Investigation of the Surface Fault Rupture Hazard Mitigation by Geosynthetics

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SUMMARY:
Ground differential movements due to faulting have caused damage to engineered structures and facilities in strong Earthquakes. Although surface fault rupture is not a new problem, there are only a few potential mitigation schemes in the world containing some type of provisions for reducing the risks. Fault setbacks or avoidance of construction in the proximity of seismically active faults, are usually supposed as the first priority but with increasing demands on land use, avoidance is becoming more difficult and so it would be prudent to have a reliable strategy available for protecting building over fault zone. This paper presents the results of an investigation of one potential mitigation scheme by using geosynthetics. Application of geosynthetic layers in the soil beneath the structure are investigated through physical and numerical modeling in this research. The results indicate that the geosynthetic reinforcement is effective in mitigating the significant hazards associated with earthquake fault rupture hazard.

Keywords: Fault Rupture, Mitigation, Geosynthetics

1. INTRODUCTION

During strong earthquakes fault rupture could arrive at the ground surface threatening the safety of the potentially existing structures. This could have devastating effects on structures overlying the faults such as what has been observed in Turkey and Taiwan earthquakes in 1999. These observations reminded the profession and researchers to devote more efforts on surface fault rupture hazard mitigation approaches and investigations.

Different approaches have been adopted to investigate the surface fault rupture hazard such as field studies (Faccioli et al. 2008, Bray et al. 1994, Lazarte et al. 1994, Bray and Kelson 2006, Anastasopoulos and Gazetas 2007, Jafari and Moosavi 2008), physical modeling (Cole and Lade 1984, Stone and Wood 1992, Bray et al. 1994a, Tani et al. 1996, Lee and Hamada 2005, Bransby et al. 2008, Moosavi et al. 2010), numerical modeling (Bray et al. 1994b, Anastasopoulos et al. 2007) and finally analytical approaches (Berill 1983, Yilmaz and Paolucci 2007).

The aim of this research is to contribute developing mitigation measures for protecting buildings against potential surface fault rupture hazards. A typical generic geometry of building in close proximity to faulting is presented in Figure 1 where a structure is considered above a shallow soil layer (around tens meters) overlying bedrock. During faulting, a displacement discontinuity at the bedrock propagates through the soil layer towards the surface. With a sufficient magnitude of fault displacement, this discontinuity will emerge at the ground surface. If the surface expression occurs beneath a structure, the structure would probably be damaged by a large differential displacement. There has not been done enough research to study such a problem and proposing some solutions for it. It is evident that avoiding construction in the fault rupture zone should be the first priority of the land use planning policy in the cities but with increasing demands on land use, the avoiding such a thing is becoming more difficult. Should the key structures be required in the vicinity of potentially active faults, it would be prudent to have a reliable strategy available for their protection. A potential mitigation scheme is investigated by using geosynthetics to reach such a goal. Application of geosynthetic layers in the soil beneath the structure are investigated through physical and numerical modelling in this research.

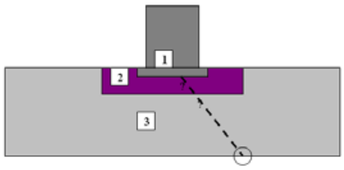

Figure 1. Schematic of a geotechnical improvement layer beneath a building for fault rupture hazard mitigation (1-building, 2-geotechnical layer, 3-shallow soil layer overlying bedrock surrounding the building)

2. FAULT RUPTURE MITIGATION MEASURES

A number of possible fault rupture mitigation measures have been proposed by Bray et al. (1993), Bray (2001), Tani (2003) and Brennan et al. 2007. These measures are mostly foreseen to absorb the fault large differential movement, leading to smaller differential displacements or gentle gradients at the ground.

Although using a geosynthetic layer near the surface to reduce differential displacement has been investigated before by others (such as Bray et al. (1993) and Bray (2001)), the differences between this research and them is that their findings are related to normal faulting and small base rock fault displacement while this article focuses on the behaviour of buildings in close proximity to reverse faulting and large base rock fault displacement. In this study, placing a geotechnical improvement layer beneath the foundation near the ground surface (Figure 1) to reduce the differential displacement of reverse dip slip faulting is introduced as a potentially useful method for mitigating surface fault rupture hazard as shown in Figure 2.

