Research Paper

Numerical Modeling of a New Mitigation Measure for Reverse Surface Fault Rupture Hazards Effects on Buildings

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ABSTRACT

Surface fault rupture can lead to significant harm to engineered structures and facilities due to differential displacement in the ground. With the growing demand for land use, it might become essential to implement strategies to protect structures against hazards arising from fault rupture propagation. This study examines a novel mitigation approach utilizing an underpinning technique. To lessen foundation rotation during a fault rupture, a pile similar to the underpinning technique is employed beneath the foundation. This pile is not used to reinforce the main foundation; rather, it serves as a structural element to reduce hazards during a fault rupture with the removed support between the foundation and the pile. The effectiveness of this pile in the soil under the structure is evaluated through a series of numerical models. The findings suggest that while this pile is effective in mitigating the dangers of surface fault rupture, such as building rotation, its application should be guided by comprehensive geotechnical investigation given the complex nature of fault-foundation interaction issues.

Keywords:
Fault rupture;
Soil-structure interaction;
Mitigation; Piled foundation

1. Introduction

The devastating earthquakes in Turkey and Taiwan (1999) have increased engineers' focus on exploring the behavior of structures during the propagation of fault rupture. Since then, increased research efforts have been dedicated to understanding the mechanisms of surface fault rupture and the ensuing interactions with structures.

Different approaches such as field studies of Bray et al. (1994a), Lazarte et al. (1994), Lettis et al. (2003), Bray and Kelson (2006), Anastasopoulos and Gazetas (2007), Faccioli et al. (2008), Jafari and Moosavi (2008), and Bray (2009), numerical and physical modeling by Cole and Lade (1984), Bray et al. (1994b), Lee and Hamada (2005), Anastasopoulos et al. (2007, 2008), Faccioli et al. (2008), Bransby et al. (2008), Moosavi et al. (2010), Fadaee et al. (2012), and Zanjani and Soroush (2014) performed to study fault rupture hazards and its features. Based on studies of Bray (2009), observations of structure's attitude, when fault rupture arrives at the ground surface, have shown different structure behaviors due to their design techniques. In some of these structures, satisfactory performance has been observed. In some cases such as studies of Lettis et al. (1999), a good structure's performance and deviation of fault rupture trace on the ground surface due to foundation rigidity are notable. Similar examples of Bray (2009), Anastasopoulos and Gazetas (2007) confirmed this view that structures could also be designed to withstand large ground differential movements due to fault ruptures. In these researches, effective factors in fault rupture propagation have been investigated. In studies of Moosavi (2010), three patterns of reverse fault rupture emergence adjacent to a shallow foundation have been reported based on foundation position and its surcharge load (Figure 1).

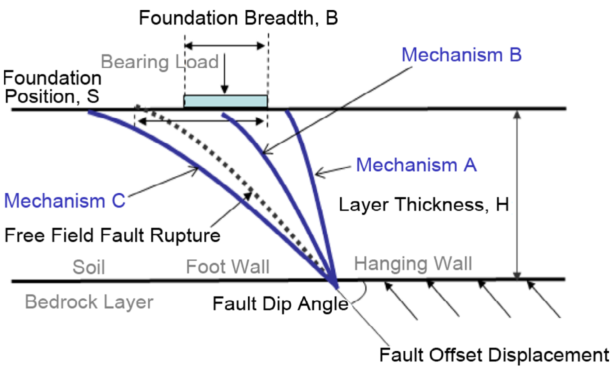


Figure 1. Fault-foundation interaction by Moosavi et al. (2010).

Several studies have been conducted to mitigate the hazards associated with fault rupture. Even though seismic codes prioritize fault setbacks and avoidance of construction in active fault zones, the increasing demand for constructible land enhances the relevance of research in this area. A survey of related literature reveals some of the measures that have been taken. For example, the use of geosynthetic layers beneath structures has been examined through physical and numerical modeling. This method has proven effective in mitigating fault rupture risks (Bray et al., 1993; Bray, 2001; Moosavi and Jafari, 2012). Other approaches include the use of large soil blocks to fragment the fault into smaller faults by Tani (2003) and the installation of a thick diaphragm-type soil bentonite wall (SBW) in front of and near the foundation by Fadaee et al. (2013).

In a study by Chiang et al. (2023), the effectiveness and optimal spacing of Geosynthetic-Encased Granular Columns (GECs) in mitigating ground surface deformation associated with reverse faulting was evaluated. The laboratory tests of this study revealed around a 30 percent reduction in the maximum angular distortion of the foundation.

A critical aspect of these strategies is that they occupy a large area around or under the structure. Given the emphasis on efficient land use, the question arises of how we can minimize fault rupture hazards without requiring a significant distance from the foundation position.

2. A Potential Mitigation Measure

The present study aims to investigate a potential foundation engineering strategy to mitigate the risk of fault rupture at the site of the structure.

Based on the results of field studies by Bray (2009), in most cases in which pile had been implemented, the structures have been fixed into the ground by piles. Therefore, severe damages and unacceptable performance of piles had been observed during fault rupture.

However, as an auxiliary approach to protecting the buildings, the underpinning technique has commonly been applied to strengthen the foundation and prevention of settlement. The quite extensive applications of this method are notable. In the underpinning technique, an extra foundation is constructed beneath the main one to transfer the building's weight to the new foundation or the strengthened one.

