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Numerical Analysis of Reverse Dip-slip Fault Rupture on Steel Buildings

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ABSTRACT

In seismic events, rupture resulted from the earthquake causes two types of ground deformation, namely, the permanent pseudo-static deviations on fault and transient dynamic fluctuations away from fault. Fault rupture extends in soil through bedrock and makes various concerns for structures made by human. On this basis, we examined reverse fault effect on ground-level buildings using numerical analysis and ABAQUS finite-element software. In this regard, some types of buildings were placed on ground near to fault and fault route angle was examined in the presence and absence of building in two layers of soil with different densities. Finally, vertical deformation of ground, horizontal strain of ground, lateral displacement of building, and bending moment of structure were examined beneath fault effect. Results reveal that fault route angle depends on soil layer material, and horizontal strain resulted from fault effect on ground increases by placing building. However, vertical displacement of ground will decrease by placing overhead (building) and the highest part of fault effect will be on columns of first floor.

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1. Introduction

Most earthquakes with tectonic origin are related to seismic and active faults which their movement during earthquake makes ground fault if extends to ground level. Fault is one of the damages resulting from earthquake which causes severe damages to buildings, facilities, and/or any other type of structure near to it. In an event caused by earthquake, resulted fault makes two types of ground deformation: permanent pseudo-static deviations on fault and transient dynamic fluctuations away from fault. Permanent deviation on fault causes changes on ground in few cases when fault rupture extends throughout its route to ground (fig (1)). Moreover, deformation in second type is the result of sequential waves made on each point on fault which extends in a big distance on ground and affects it, and is very important related to security and safety of engineering structures.

Devastative earthquakes like Kocaeli in Turkey and Chi Chi in Taiwan in 1999 showed that ground-level fault can cause huge harms for structures near or adjacent to fault area [1–3]. In a study published in 2001, it was shown that the type of ground movement, depth of material on bedrock, and soil material have an important effect on fault characteristics [4]. Various field, experimental and numerical studies have been done on fault extension on ground [3–15].

Fig. 1. An example of fault made in Kermanshah earthquake 2017.

Based on field examinations done on Anastasopoulos and Gazetas study in Kocaeli earthquake (1999) in Turkey, it was determined that the type of structure foundation has an important role in response to displacements [3]. Based on field study conducted by Faccioli et al., foundations with high rigidity have a good performance against fault [5]. Moosavi et al. studied effect of overload and foundation distance from fault in free field form by using physical modeling. It was determined in this study that amount of overload and position of foundation have a more significant effect on resulted fault route than free field fault route and make deviation from it [14].

Anastasopoulos et al. studied overload effect on foundation and effect of foundation distance from fault on fault route change, and concluded that increasing overload changes fault route [16]. Oettle and Bray examined effect of soil layer thickness and characteristics and foundation type on fault route by using numerical study. Results showed that soil layer thickness and characteristics have a significant effect characteristics of ground-level fault and fault absorption in soil layer [15]. Baziar et al. examined effect of interaction of dip-slip fault and ground-level foundation by using numerical modeling. Results revealed that ground-level displacement decreases by using geo-grid [17]. Hazeghian and Soroush examined fault route and shear band effect on grain soil by using numerical analysis and results showed that amount of strain resulted from reverse fault is higher than normal fault [18].

Considering the previous studies, less attention has been paid to the influence of soil layering on the ground response and the performance of buildings. Additionally, the type of the foundation of a building could result in a certain performance within the structure. With regard to studies conducted, direct effect of fault on building performance has occasionally been studied. Thus, we examine effect of soil layers with different densities on fault route and performance of buildings with different floors and foundation type by using numerical modeling.

2. Modelling

In order to examine performance of building under fault effect, two types of building with 2 and 5 floors were designed as a frame. Building design was done by using SAP2000 software as a steel two-dimensional frame based on common legislations of Iran with three spans (each one 4 m) which each floor has 3 m height. Building was designed based on dead load 500 kg/m^2 and live load 200 kg/m^2 and a 4 m loading span for each beam. Tables (1) and (2) present characteristics of sections of designed buildings frame and dimensions of foundation for each building, respectively. Moreover, fig (2) shows a schematic view of foundation of buildings with 2 and 5 floors. The foundation is made of concrete with the compressive strength of 30 MPa, the mass density of 2500 kg/m^3, and Young's modulus of 250 GPa.

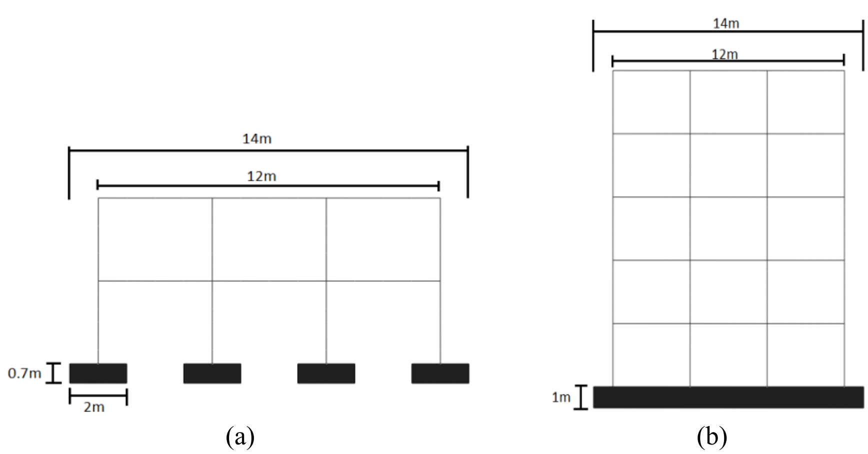


Fig. 2. Schematic view of building foundation: (a) building with 2 floors and (b) building with 5 floors.

Numerical modeling of reverse fault effect on building placed on ground was done using ABAQUS finite-element software in two-dimensional conditions by coding method. It was shown in experimental and numerical studies that post-rupture soil behavior is an important factor in fault extension and reaching ground level. Therefore, such structural model for stimulating completion of shear form deformation resulted from fault has been presented in previous studies. Bray et al. used hyperbolic non-linear elastic constitutive law for saturated clay modeling. Lin et al used tri-shear model with elastic-plastic Mohr-Coloumb structural behavior for numerical stimulation of sand sediments. Johnson and Konagasi used hypo-plastic structural law [9,19,20].

Table 1
Characteristics of frames sections.