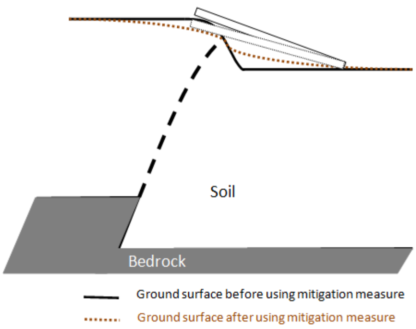

Figure 2. Reducing differential displacement of dip slip faults using a geotechnical improvement layer beneath the foundation

3. PHYSICAL MODELING

The 1-g physical modeling approach was adopted in the present study. The device used for performing the 1-g model tests was designed in such a way that the reverse fault rupture events could be modeled along different dip angles as well as the normal fault. Two Plexiglas plates with a thickness of 5 centimetres were provided at each side of the box and perpendicular to the fault strike, in order to enable digital photography of the vertical section throughout the soil (Figure 3). The performed tests investigated reverse fault rupture propagation with a dip angle of 45 degree through the bedrock in a quasi- static mode using a hydraulic piston beneath the moving floor.

Figure 3. The 1-g model tests apparatus

The sand used in the present study was the well known Firoozkooh sand (No.161), commercially available from the Firoozkooh mine in north east of Tehran. It has a uniformly graded (SP) size distribution as well as a mean grain size (D50) of 0.25 mm. The sand layer in the box had a length, width and thickness of 150, 50 and 20 cm, respectively, approximately modeling the plane strain condition. The pluviation technique with a pre-defined height and velocity of a sand rainer was also used to fill the box with a relative density of approximately 80% (Figure 4).

Figure 4. The pluviation technique with an electric sand rainer

To compare the test results as shown schematically in figure 2, firstly the propagation of a reverse fault through soil was conducted in absence of a footing ("free field test") to find where the free field fault would emerge at the ground surface, and then the test result was further used to locate the foundation position in the foregoing tests with presence of a foundation or so called the benchmark test(test identifier is 14N), and for the next step the test was held (test identifier is 23N) with a geosynthetic layer beneath the footing. The middle of width of the geotechnical layer in test 23N is located in middle of width of the footing in the benchmark test (test identifier is 14N). A block, with a width (B) of 150 mm, a height of 20mm and a length of 500 mm, was placed on the top surface of the soil in order to represent the rigid shallow footing and imposed with a bearing pressure of 0.5 kPa. The geotechnical layer in test 23N is located in the depth of 50 mm. The two tests (14N & 23N) were carried out on a soil model of 1/100 scale, so soil depth of 20 cm is represented as a 20 m soil depth in the prototype and also the geotechnical layer depth is 5 m in the prototype. The main parameter that had to be compared in the results was the foundation rotation.

Geosynthetic materials, such as geotextiles and geogrid reinforcement element have been successfully used in soil structures such as walls, slopes and others. In this investigation based on the physical modeling of fault rupture propagation in sand, geogrid is selected to reinforce the sand. When geogrids are used as reinforcement and they are subjected to stress perpendicular to their horizontal plane, they deform like a membrane. The transverse members of the geogrid and the longitudinal ribs of it, together frictionally interact with the soil, mobilizing interfacial shear strength opposing the lateral flow. The frictional interaction is not just made by the interfacial one but also due to the passive resistance mobilized by the bearing of soil particles against the lateral (transverse) elements. So, geogrids generally offer a higher interfacial shearing resistance than geotextiles and because of that they were selected in this research. CE121 geogrid produced by MESHIRAN with 7.68 kN/m tensile strength is used. The length of it is 45 centimetres and is aperture size is 6*8mm.

Test results are shown in Figure 5 and also the results of the foundation rotation as a function of fault displacements is compared in Figure 6.