The research conducted by Rasouli and Fatahi (2021) on the interaction between a piled raft foundation and fault rupture under large ground deformations demonstrated promising results. Their numerical studies focused on a method involving the use of a geosynthetics-reinforced layer designed to separate the piles from the raft. The findings indicated that this approach enhanced the safety and operational efficiency of the foundation when confronted with strike-slip fault ruptures.

This research explores the concept of using piles as a novel approach to mitigate the risks of surface fault rupture. It is presumed that the structure has already undergone settlement due to its own weight prior to the introduction of the piles under the foundation, with no support considered between the foundation and the pile. These piles are not designed to bear the weight of the building but are instead installed under the foundation as a structural strategy aimed at reducing foundation rotation in the event of fault rupture. The effect of these piles on reducing foundation rotation during a fault rupture was analyzed through some numerical models.

3. Numerical Modelling

The two-dimensional (2D), plane strain, finite element program (PLAXIS) is employed to assess the potential effects of earthquake ruptures on the surface fault rupture process for the case of dip-slip faulting. In all models, the rigid foundation with breadth, $B = 20$ m and bearing pressure, $q = 90$ kpa (9-storey building); embedment depth, $D = 0$ m was used in this study. The soil parameters have been shown in Table (1).

Table 1. Soil mechanical properties.

Soil	Fontainbleau (Based on Anastaspoulos et al., 2008)
Model	Mohr-Coulomb
Friction Angle	37
Dilation Angle	0
Elastic Modulus	675 Mpa
Poisson's Ratio	0.35

An active fault propagates upward from the bedrock through a soil layer of thickness $H = 25$ m, where it may emerge at the ground surface either beneath the foundation or on either side of it. The fault has a dip angle, $\alpha = 60°$at the rock-soil interface. A rigid layer with a thickness of 5 m was introduced beneath the soil layer to model the bedrock. The foundation experiences significant displacement of h. The geometry of the model is shown schematically in Figure (2).

In order to study the effects of piles, a pile length of L has considered beneath the foundation ($E = 10^7$ KNm^2 and $\gamma = 24$ KNm^3 and diameter, $D = 1.5$ m). Figure (3), shows the used model schematically. In the present study, more than 50 numerical models for $SF = 0$ m and $SF = 4$ m, $SP = 0, 1, 2, 3, 4$ m and $L = 1, 2, 3, 5, 8$ m were investigated and their results discussed.

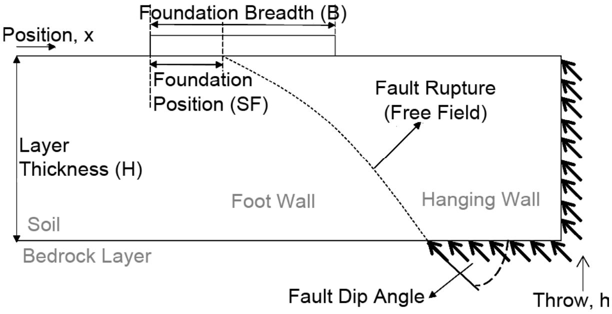


Figure 2. Geometry of reverse fault rupture emergence adjacent to a shallow foundation

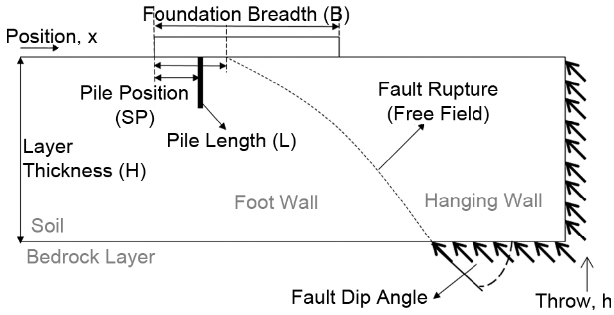


Figure 3. Definition and geometry of the studied problem (application of pile).

4. Results

4.1. Free-Field Condition

The first model was made to investigate the fault rupture emergence on the ground surface through the soil layer, in the absence of structure (free-field). The test result was further used to locate the foundation position in other models of this research. The result shows that the fault rupture propagation trace has arrived at $x = 47.7$ m on the ground surface (Figure 4).

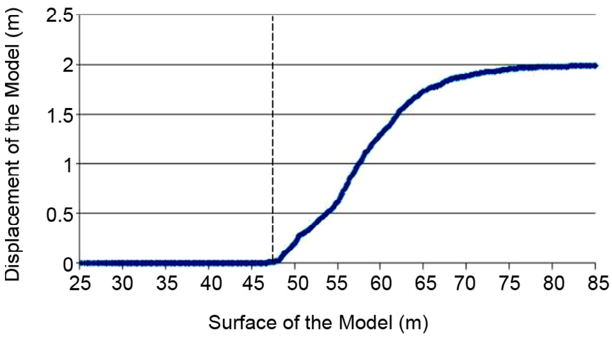


Figure 4. Free-field fault rupture propagation through.

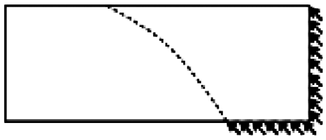
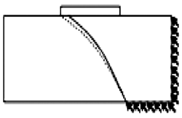
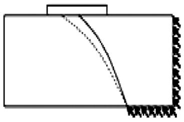
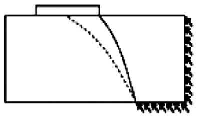
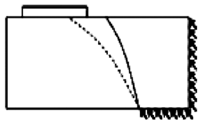
4.2. Changing Foundation Location

After determination of emerged fault rupture location on the ground surface in free-field condition, different locations of foundation were studied. Based on the results, the foundation rotation for $SF = 10$ m and $SF = 16$ m are negligible. Table (2) demonstrates the foundation rotation results in different positions.

