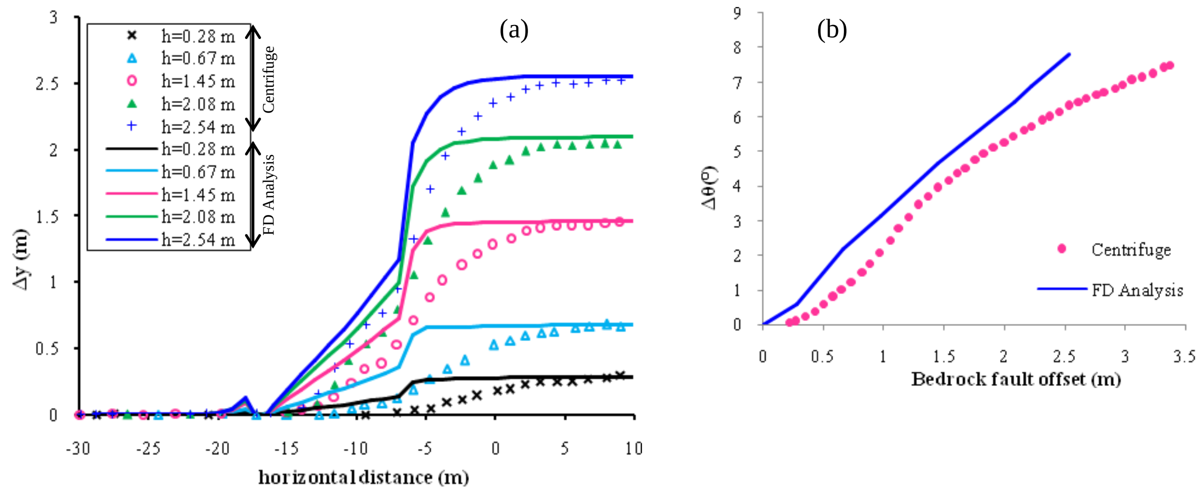


Figure 5. Interaction of rigid 10 m foundation, subjected to surcharge load 37 kPa and left side distance s=5.9 m relative to free field rupture with reverse fault (a) surface vertical displacement profile, (b) foundation rotation Δθ

5. THE NUMERICAL ANALYSES OF THE EFFECT OF FOUNDATION EMBEDMENT DEPTH AND DISCUSSION

A series of the FD numerical analyses is performed on the interaction shallow foundation and dip-slip fault rupture with considering the foundation embedment depth. The considered foundation embedment depths in this study are D=0 (surface foundation), 1m and 2 m (embedded foundations). The depth of D=0 is respected to the foundation on the surface (without the embedment depth). The numerical analyses fulfilled are as below:

- Analysis #I: B=10m, q=91 kPa, s=3.0m – normal faulting
- Analysis #II: B=10m, q=37 kPa, s=3.0m – normal faulting
- Analysis #III: B=10m, q=91 kPa, s=8.0m – normal faulting
- Analysis #IV: B=10m, q=91 kPa, s=4.0m – reverse faulting
- Analysis #V: B=10m, q=37 kPa, s=4.0m – reverse faulting

It is worth mentioning that in these numerical models the foundation width (B) is kept constant; and the surcharge on the foundation (q) and the distance of free field fault rupture emerging with foundation beneath (s) have been changed. Furthermore, the soil depth (H) and the relative density (Dr) are taken 25m and 60%, respectively.

5.1. Analysis #I: B=10m, q= 91kPa, S=3.0, normal faulting

In this numerical modeling, the foundation is situated in three various depths, D=0 (at the soil surface), D=1m and D=2m. The variation of foundation rotation $\Delta\theta$ with respect to the fault offset is shown in Fig. 6. As depicted in the Fig. 6, generally, increasing the foundation embedment depth, D increases the foundation rotation $\Delta\theta$. Also, it can be observed as the foundation embedment depth increases in less vertical offsets of fault (h), the foundation rotation $\Delta\theta$ decreases. The reason for decreasing the rotation subjected to less fault movements could be due to the surrounding soil preventing the foundation from rotating, but when the foundation is situated on the soil surface it can rotate more and without restriction. However, regarding to the more fault movements, as the foundation is situated on the soil surface it can slip and consequently the rotation can be reduced, but for the foundation embedded in the soil, it is subject to the additional rotations which are applied through the fault due to the surrounding soil preventing from the slip.