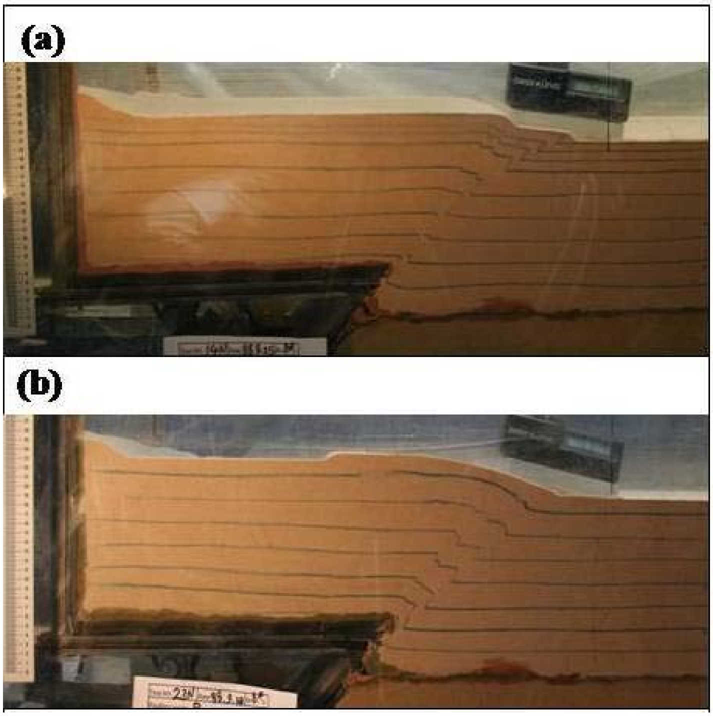

Figure 5. Test results with foundation; (a) benchmark test(14N) at 51.4mm fault displacements ; (b) Test 23N with geotechnical layer beneath the foundation at 51mm fault displacements

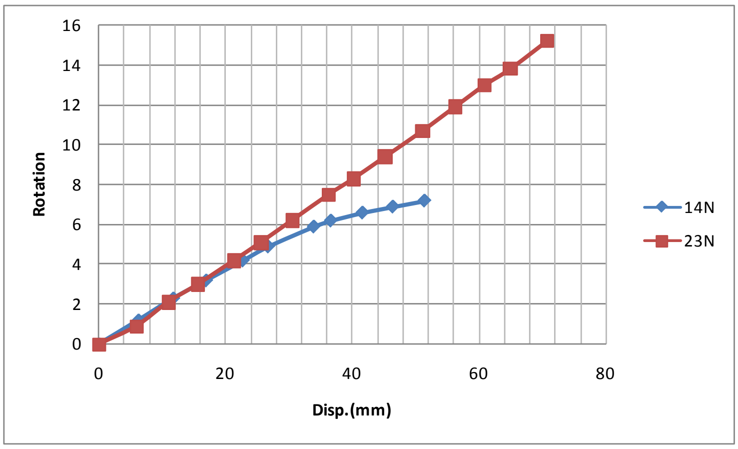

Figure 6. Foundation rotation (per degree) as a function of fault displacements test 14N (without geotechnical layer) and test 23N with geotechnical layer beneath foundation

4. DISCUSSION

Although based on foundation rotation (figure 6) it seems that geotechnical layer is not efficient, figure 5 has shown the main idea of this research on reducing differential displacement of dip slip faults (e.g. Figure 2) by using a geotechnical improvement layer beneath foundation is possible. There are two major factors affecting this problem such as changing mechanism and similitude considerations.

Regard changing mechanism, It can be explained that main mechanisms of fault-foundation interaction are as the following (also shown in figure 7):

- Mechanism A: Due to the presence of the rigid foundation, the fault is deviated to the right side, remaining the foundation undisturbed on the footwall.
- Mechanism B: The fault emerges beneath the foundation.
- Mechanism C: Due to the presence of the rigid foundation, the fault is deviated to the left side, remaining the foundation settling on the hanging wall.