The result shows as the foundation is moved toward the footwall, the rotation amount is reduced. As Table (2) indicates, for $SF = 16$ m, foundation rotation has been reduced to 0.28°.

Figures (5) and (6) compare the vertical displacement at the ground surface for $SF = 0$ m

Table 2. The schematically results of the foundation position.

Free- Field				
SF	**SF = 0**	**SF = 4**	**SF = 10**	**SF = 16**
Foundation Rotation (Degree)	4.94	4.2	0.37	0.28
Reverse Fault Rupture Path				

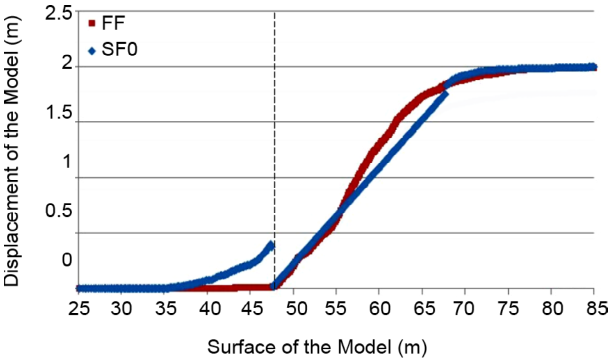


Figure 5. Interaction of reverse α = 60 degree fault rupture, through H = 25 m sand deposit, with rigid B = 20 m foundation subjected to bearing pressure q = 90 kpa, positioned at distance SF = 0 m.

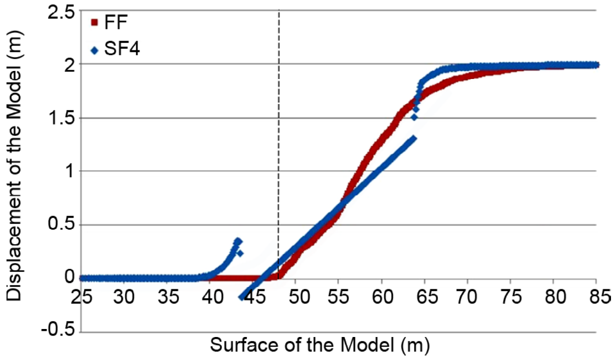


Figure 6. Interaction of reverse α = 60 degree fault rupture, through H = 25 m sand deposit, with rigid B = 20 m foundation subjected to bearing pressure q = 90 kpa, positioned at distance SF = 4 m.

and *SF* = 4 m, predicted by the numerical analysis to free-field condition.

4.3. Pile Application

After investigation on foundation location effect, it has obtained that rotation of foundation in *SF* = 0 & 4 m is more than other positions. Therefore, in the following, for these two foundation positions, different lengths of the pile were placed and rotation of foundation due to fault rupture propagation in soil was measured. Tables (3) to (7) illustrate the results schematically.

4.3.1. Effect of the Pile Lngth of L = 1 m

As it has been shown in Table (3), two different fault rupture mechanisms have been observed for pile length L=1 m. The results of these models don't indicate a satisfactory performance for this length of the pile.

4.3.2 Effect of the Pile Length of L = 2 m

Based on the results for *L* = 2 m, the same fault rupture mechanism is observed for all models with *SF* = 0.

Although generally, the foundation rotation has reduced in comparison with Table (3), this length of pile still has not had an acceptable performance for *SF* = 0 m.

4.3.3. Effect of the Pile Length of L = 3 m

The results demonstrate that for each group of *SF* = 0 and *SF* = 4 m models, the same fault rupture mechanism has accrued. Based on the outcomes, it can be mentioned that, by increasing the length, the foundation rotation has generally decreased.

4.3.4 Effect of the Pile Length of L = 5 m

Table (6) results shows, by increasing the length of the pile, the performance of models for *SF* = 4 m, still have more satisfactory results than *SF* = 0. Furthermore, in this table (*L* = 5 m), the least amount of foundation rotation for *SF* = 4 m has been observed in *SP* = 1 m.

Table 3. The schematically results of the pile position (L = 1 m).

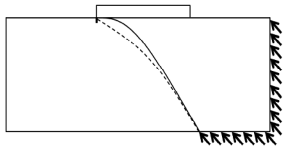
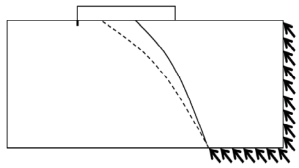
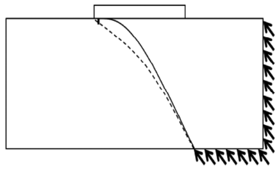
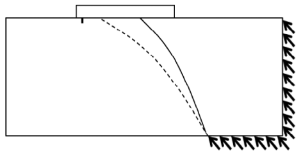
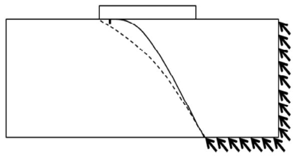
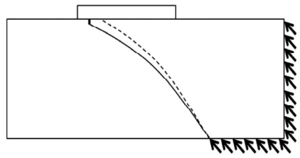
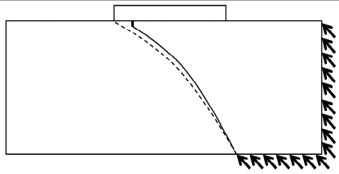
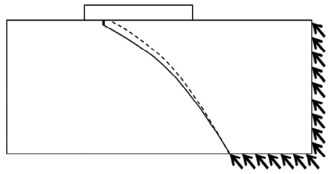
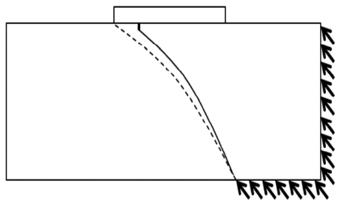
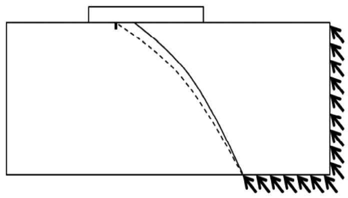
L = 1 m	SF = 0 m	SF = 4 m
	θ = 5.48°	θ = 4.15°
SP = 0 m		
	θ = 5.14°	θ = 4.55°
SP = 1 m		
	θ = 4.97°	θ = 4.08°
SP = 2 m		
	θ = 5.14°	θ = 4.12°
SP=3 m		
	θ = 5.31°	θ = 3.97°
SP = 4 m		