2 story		
Story No.	Column section	Beam section
1,2	Box 140×140×10	IPE 240
5 story		
1,2,3	Box 200×200×20	IPE 270
4,5	Box 160×160×10	IPE 240

Table 2
Characteristics of used steel.

Frame	γ (KN/m³)	E (MPa)	υ
2 and 5 story	78.5	2×10^5	0.3

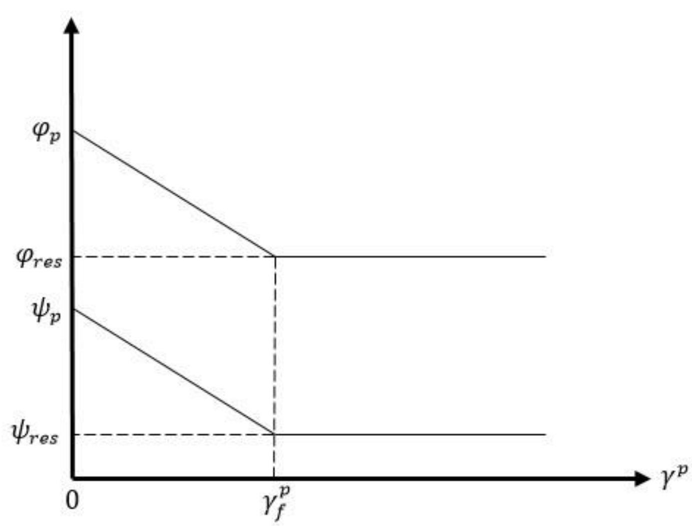


Fig. 3. Changes in friction angle and dilation angle with plastic shearing strain.

Previous studies showed that considering post-peak soil behavior has an important role in extension of fault rupture. Elastic-plastic Mohr-Coloumb structural model with isotope softening strain and non-associated flow rule were used in current research. Softening strain behavior was modeled by using ABAQUS limited element software and by a determined subroutine through gradual decrease of friction angle and dilation angle (φ and ψ) and by increasing plastic shearing strain (y^p) (fig (3)).

Φ_p and ψ_p are friction angle and dilation angle, φ_{res} and ψ_{res} are resident friction angle and dilation angle, and $y^p{}_f$ is plastic shearing strain with completed softening. As it was mentioned, ground in this study was modeled as two layer of soil with different density (loose sand, middle sand, and dense sand) in different forms. Characteristics of soil material are presented in table (3).

Table 3
Characteristics of soil material used [21].

Soil	Abbreviation	γ (kN/m³)	C (kPa)	φ_p (°)	φ_{res} (°)	Ψ_p (°)	Ψ_{res} (°)	υ	E (MPa)
Loose Sand	LS	18	5	30	30	0	0	0.3	10
Medium Dense Sand	MS	19	5	38	33	8	3	0.3	20
Dense Sand	DS	20	5	46	36	16	6	0.3	40

Fig (4) shows schematic of simulated model by software. Model dimensions were selected based on conducted studies [3,22]. Thus, model height (H) was considered 40m and model width (B) will be 5 times more than height [3,21,22]. For a double-layer soil, the thickness of each layer was considered to be equal to H/2. In addition, fault angle equal to 60° [23] was used and horizontal distance of fault (S=4 m) on ground for each model was considered from lateral left column to theinside of building.

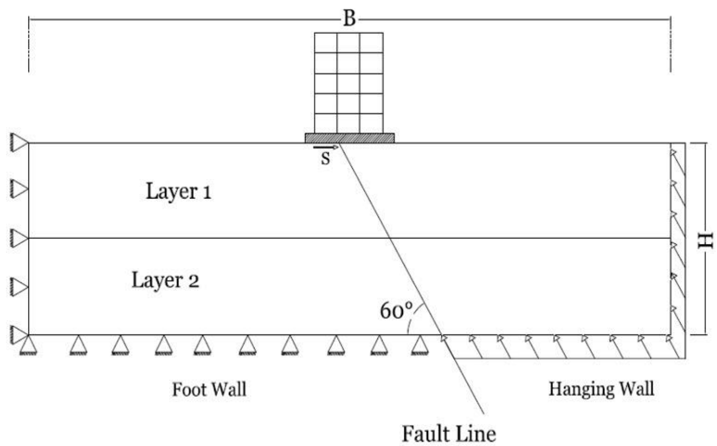


Fig 4. Schematic of model with dimensions and boundary conditions.

Boundary conditions were considered such that lateral bounds are placed horizontally and bottom bound is placed horizontally and vertically. However, fault effect of lateral bound along with horizontal bound in left side of model was freed from beginning of calculation and diagonal deformation was used according to fault route equal to 5% of ground layer depth. With regard to results of verification model for interface between foundation and soil, Tie element was used in modeling. For analysis purposes, the simulated model was initially subjected to the body-force conditions, followed by applying the displacement due to fault rupture.

With regard to verification model and precision of results, model meshing used for soil layers was standard four-node continum element of decreased integral (CPE4R). Moreover, CPE4R was used for foundation and two-dimensional two beam elements (B21) was used for building. In area near to place of fault beginning and beneath building, smaller meshing was used due to sensivity and precision of results. In this regard, meshings were fixed equal to foundation width from place of fault beginning to hanging wall and equal to foundation width from left side of building to foot wall. Meshings became bigger by going away from this area. Fig (5) shows an example of meshing of soil layers and modeled building in ABAQUS software.

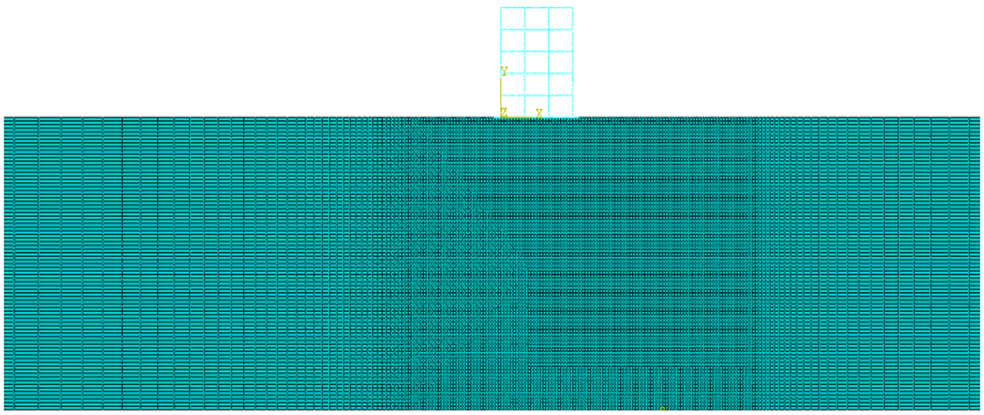


Fig 5. An example of meshing of soil layers and adjacent building in ABAQUS software.