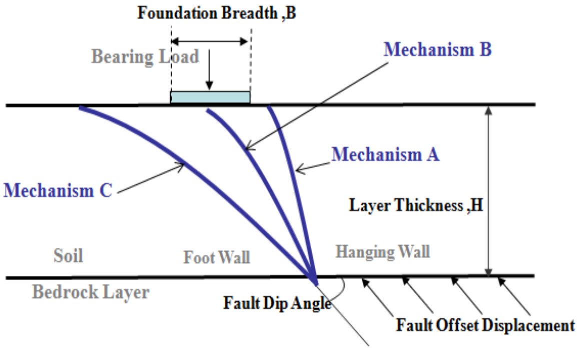

Figure 7. Main mechanisms of fault-foundation interaction

It is evident that a number of variables can significantly influence the reverse faulting-foundation interaction mechanisms. For example, the foundation's position and its bearing pressure will certainly influence interaction of the fault rupture propagation and the rigid shallow foundations mechanisms (Moosavi et al. 2010). Additionally, the footing breadth may be significant. Moreover; the magnitude of fault movement will exert considerable influence on the interaction of the fault rupture propagation and the rigid shallow foundations mechanisms.

Although in the test 14N the fault firstly emerges beneath the foundation (i.e. mechanism B), additional fault throw changes the form of fault rupture to another previously described mechanism (Figure 7) i.e. mechanism A. But in the test 23N no change of mechanism occurs which could be due to foundation-geotechnical layer interaction leading the increasing of bearing capacity.

Regard similitude considerations the scaling laws should be used exact. Although it is clear that perfect scaling down of the prototype geogrid to a desired scale factor may not be feasible, it is required to scale down the geogrid. Otherwise as it is discussed by Viswandham and Konig (2004), it ends up overestimating the effect of reinforcement in interpretation of test results. Reinforcing elements in soil structures provide improved stiffness via two modes; namely: (i) in plane tension and (ii) in bending. In geogrid reinforcement, the extensional stiffness is usually much greater than the flexural counterpart. When the geogrid is used over a large plan area the dominant reinforcement action is derived via extensional stiffness and this is an essential requirement of using reinforcing elements in soil for mitigation of surface fault rupture hazards in contradiction of bending stiffness, Because when a reinforcing element with high bending stiffness is used in soil two reactions may happen : (i) rigid displacement (ii) breaking, So there will be no interaction between the reinforcing element and soil. As shown in figure 8 it seems that although a very soft geogrid is used, the geogrid bending stiffness is not in a true scale.

So it seems that it is better to investigate application of geosynthetic layers in the soil as a potential mitigation scheme for surface fault rupture hazard by numerical modelling. On the other hand based on what was mentioned before it seems better to investigate the geogrid effect in this problem without footing, and also for making reinforcement action geogrid via extensional stiffness, the fault dip angle base displacement would be better to be around 90 degrees. In this regard numerical modelling will be considered under the conditions that were mentioned above.

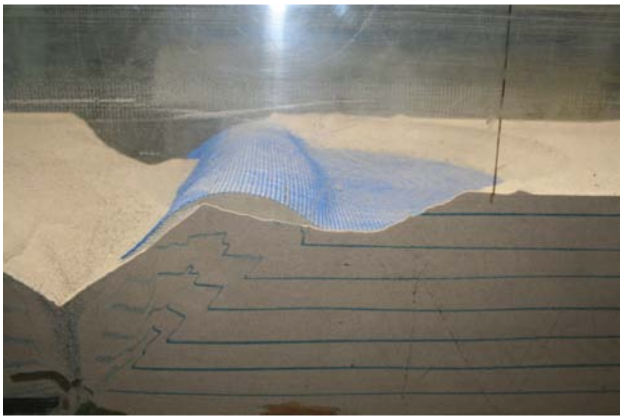

Figure 8. Geogrid situation beneath foundation after test 23N

Previous numerical studies of fault rupture propagation through earth materials suggest that the finite element method can be applied to this class of problems, providing an incremental nonlinear stress strain soil behavior model. The well known Plaxis Software based on the non-linear time-stepping finite element approach was used to carry out the numerical analysis. In addition Mohr-Coulomb model with the following mechanical properties was used to simulate the elasto-plastic behaviour of the Fontainebleau Sand (based on Anastasopoulos et. al, 2008):

- Friction Angle φ =37◦
- Dilation Angle ψ =0 ◦
- Elastic Modulus E=675MPa
- Poisson's Ratio ν=0.35