Table 4. The schematically results of the pile position (L = 2 m).

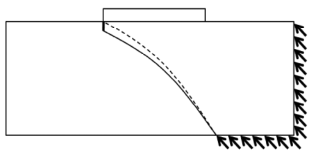
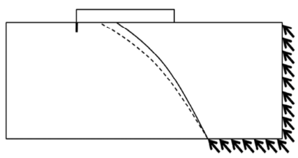
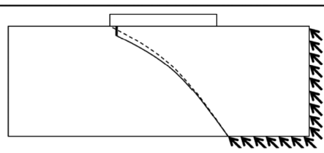
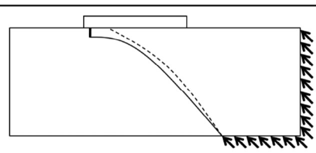
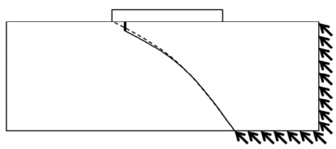
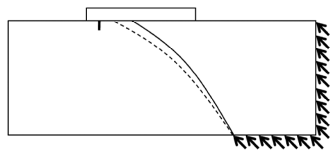
L = 2 m	SF = 0 m	SF = 4 m
	θ = 5.03°	θ = 4.12°
SP = 0 m		
	θ = 5.26°	θ = 4.12°
SP = 1 m		
	θ = 4.86°	θ = 4.03°
SP = 2 m		

Table 4. Continue

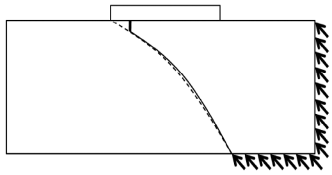
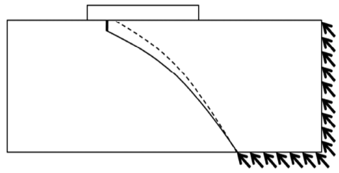
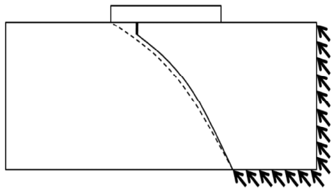
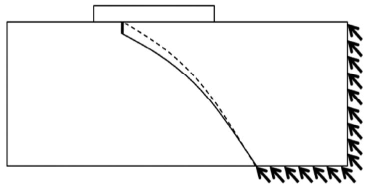
L = 2 m	SF = 0 m	SF = 4 m
SP = 3 m	$\theta = 4.77°$ 	$\theta = 3.86°$ 
SP = 4 m	$\theta = 5.11°$ 	$\theta = 4.06°$ 

Table 5. The schematically results of the pile position (L = 3 m).

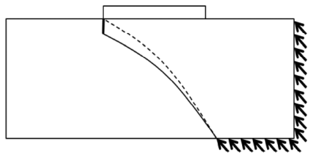
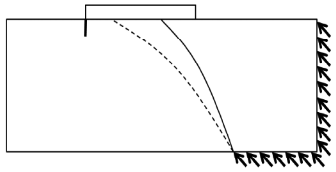
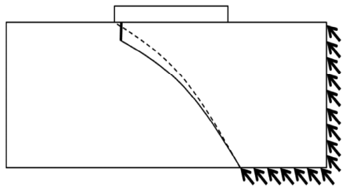
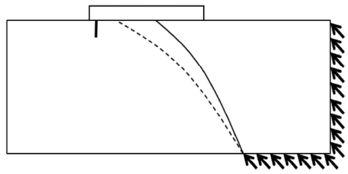
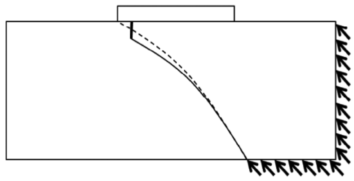
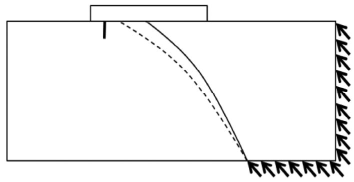
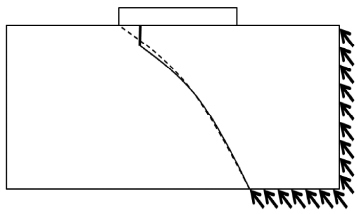
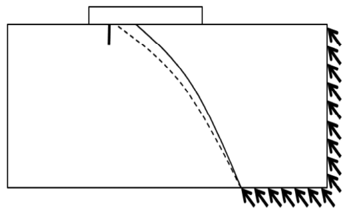
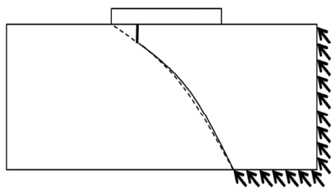
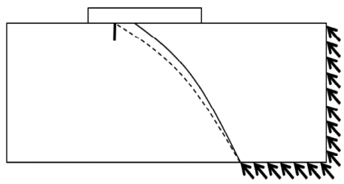
L = 3 m	SF = 0 m	SF = 4 m
SP = 0 m	$\theta = 4.92°$ 	$\theta = 4.35°$ 
SP = 1 m	$\theta = 4.85°$ 	$\theta = 3.58°$ 
SP = 2 m	$\theta = 4.63°$ 	$\theta = 3.98°$ 
SP = 3 m	$\theta = 4.94°$ 	$\theta = 3.52°$ 
SP = 4 m	$\theta = 4.92°$ 	$\theta = 3.69°$ 