3. Verification

In order to examine ability of numerical method and FE software in considering real soil behavior, centrifuge experiments done by Bransby et al. were modeled numerically [23]. Dimensions for real and experimental models are shown in fig (6). Sand soil for introducing to model with relative density equal to 60% has γ=15.7 kN/m^3, φ=35° and ψ=6°. In this simulation, a reverse fault with angle 60 and maximumdisplacement 3.8m was used for model. Fig (7) shows results for numerical and experimental methods as maximum vertical displacement at the end of fault. With regard to figure, prediction of vertical deformation of ground by numerical method and with ABAQUS software is consistent with experimental results. Therefore, finite-element software used and structural model considered for soil have good ability to model fault.

4. Results

In this section, results of reverse fault effect on extension route in two soil layers with different densities and also its effect on building are presented. Results are divided to with and without structure.

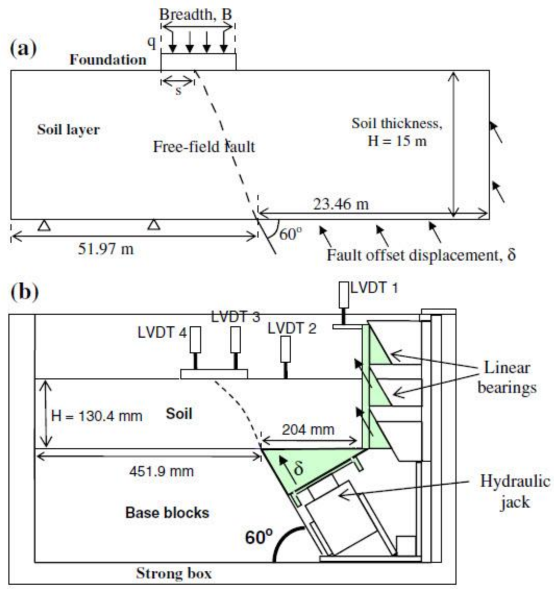


Fig 6. Schematic of real and experimental model [23].

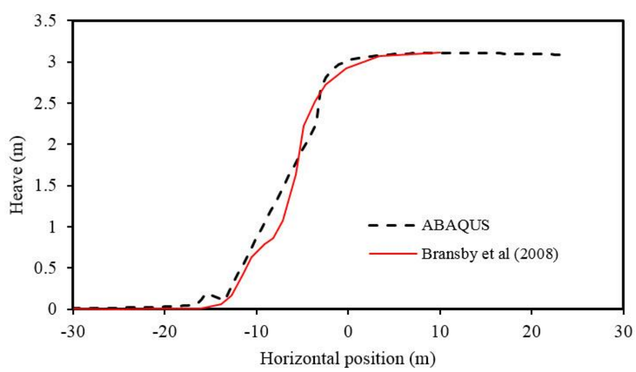


Fig 7. Comparison of results of numerical and experimental studies.

4.1. Without structure

Fig (8) shows displacement resulted from fault effect on extension route in one-layer soil with LS, MS and DS densities. As it can be seen, fault extension route in LS layer tends to vertical direction with 90° angle which results from existence of weak material along fault route. In fact, weak material tends to make the closest rupture route to ground level. In MS which is made of materials with middle density, this makes fault route to tend to ground with angle 70°, and finally, in DS it tends to ground with main angle which is 60. It can be said that in weak material fault angle passes closer route to reach ground and in dense material, fault extension angle at ground is closer to fault movement angle. It should be noted that amount of plastic strain as the result of fault effect is higher with dense material than weak material.

In fig (9), two structures have been considered for two-layer ground. In fig (9a), LS soil is on MS soil which this will be shown as LS-MS. With regard to figure, it is clear that fault route in lower layer tends vertically and then by slapping a layer with lower density makes a more vertical route to reach ground level. In fig (9b), ground structure is LS-DS where fault route in lower layer with high density has slapped to upper layer with angle 60 and then tends to ground with angle

90. In both figures, fault route has tended horizontally about 10 m to ground and finally, with angle near to 75° has slapped ground level.

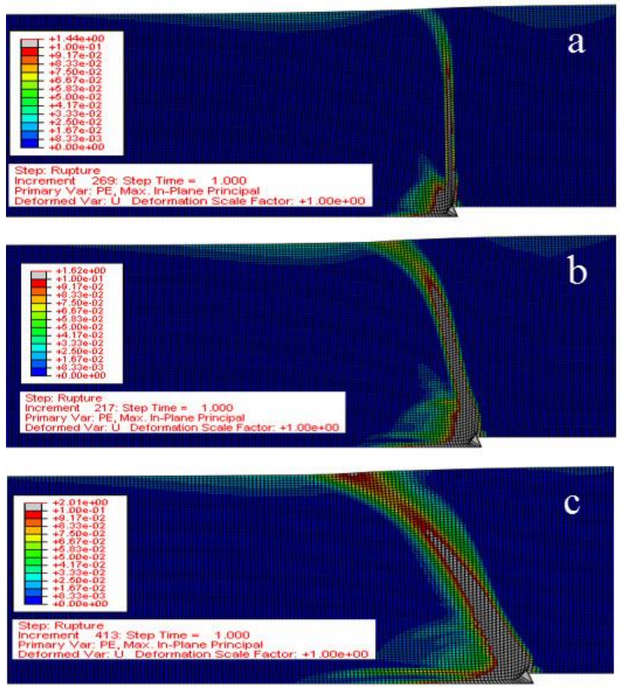


Fig. 8. Comparison of fault route angle for one-layer model without structure: (a) LS; (b) MS; and (c) DS.