The geometry of the numerical model was assumed as shown in figure 9 and details of different cases are shown in Table 4.1. Interface elements similar to those used by Langen and Vermeer (1991) for analysis of trapdoor problems were used in order to model the onset of the rupture (Fig. 9). A rigid layer with a thickness of 5 meters was introduced beneath the soil layer in order to model the bed rock. The static displacement was imposed upwards at those boundary nodes lying at the right hand side of the fault rupture trace in order to simulate the reverse fault rupture through the bed rock. In all of the cases, the reinforcements were modeled as elastic geogrid elements in Plaxis Software with no bending stiffness and compression force. The geogrid elements used in the analyses were one dimensional axial elements described in terms of axial stiffness (EA).

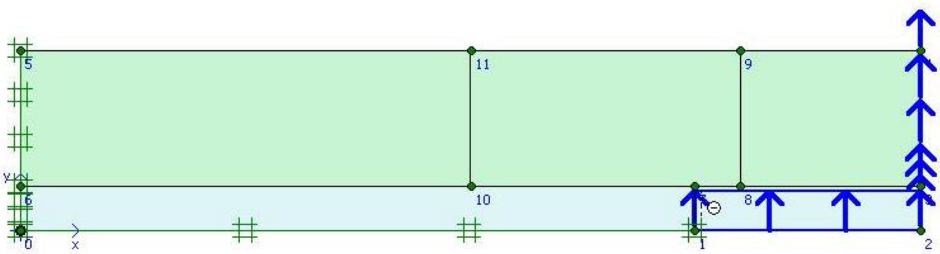

Figure 9. Geometry of the model

Table 4.1. Different Cases

Case Name	Case Description	Fault Dip Angle	Vertical Base Dislocation (m)	Soil Thickness (m)	Bedrock Thickness (m)
FF90	FREE FIELD WHITOUT GEOGRID	90	2.5	15	5
90A	WITH GEOGRID EA=10^4 KN/m	90	2.5	15	5
BFF90	FREE FIELD WHITOUT GEOGRID	90	1	4	2
B90A	WITH GEOGRID EA=10^4 KN/m	90	1	4	2

Figure 10 demonstrates the deformed geometry of the medium with the super imposed shear strain contours corresponding to the cases FF90. As can be seen in figure 11, regard displacement of surface, the numerical results confirm the main idea of the research on application of geosynthetic layers in the soil as a potential mitigation scheme for surface fault rupture hazard. On the other hand as can be seen in figure 10 shear band propagates in soil as a gradually reduce of dip angle from 90 degree occurs. As it was mentioned before for making reinforcement action geogrid via extensional stiffness, the fault dip angle base displacement would be better to be around 90 degrees. Two other cases were analyzed (BFF90 & B90A) and as can be seen in figure 12 the numerical results confirm this matter obviously.

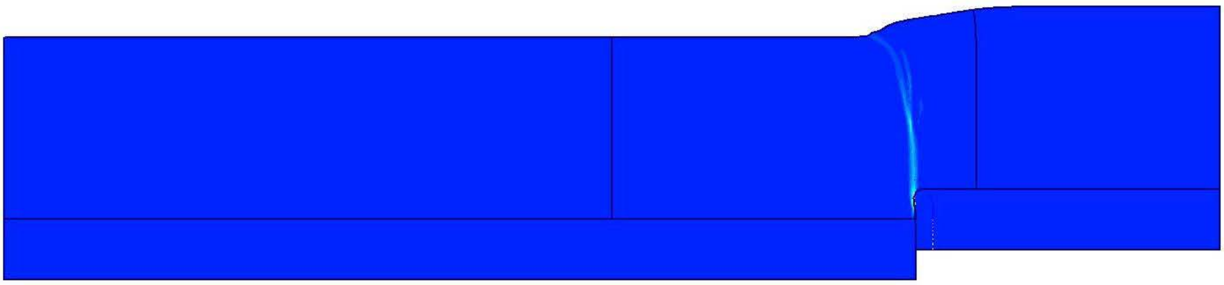

Figure 10. FE deformed mesh with shear strain contours(FF90)