Table 6. The schematically results of the pile position (L = 5 m).

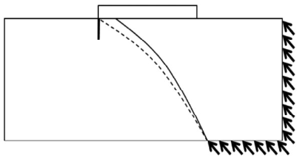
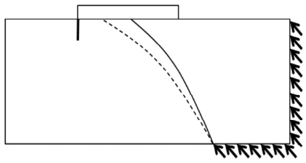
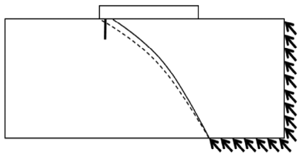
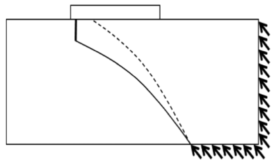
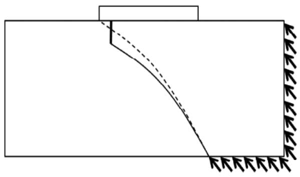
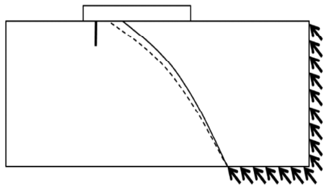
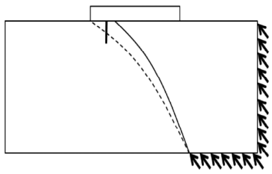
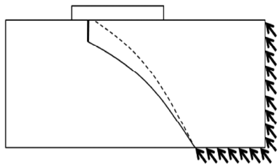
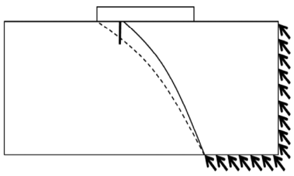
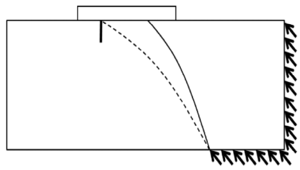
L = 5 m	SF = 0 m	SF = 4 m
	θ = 5.26°	θ = 3.8°
SP = 0 m		
	θ = 4.34°	θ = 3.18°
SP = 1 m		
	θ = 4.43°	θ = 3.29°
SP = 2 m		
	θ = 4.68°	θ = 3.38°
SP = 3 m		
	θ = 4.83°	θ = 3.35°
SP = 4 m		

Table 7. The schematically results of the pile position (L = 8 m).

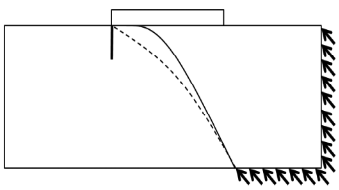
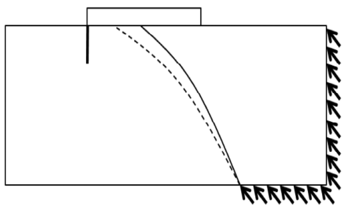
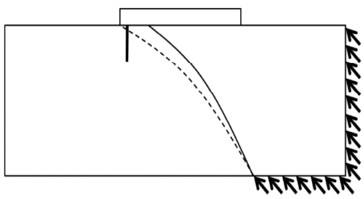
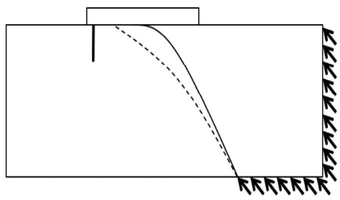
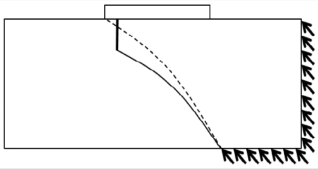
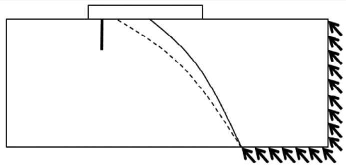
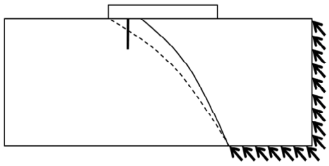
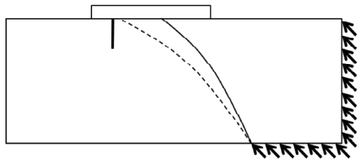
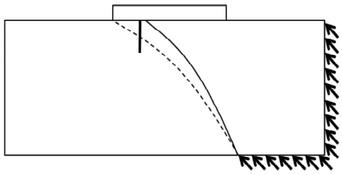
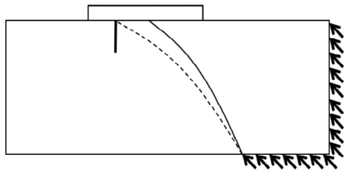
L = 8 m	SF = 0 m	SF = 4 m
	θ = 5°	θ = 3.43°
SP = 0 m		
	θ = 4.65°	θ = 3.43°
SP = 1 m		