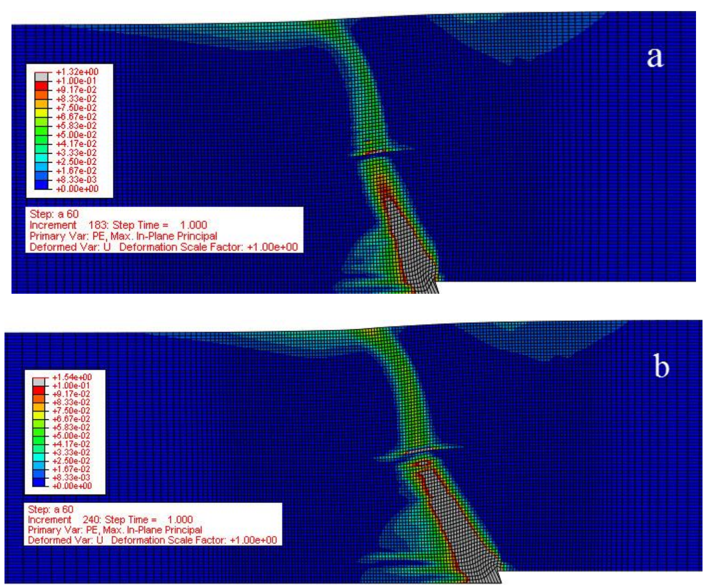


Fig. 9. Comparison of fault route for two-layer model: (a) LS-MS and (b) LS-DS.

Fig (10) shows two structures for two-layer soil. In fig (10a), MS soil is on LS soil.With regard to figure, it is clear that fault extension for lower layer which is made of weak sand has made rupture in form of two routes. These two routes make angles 60° and 90° with horizon. In fact, extension route with angle 90° is the result of weak material and formation of shortest rupture route and the highest shearing srtrain has been made in this route. In figs (10b) and (10c), two structures with middle and high density have been used. In fig (10b), ground is in MS-DS form and the reverse is in fig (10d). in both structures, fault route passes a certain angle to reach ground level. However, in fig (10c), ground is DS-LS and as it can be seen, fault rout angle for lower layer which is made of weak sand has made rupture in form of two routes. These two routes make angles 60 and 90 with horizon. In fact, plastic strain is lower in weak material and this makes lower strain for upper layers.

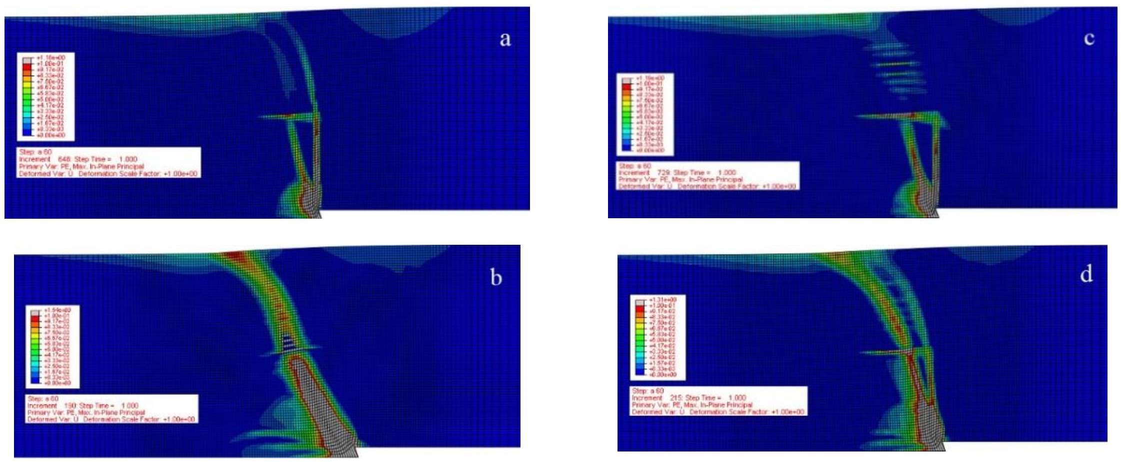


Fig. 10. Comparison fault route angle for two soil layers with different densities: (a) MS-LS, (b) MS-DS, (c) DS-LS and (d) DS-MS.

In fig (11), vertical displacement of ground has been shown. In figure (11a), the highest displacement has occurred on LS-DS structure. In fig (11b), the highest displacement has occurred on MS-DS structure. On this basis, it can be said that main priorities for maximising vertical displacement of ground are density of lower layer and then density of upper layer. Therefore, vertical displacement is higher in structures with more dense layers.

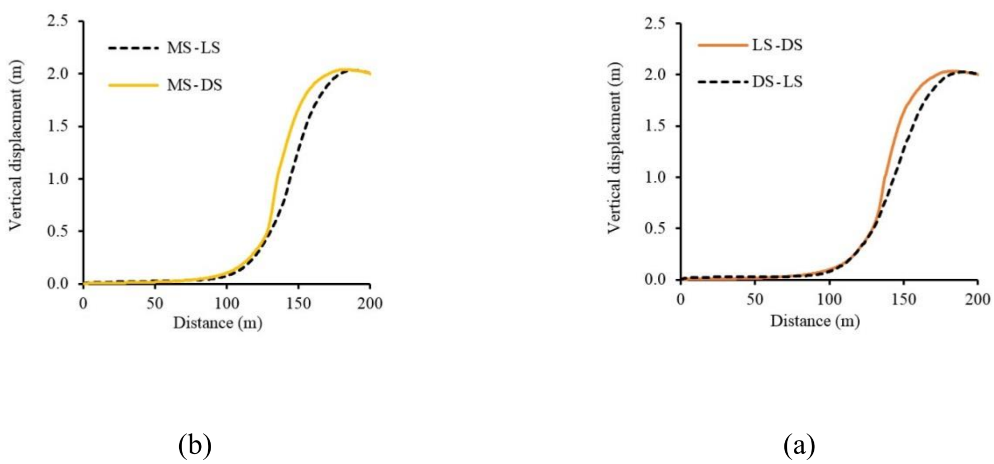
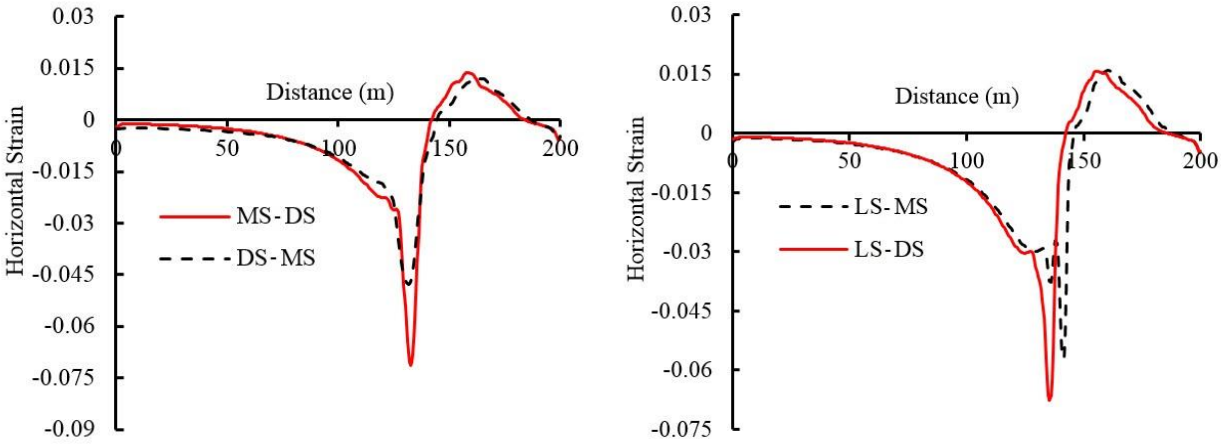