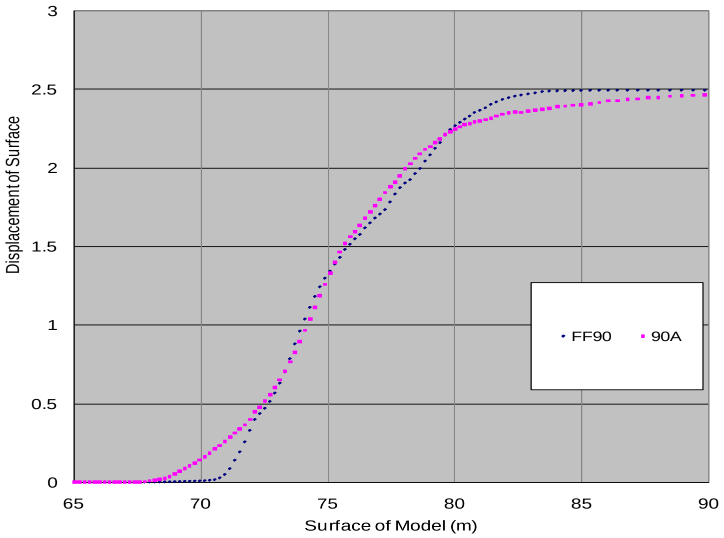

Figure 11. Surface Displacement

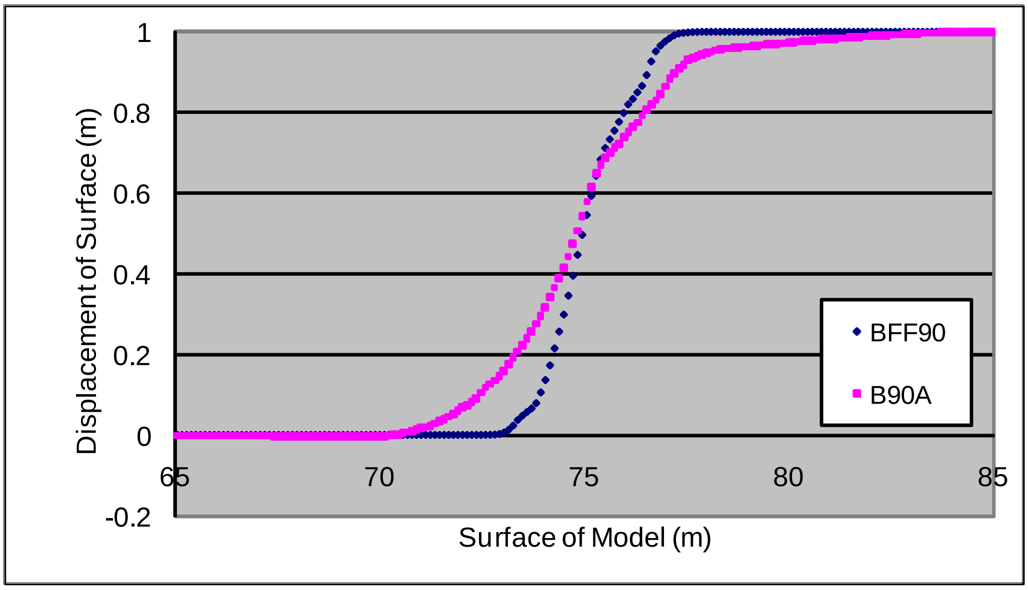

Figure 12. Surface Displacement

5. CONCLUSION

Using a geogrid layer beneath the foundation can decrease the magnitude of differential displacement leading us to an acceptable approach of mitigating surface rupture hazards, although in the term of decreasing the foundation rotation it seemed helpless but considering the interaction between the reverse fault propagation pattern and the rigid shallow foundation and numerical modelling in Plaxis showed that the main idea of the research on application of geosynthetic layers in the soil as a potential mitigation scheme for surface fault rupture hazard is acceptable and can be affective. In conclusion the physical modelling confirmed that geosynthetics can be a solution to surface fault rupture hazards although it should be pay more attention to this type of fault rupture hazard mitigation strategy. It would be the subject of our further investigation in our ongoing research in this field.

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