Table 7. Continue

L = 8 m	SF = 0 m	SF = 4 m
	θ = 4.15°	θ = 3.35°
SP = 2 m		
	θ = 4.63°	θ = 3.35°
SP = 3 m		
	θ = 4.46°	θ = 3.52°
SP = 4 m		

4.3.5. Effect of the Pile Length of L = 8 m

By increasing the length of the pile, more satisfying results have been reported for L = 5 m and L = 8 m. In this table, the same rupture pattern is observed for all models in SF = 4 m.

Figures (7) to (11) indicate the foundation rotation for different pile lengths. Footing rotation for SF = 0 m and SF = 4 m has been shown by dashes in all figures.

Generally, according to Figures (7) to (11), by increasing the length of the pile, rotation of the foundation is decreasing and the pile with L = 1 m

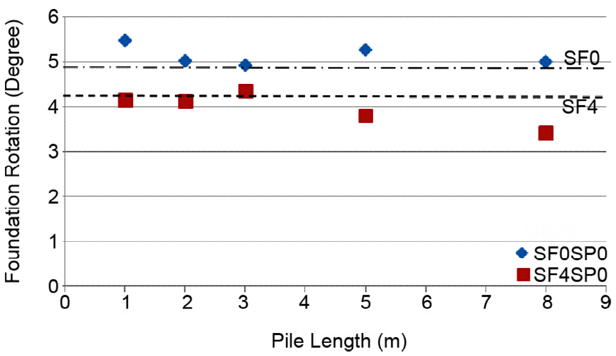


Figure 7. Foundation rotation as a function of pile length for SP = 0 m.

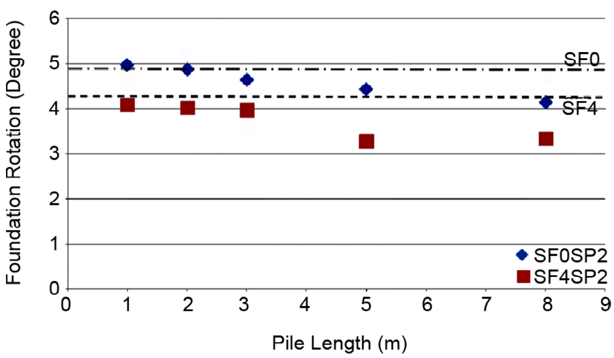


Figure 9. Foundation rotation as a function of pile length for SP = 2 m.

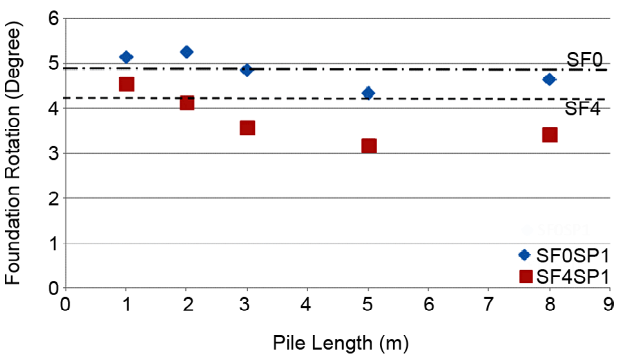


Figure 8. Foundation rotation as a function of pile length for SP = 1 m.

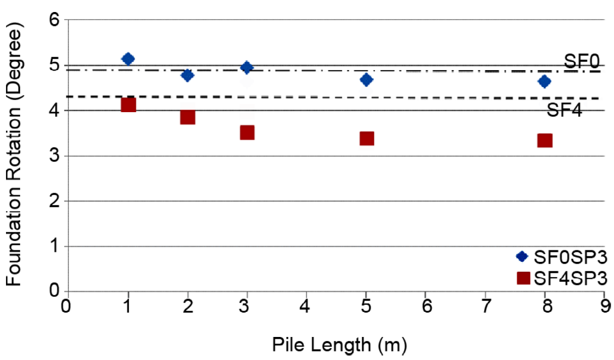


Figure 10. Foundation rotation as a function of pile length for SP = 3 m.

has not had a satisfactory performance.

Figures (12) and (13) indicate the foundation rotation for different pile lengths. These figures illustrate the rotation variations well.

Figures (13) and (14) indicate the decreased foundation rotation but these amounts have increased for pile length of L = 8 m. It can be

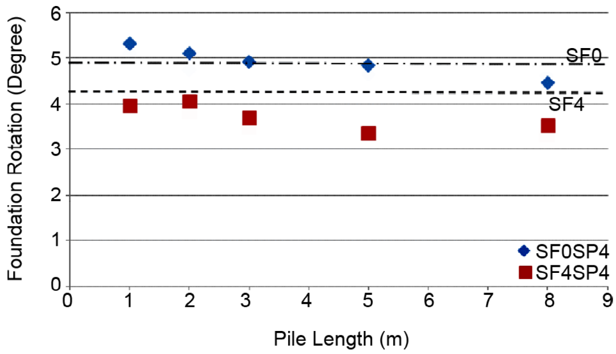


Figure 11. Foundation rotation as a function of pile length for SP = 4 m.