It is worth mentioning that the dominant mechanism of the interaction is rotational mechanism in less fault movements; and the rotational-slippage mechanism is dominant in the large fault movements.

5.2. Analysis #II: B=10m, q= 37kPa, S=3.0, normal faulting

Having compared to the analysis #I, the difference of this analysis is in the surcharge applied to the foundation. The foundation rotation $\Delta\theta$ with respect to the fault offset is shown in Fig. 7. As it is observed in this Figure and in the comparison of the results of analysis #I (see Fig. 6), the same results of the analysis #I can be obtained by reducing the foundation surcharge load.

5.3. Analysis #III: B=10m, q= 91kPa, S=8.0, normal faulting

In order to study the effect of foundation position relative to free-field fault rupture (s), the foundation position has been changed. The change with respect to this analysis (Fig. 8) which is observed when compared to analysis #I (Fig. 6) is related to the required fault offset to change the mechanism of the fault rupture-foundation interaction from rotational to slippage-rotational mechanism which is due to the difference at the foundation positions in analyses I and II. The fault outcropping beneath the foundation in analysis #I is on the left side of the foundation center of gravity, and in analysis #II it is on the right side. Therefore, Analysis #II requires more fault offset to convert the rotational mechanism to slippage-rotational one.

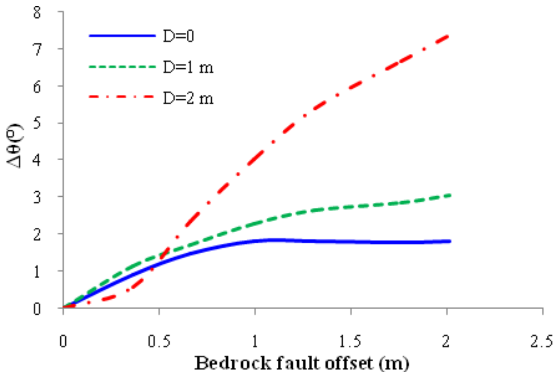


Figure 6. Rotation Δθ due to interaction of rigid 10 m foundation, subjected to surcharge load 91 kPa and left side distance s=3.0 m relative to free field rupture with normal fault (analysis #I) – Dr=60%

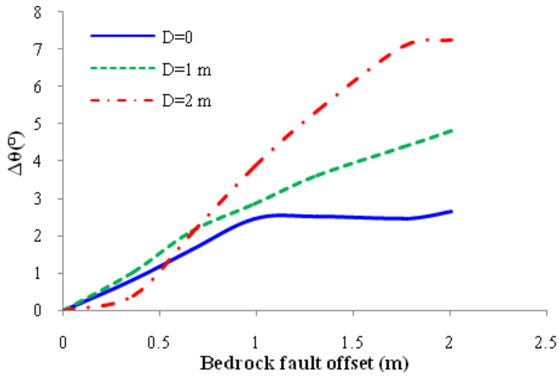


Figure 7. Rotation Δθ due to interaction of rigid 10 m foundation, subjected to surcharge load 37 kPa and left side distance s=3.0 m relative to free field rupture with normal fault (analysis #II) – Dr=60%