Fig. 11. vertical displacement of ground with two-layer structure: (a) LS-DS and DS-LS, (b) MS-LS and MS-DS.



(b) (a)

Fig. 12. horizontal strain of ground with two-layer structure: (a) LS-DS and DS-LS, (b) MS-LS and MS-DS.

In fig 12, horizontal strain of ground with two-layer structure has been shown. In fig (12a), the highest horizontal strain has occurred on MS-DS structure. In fig (12b), the highest horizontal strain has occurred on LS-DS structure. On this basis, it can be said that main priorities for maximising horizontal strain of ground are density of lower layer and then density of upper layer.

4.2. With strucrure

Comparison of fault route angle with and without structure for a 5 floor building with raft and single foundation has been shown in fig (13). As it can be seen in figure, building causes deviation in fault route to right corner for both models. In fact, weakness of lower layer makes fault route tend vertically which results in deviation from fault route in upper layer. However, because upper layer is dense it tries to continue with main angle and thus, fault route in both models doesn't totally go out of foundation. This is seen for MS-LS in fig (14); however, because ground is more weak than previous form fault route doesn't continue in beneath of foundation and type of foundation doesn't affect fault route significantly. However, it should be noted that fault route slappes with angle 80° to ground in the case of lack of building, but presence of building and putting load on ground makes soil more dense and deviates fault route to out of building area.

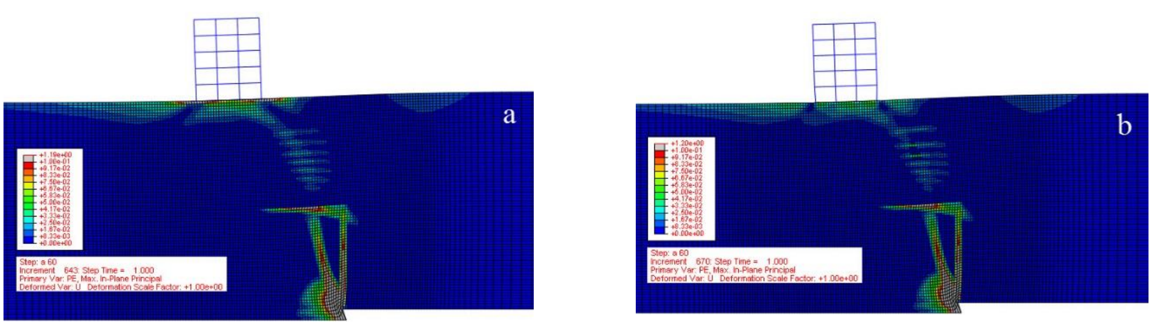


Fig. 13. Fault route in two soil layers with DS-LS density for a 5 floor building: (a) raft foundation and (b) single foundation.

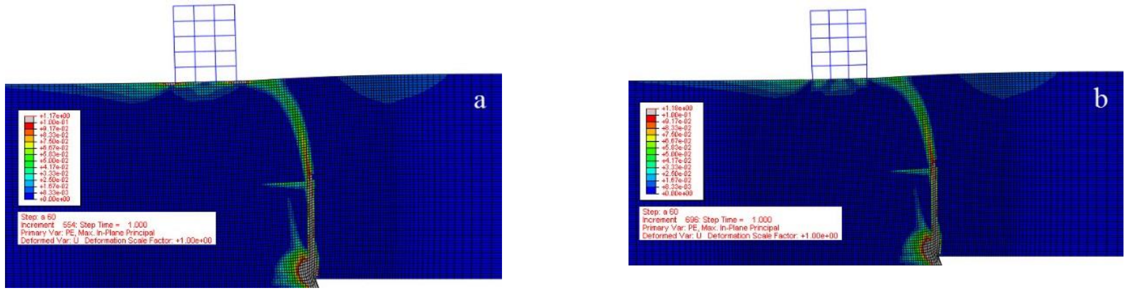
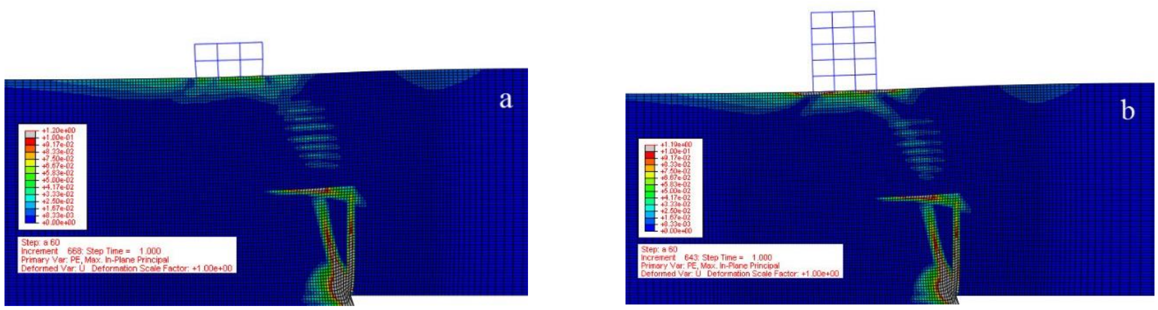
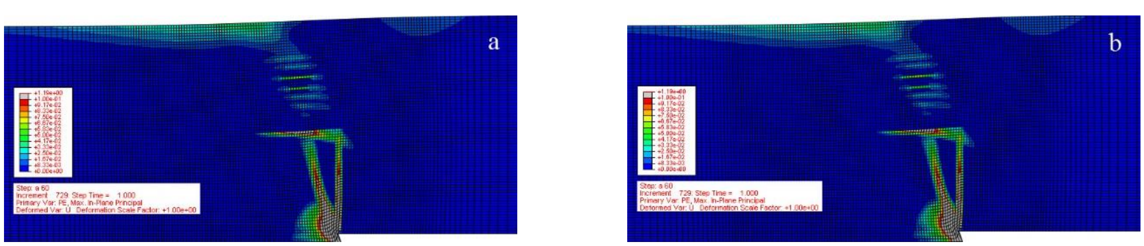


Fig. 14. Fault route in MS-LS ground and with a 5 floor building: (a) raft foundation and (b) single foundation.