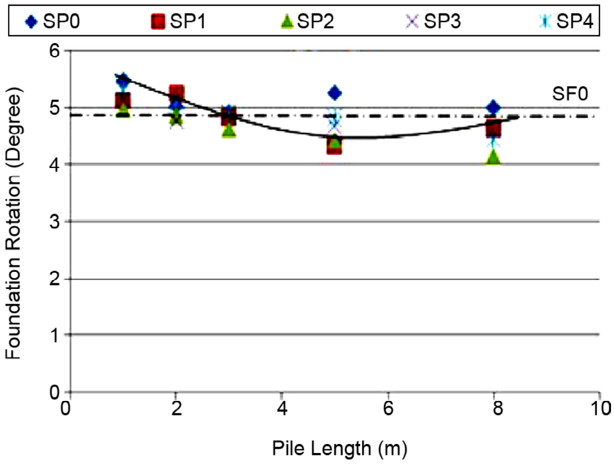


Figure 12. Foundation rotation as a function of pile length for SF = 0 m.

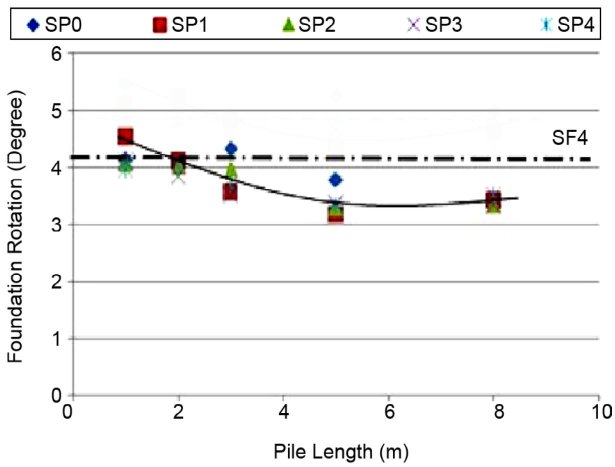


Figure 13. Foundation rotation as a function of pile length for SF = 4 m.

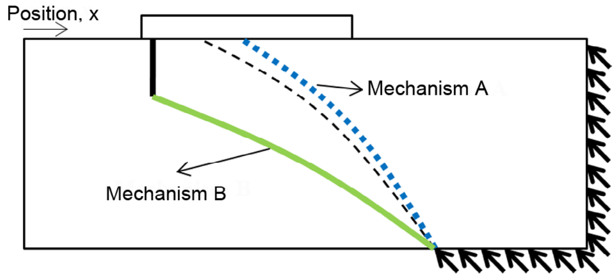


Figure 14. Fault- foundation-pile interaction.

mentioned that the presence of pile for L = 1 m has not been effective and the performance of the foundation has been worse. For other lengths of the pile at SF = 0 and SP = 0, the pile presence has not been beneficial.

In all these analysis, generally, two mechanisms of fault-foundation-pile interaction in the surface fault rupture propagation path were observed (Figure 14).

Fault rupture path arrives after free-field position at the ground surface.

Fault rupture path arrives at the end of the pile.

5. Conclusions

In this paper, after the discussion about the foundation position effects on the rotation of footing, an investigation of the fault rupture hazards mitigation approaches was conducted. In this way, the application of a special kind of pile was investigated.

From the results, when SF = 0, the optimum state is pile length of L = 8 m and SP = 2 m, which has decreased the rotation of pile to 4.15° that is around 16% reduction and at SF = 4 m, the optimum state is pile length of L = 5 m and SP = 1 m. This pile has decreased the rotation of the pile to 3.18° (24% reduction in foundation rotation). In most analyses, for SF = 0, the performance of the pile is not acceptable even though for SF = 0, certain pile lengths and positions resulted in reduction of foundation rotation; it is recommended to consider alternative techniques for mitigating the hazards of the fault rupture.

Faulting diversion in the results shows that the applied methodology has the potential to divert the fault rupture path away from structures as a good strategy for mitigating the potential damages caused by surface fault rupture. Since Geotechnical mitigation strategies aim to minimize the adverse effects of fault-induced ground deformation on structures built on or near active faults, this approach requires detailed fault characterization and careful design considerations. Fault diversion strategies, when successfully implemented, can protect structures from fault movements.

Although, past studies' findings reveal that piles have had damaging effects on structures during the propagation of surface fault rupture, the accomplishment of this particular pile caused a reduction in foundation rotation in the most analyzed cases. However, it is important to state that this cannot be regarded as an entirely adequate method for reducing fault rupture hazards. Owing to the complexity of interaction issues, each geotechnical problem necessitates thorough evaluation.

References

Anastasopoulos, I., Callerio, A., Bransby, M., Davies, M., Nahas, A., Faccioli, E., Gazetas, G., Masella, A., Paolucci, R., Pecker, A., & Rossignol, E. (2008). Numerical analyses of fault-foundation interaction. Bulletin of Earthquake Engineering, 6, 645-675.

Anastasopoulos, I., & Gazetas, G. (2007). Foundation-structure systems over a rupturing normal fault: Part I. Observations after the Kocaeli 1999 earthquake. *Bulletin of Earthquake Engineering*, *5*(5), 253-275.