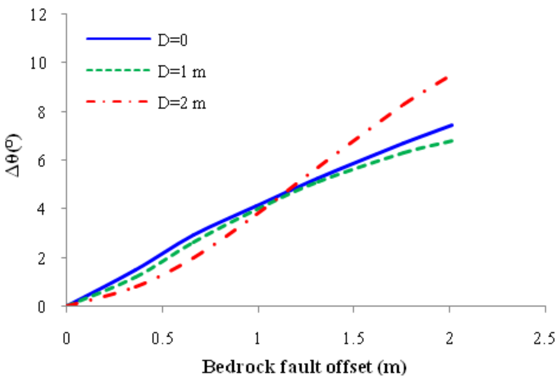


Figure 8. Rotation Δθ due to interaction of rigid 10 m foundation, subjected to surcharge load 91 kPa and left side distance s=8.0 m relative to free field rupture with normal fault (analysis #III) – Dr=60%

5.4. Analysis #IV: B=10m, q= 91kPa, S=4.0, reverse faulting

Also, the effect of foundation embedment depth on the foundation behavior is investigated for the reverse faulting. Fig. 9 shows the fault rupture propagation through soil for surface foundation (D=0) (Fig. 9a) and embedded foundation, D=2m (Fig. 9b), respectively. As illustrated in these figures, the embedment depth effects on the direction of rupture path when the foundation depth varies. The bifurcation phenomena is observed in Fig. 9a. However, the embedded foundation (Fig. 9b) has slightly made chang the type and direction of fault rupture.

The foundation rotation with respect to the reverse fault offset is shown in Fig. 10. It can also be concluded that the foundation rotation is increased with the increasing of the foundation embedment depth, but the changes rate is not very large. As it is observed in Fig. 11, the fault rupture outcropping (the reverse faulting) on the left side of the foundation, the soil is lifted up (as indicated in circles in Fig. 11a, b). Therefore, this prevents foundation from the slip. Hence, the rotational mechanism is not converted to the slippage-rotational mechanism by increasing the fault offset.

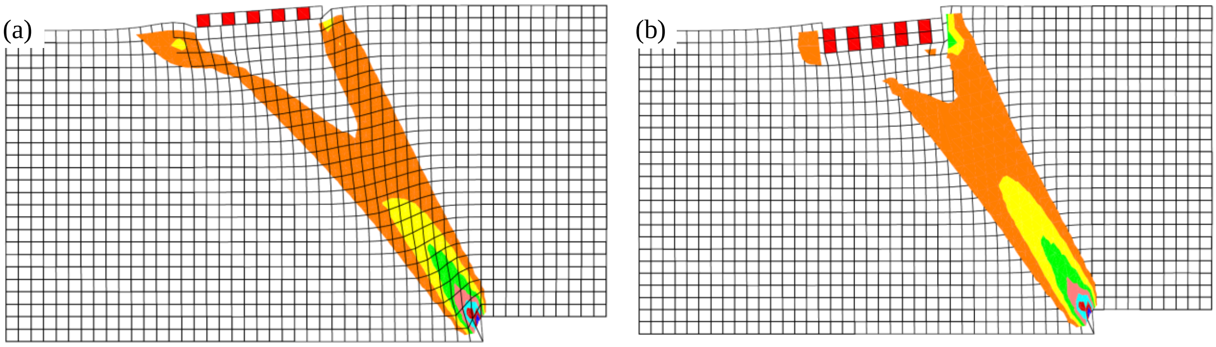


Figure 9. Interaction of rigid 10 m foundation, subjected to surcharge load (q) 91 kPa and left side distance s=4.0 m relative to free field rupture with reverse fault (analysis #IV) (a) deformed mesh with shear strain contours, surface foundation, D=0, (b) deformed mesh with shear strain contours, embedded foundation, D=2m, for h=2.0m