Comparison of fault route angle with and without structure for 2 and 5 floor buildings with single foundationhas been shown in fig (15). As it can be seen, fault route for DS-LS structure in lower layer doesn't change with presence of building for both models; however, fault route extension has been weakened for 5 floor building in upper layer. Presence of building made slight deviation of fault route to right corner in both models. In fact, weakness of lower layer makes fault route to tend vertically and as a result, fault route is deviated in upper layer. In fig (16), fault route doesn't continue to beneath of foundation due to weakness of ground for MS-LS groun and type of building doesn't affect extension of fault route significantly. However, amount of plastic strain is higher in 2 floor building than 5 floor building.

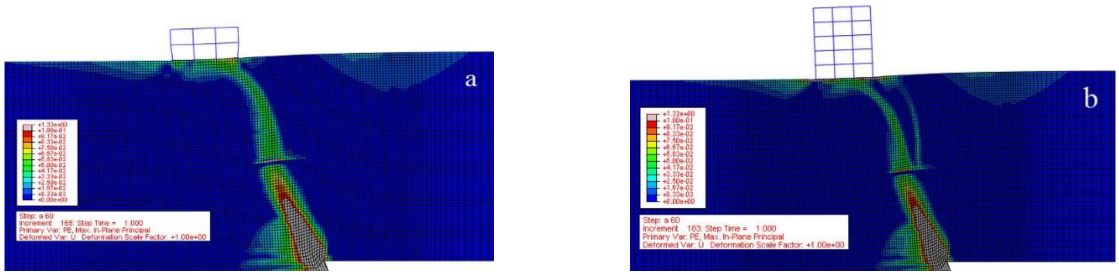


With structure

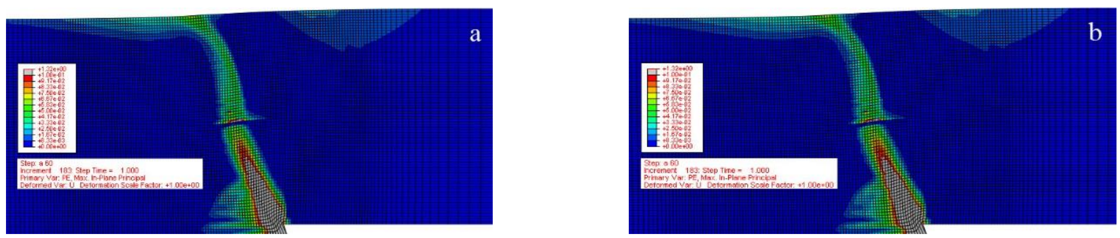


Without structure

Fig. 15. Fault route in two soil layer with DS-LS density: (a) 2 floors and (b) 5 floors.



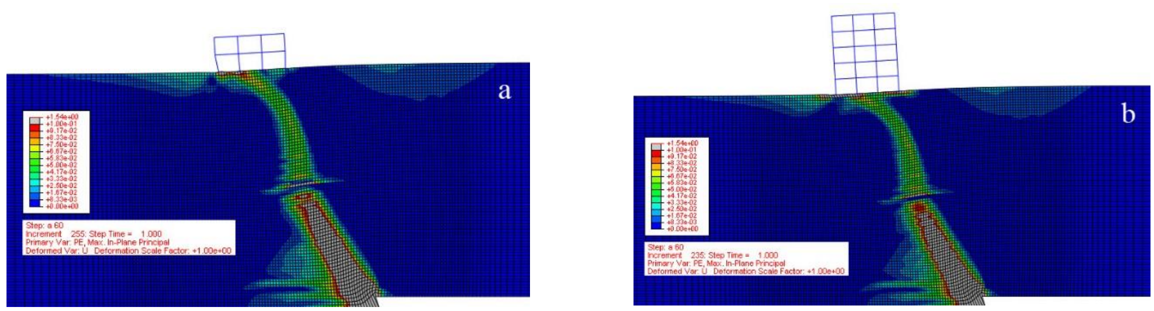
(With structure)



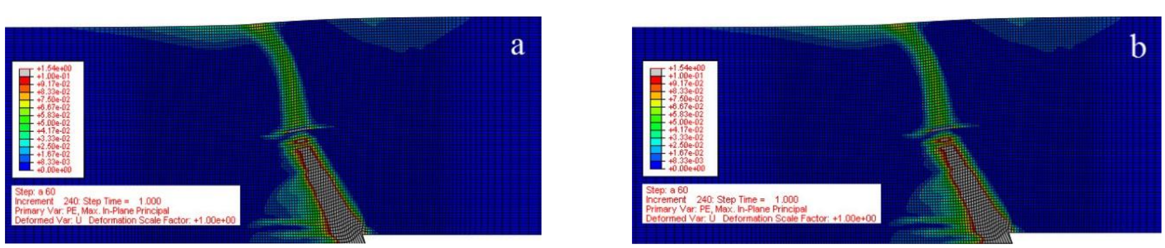
(Without structure)

Fig. 16. Fault route in two soil layer with MS-LS density: (a) 2 floors and (b) 5 floors.

Fig (17) shows fault route in LS-DS form with and without structure. Because lower layer is dense, fault route slappes border between two layers with main angle (60°) and tends vertically due to weakness of upper layer. However, fault can't do sufficient deviation because amount of S is low (equal to 4) and as a result, fault route goes to beneath of foundation in both models.



With structure



Without structure

Fig. 17. Fault route in two soil layers with LS-DS density: (a) 2 floors and (b) 5 floors.