Anastasopoulos, I., Gazetas, G., Bransby, F., Davies, M.C.R., & El Nahas, A. (2007). Fault rupture propagation through sand: Finite element analysis and validation through centrifuge experiments. *Journal of Geotechnical and Geoenvironmental Engineering*, *133*(8), 943-958.

Bray, J.D. (2009). *Designing Buildings to Accommodate Earthquake Surface Fault Rupture*. ASCE (Ed. 41084), San Francisco, California.

Bray, J.D., Seed, R.B., & Seed, H.B. (1994b). Analysis of earthquake fault rupture propagation through cohesive soil. *Journal of Geotechnical Engineering*, *120*(3), 562-580.

Bray, J.D., Seed, R.B., Cluff, L.S., & Seed, H.B. (1994a). Earthquake fault rupture propagation through soil. *Journal of Geotechnical Engineering*, *120*(3), 543-561.

Bray, J.D., & Kelson, K.I. (2006). Observations of surface fault rupture from the 1906 earthquake in the context of current practice. *Earthquake Spectra*, *22*(S2), S69-S89.

Bray, J. D., Ashmawy, A., Mukhopadhyay, G., & Gath, E. M. (1993). Use of geosynthetics to mitigate earthquake fault rupture propagation through compacted fill. *Proceedings of the Geosynthetics 93 Conference*, *1*, 379-392.

Bray, J.D. (2001). *Developing Mitigation Measures for the Hazards Associated with Earthquake Surface Fault Rupture*. Seismic Fault-Induced Failures Workshop, Japan Society for the Promotion of Science, University of Tokyo, Japan, 55-79.

Bransby, M.F., Davies, M.C.R., El Nahas, A., & Nagaoka, S. (2008). Centrifuge modelling of reverse fault-foundation interaction. *Bulletin of Earthquake Engineering*, *6*(4), 607-628.

Chiang, J., Michel, E.E.B., Yang, K., & Zornberg, J.G. (2023). *Mitigation of Reverse Faulting in Foundation Soils Using Geosynthetic-Encased Granular Columns*. SSRN.

Cole, D.A., & Lade, P.V. (1984). Influence zones in alluvium over dip-slip faults. *Journal of Geotechnical Engineering*, *110*(5), 599-615.

Faccioli, E., Anastasopoulos, I., Callerio, A., & Gazetas, G. (2008). Case histories of fault-foundation interaction. *Bulletin of Earthquake Engineering*, *6*(4), 557-583.

Fadaee, M., Jafari, M.K., Kamalian, M., & Mustafa, S.A. (2012). Fault rupture propagation in alluvium and its interaction with foundation: New insights from 1g modelling via high resolution optical image processing techniques. *Journal of Seismology and Earthquake Engineering*, *14*(4), 271.

Fadaee, M., Anastasopoulos, I., Gazetas, G., Jafari, M.K., & Kamalian, M. (2013). Soil bentonite wall protects foundation from thrust faulting: Analyses and experiment. *Earthquake Engineering and Engineering Vibration*, *12*, 473-486.

Jafari, M.K., & Moosavi, S.M. (2008). Lessons to be learned from surface fault ruptures in Iran earthquakes. *Sixth International Conference on Case Histories in Geotechnical Engineering and Symposium in Honor of Professor James K. Mitchell*, Arlington, VA (USA).

Lazarte, C.A., Bray, J.D., Johnson, A.M., & Lemmer, R.E. (1994). Surface breakage of the 1992 Landers earthquake and its effects on structures. *Bulletin of the Seismological Society of America*, *84*(3), 547-561.

Lettis, W., Bachhuber, J., Witter, R., Barka, A., Bray, J., Page, W., & Swan, F. (1999). Surface fault rupture. *The Kocaeli, Turkey earthquake of August 17, Reconnaissance Report, Earthquake Spectra, EERI, Chapter 2*, *16*(SA), 11-53.

Lettis, W. & Associates. (2003). *Surface Deformation Produced by the 1999 Chi-Chi (Taiwan) Earthquake and Interactions with Built Structures.* U.S. Geological Survey, National Earthquake Hazards Reduction Program.

Lee, J.W., & Hamada, M. (2005). An experimental study on earthquake fault rupture propagation through a sandy soil deposit. *Structural Engineering / Earthquake Engineering*, *22*(1), 1s-13s.

Moosavi, S.M. (2010). *Earthquake Fault Rupture Propagation Through Soil: Reduction of Seismic Risk Through the Application of Geotechnical Engineering Techniques* (Doctoral dissertation, International Institute of Earthquake Engineering and Seismology, Tehran, Iran) (in Persian).

Moosavi, S.M., Jafari, M.K., Kamalian, M., & Shafiee, A. (2010). Experimental investigation of reverse fault rupture-rigid shallow foundation interaction. *International Journal of Civil Engineering*, *8*(2), 85-98.

Moosavi, S.M., & Jafari, M.K. (2012). Investigation of the surface fault rupture hazard mitigation by geosynthetics. *15th World Conference on Earthquake Engineering*.

Rasouli, H., & Fatahi, B. (2021). Geosynthetics reinforced interposed layer to protect structures on deep foundations against strike-slip fault rupture. *Geotextiles and Geomembranes*, *49*, 722-736.

Tani, K. (2003). Proposal of ground improvement method to prevent fault rupture modification. *Proceedings of the 11th International Conference on Soil Dynamics and Earthquake Engineering*, U.C. Berkeley, USA, 590-597.

Zanjani, M.M., & Soroush, A. (2014). Numerical modeling of fault rupture propagation through two-layered sands. *Scientia Iranica*, Trans