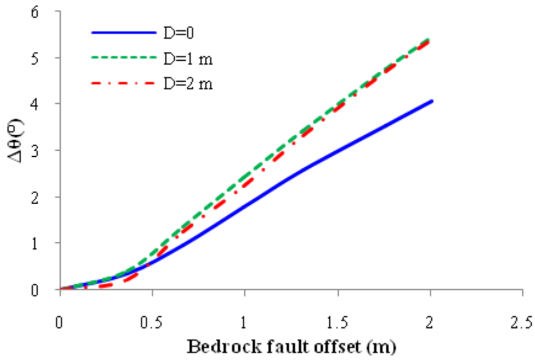
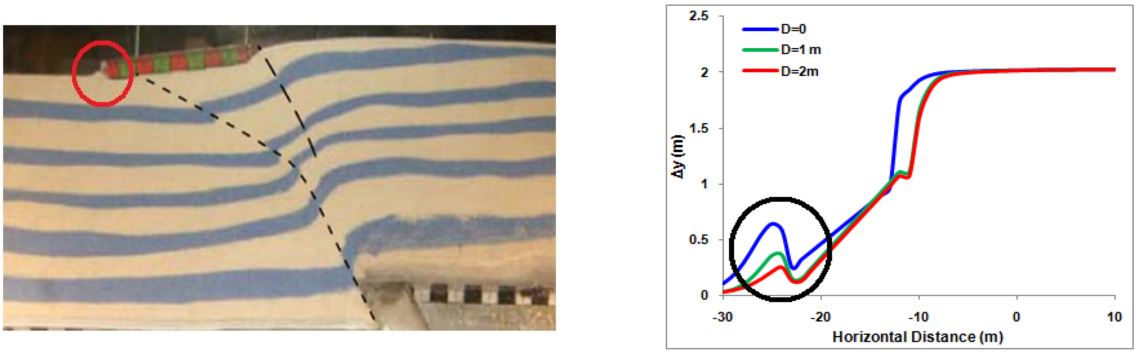


Figure 10. Rotation Δθ due to interaction of rigid 10 m foundation, subjected to surcharge load 91 kPa and left side distance s=4.0 m relative to free field rupture with reverse fault (analysis #IV) – Dr=60%



(a) (b)

Figure 11. Ground surface profile due to reverse fault rupture propagation through soil (a) centrifuge model test image (Bransby et al., 2008b), (b) Finite-Difference surface vertical displacement in analysis #IV

5.5. Analysis #V: B=10m, q= 37kPa, S=4.0, reverse faulting

Same as the analyses for the normal faulting, the effect of surcharge load on the foundation behavior subjected to reverse fault rupture is also carried out. As it can be observed in Fig. 12, with increase of the foundation embedment depth, its rotation also increases, but the changes rate is not too much.

6. CONCLUSION

In this paper, the effect of the foundation embedment depth on the shallow foundations-dip slip fault ruptures interaction has been investigated by the numerical modeling. The results show that the rupture mechanism of the shallow foundation without embedment depth (D=0) is different when the shallow foundation is embedded into the ground (D≠0). When the surface foundation (i.e. D=0) subjected to dip-slip fault rupture, the dominant mechanism is a combination of the rotation and slip of foundation on the soil surface (i.e. rotational-slippage mechanism), but by increasing the embedment depth, the dominant mechanism is the rotation of foundation (i.e. rotational mechanism). However, it is worth mentioning that it requires more precise studies to understand the rupture mechanism better.

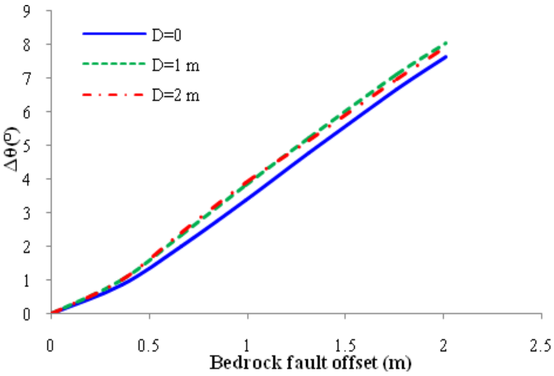


Figure 12. Rotation Δθ due to interaction of rigid 10 m foundation, subjected to surcharge load 37 kPa and left side distance s=4.0 m relative to free field rupture with reverse fault (analysis #V) – Dr=60%

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