In fig (18), vertical displacement of ground has been shown for 5 floor buiding. As it can be seen, type of foundation doesn't affect maximum vertical displacement of ground level. The results have revealed that the more the number of stories a building has, the less the type of foundation affects the ground response. In other words, the influence of the type of foundation will diminish by increasing the weight of a building. In fig (19), vertical displacement of ground has been shown for 2 and 5 floor building with single foundation. As it can be seen, layering structure is identical for 2 floor building and 5 floor building and this makes identical displacement for both buildings. However, in place of building displacement is lower in 5 floor building than 2 floor building due to higher weight. It can be concluded with regard to figs (18) and (19) that maximum displacement is where building positioned which results in high subsidence and thus, rotation of building about more than 0.03. Based on Iran legislations, alloawble amount of rotation for damage limit of buildings is between 0.004 and 0.0067, and for crack limit is between 0.002 and 0.0033 which damage and crack should occur in building on this basis.

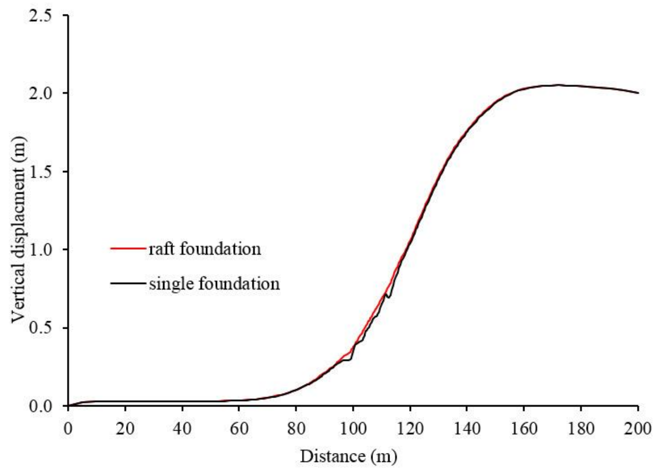


Fig. 18. Comparison of vertical displacement of ground for 5 floor building with single and raft foundation with DS-LS density.

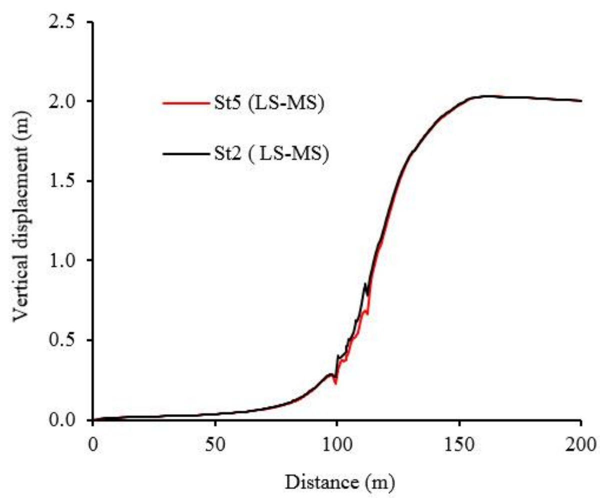


Fig. 19. Comparison of vertical displacement of ground for 2 and 5 floor buildings with single foundation.

Fig (20) shows comparison of horizontal strain of ground in free field form and with 5 floor building with single foundation in DS-LS density. It can be said that building affects significantly on changes of horizontal strain of ground and in case of presecnce of structure, horizontal strain is maximum in space between two single foundations of building and tends to zero beneath the foundation. It can be said on this basis that single foundation causes maximum horizontal strain beneath the building.

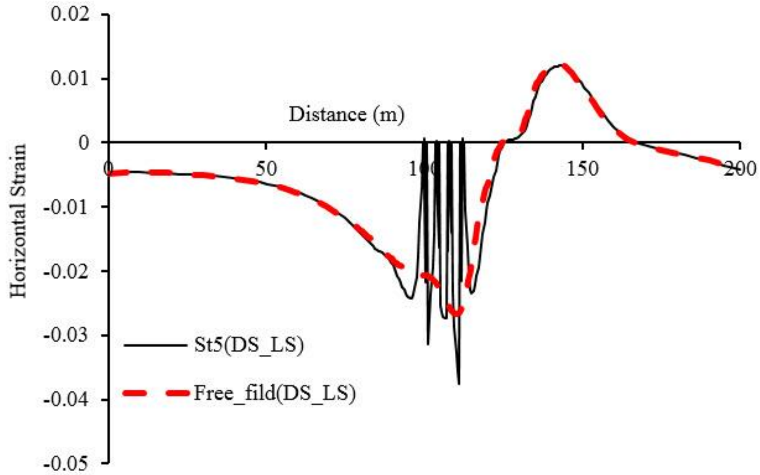


Fig. 20. Horizontal strain of ground with and without structure for 5 floor building with single foundation and with DS-LS density.

Fig (21) shows horizontal strain of ground for 5 floor building with single and raft foundation in DS-LS density. As it can be seen, raft foundation deviates horizontal strain to building corners. Moreover, horizontal strain is zero in place of foundation and is maximum in corners. However, single foundation makes horizontal strain maximum beneath the building and minimizes horizontal strain in building corners.

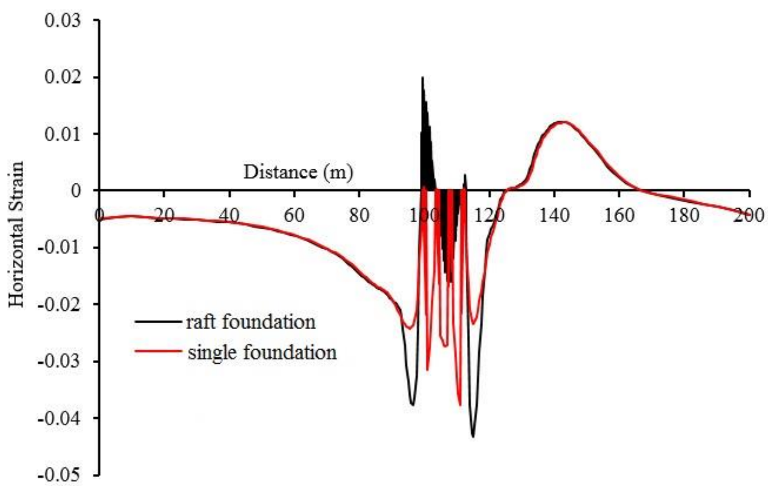
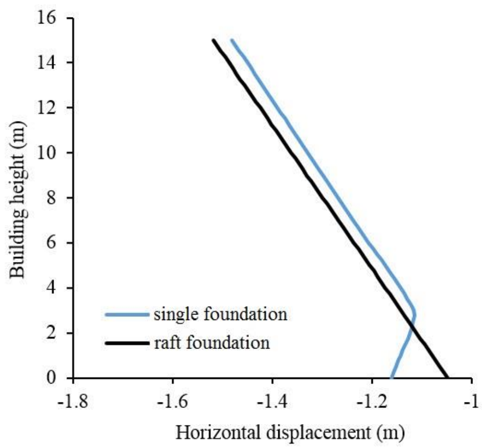


Fig. 21. Comparison of horizontal strain of ground for 5 floor building with single and raft foundation in DS-LS density.

Fig (22) shows lateral displacement of 5 floor building with single and raft foundations. Maximum displacement has been occurred in the layer with weaker material for both foundations. Foundation fail is seen in floor 1 for single foundation. In fact, it can be said that building with single foundation causes severe damage to structure due to not having lateral bending momen. It is worth noting that lateral displacement for building with raft foundation is in form of a rigid block.



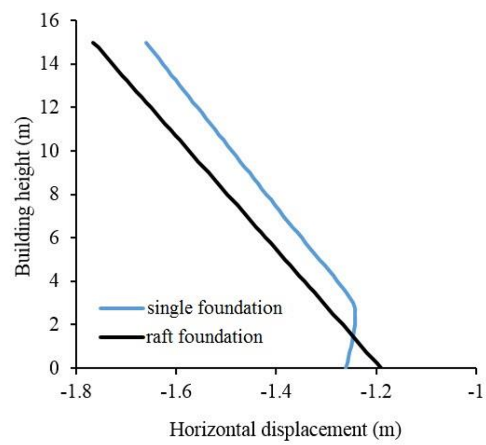


Fig. 22. Comparison of lateral displacement of structure for 5 floor building with single and raft foundations: (a) LS-MS and (b) DS-LS.

In order to examine bending moment of the structure, column 1 in floor 1 was analyzed. Fig (23) shows schematic view of this column for analyzing bending moment for a 5 floor structure with raft foundation. Maximum bending moment before fault, after fault and under effect of fault has been compared for this column. Maximum bending moment for a 5 floor building with single foundation and with different soil densities was analyzed and results are presented in Fig (24). It can be said that bending moment befor fault is very lower than after fault and as a result, maximum bending moment will be made for all soil layers. Maximum bendig moment for a 5 floor building with raft foundation and different soil densities is presented in Fig (25). With regard to table, bending moment in different forms is very lower than building with single foundation. Therefore, considering type of foundation for buildings placed in fault route is very important which as a result of this, bending moment on structural elements decreases significantly by using raft foundation.

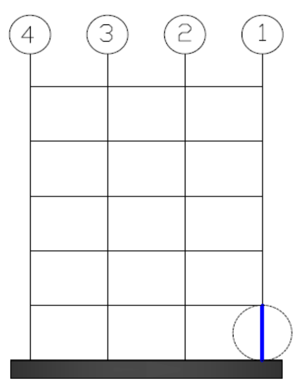


Fig. 23. Schematic of column for analyzing bending moment.

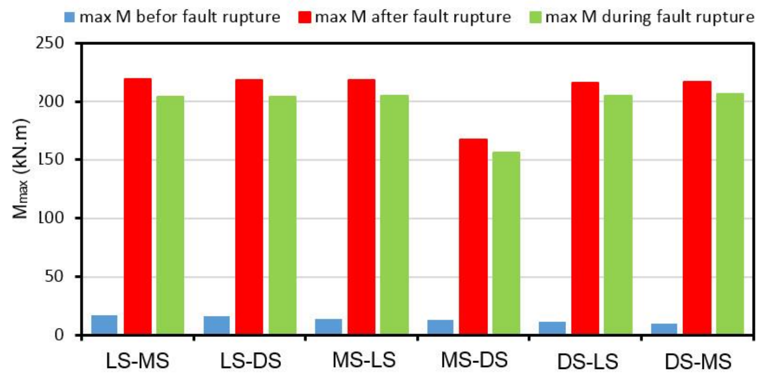


Fig. 24. Maximum bending moment of column 1 for 5 floor building with single foundation.

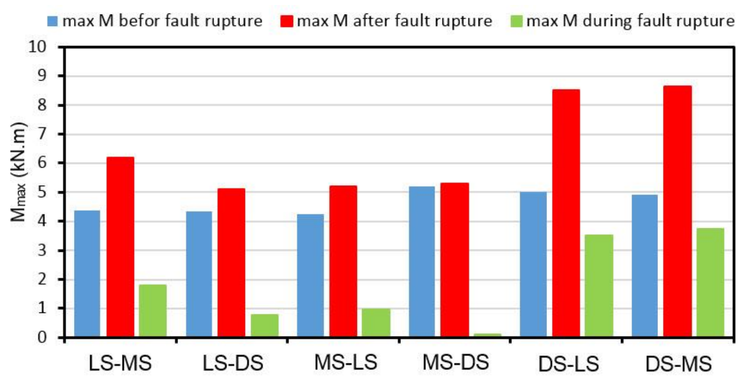


Fig. 25. Maximum bending moment of column 1 for 5 floor building with raft foundation.

5. Conclusion

In this study, reverse fault effect in ground with two-layer soil on fault extension route and building placed on ground level was examined by using numerical modeling. Thus, two types of building with 2 and 5 floors with single and raft foundations were examined in two-layer soil. Resluts of study are as follow:

If soil material is weak, fault angle passes a closer route to reach ground and if material is dense, fault extension angle is closer to fault movement route. Main priorities for maximizing horizaontal strain and vertical displacement are density of lower layer and then upeer layer, respectively. Displacement absorption resulted from fault is lower than weak soils if soil layer is more dense.

Fault deviation route depends on amount of S and lower layer material. It means that fault angle deviates out of foundation if lower layer material is weak. In fact, strain made in this layer finds a closer route to ground level if soil is weak. Moreover, building weight puts pressure on beneath of structure in weaker layers. As a result, soil under the foundation is improved and directs fault route to weak poins.

Type of foundation has a direct effect in place of formation of horizontal strains at ground level, such that maximum horizontal strain forms in building corners in raft foundation and forms beneath the building in single foundation. Raft foundation causes uniform displacement in building, such that building becomes tilted without any serious damage to structure. However, single foundation causes serious damage to building due to lack of rigidity. As a result, it is better to use raft foundation in places where there is fault. Moreover, raft foundation decreases bending moment in building floors more than single foundation.

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Conflicts of interest

The authors declare no conflict of interest.

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