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Research Article

Seismic Resistance and Displacement Mechanism of the Concrete Footing

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A realistic seismic simulation of the concrete footing has been made by using finite element method (FEM) software called ABAQUS. The effect of concrete footing embedment in soil on concrete footing-soil foundation interaction has numerically been simulated for considering displacement, stress, strain, and seismic acceleration load response at the base of a concrete footing. The results showed that the height of embedded concrete footing in soil foundation controls (i) mechanism and magnitude of lateral, vertical, and differential displacements of the concrete footing, (ii) strain energy, the acceleration load response, and stress paths, and (iii) concrete footing-soil foundation interaction. Compared with various theoretical and experimental results reported in the literature, the present study provides realistic seismic behavior of concrete footing-soil foundation interaction.

1. Introduction

From the available literature [1–9], it is demonstrated that the displacement of soil foundation is very important in the design of view to construct a stable infrastructure. There are several analytical, experimental, and numerical investigations for understanding the static and dynamic response of soil. In order to investigate the failure mitigation of soil foundation, soil bearing capacity, and soil improvement [1–3], several analytical investigations were reported. The differential settlement and seismic mitigation of embankment models were studied [4, 5]. The displacement of concrete footing was numerically analyzed using ABAQUS [6], and the dynamic behavior of soil foundation during liquefaction was reviewed [7]. ABAQUS software is used in simulation displacement of reinforced rock-soil slopes [8], and FLAC-3D software is employed for numerically simulating displacement and shear strain of sandy soil subjected to cyclic loading [9]. In all the methods, the static, dynamic, and seismic response of whole soil mass or soil models is investigated. On the contrary, in many projects, the improvement of soil needs to be done if the soil cannot provide enough bearing capacity and strength to sustain the applied load on the soil. The most common soil improvement techniques are reinforcing, grouting, densification, deep mixing, and drainage. Inattention to the complexity of static, dynamic, and seismic behaviors of soil, it requires to investigate and soil load response in specific cross-section of soil for accurate soil improvement process. On the contrary, only the subsoil analysis will not perfectly support the soil foundation and concrete foundation design.

In the present study, the ABAQUS is used for study displacement of the concrete footing. The analysis was done by using a new technique in numerical analysis. There is not any numerical analysis report by using ABAQUS on the seismic concrete footing-soil foundation interaction with considering the vertical and horizontal displacement of concrete footing, strain, stress, and seismic acceleration load response at the underneath concrete footing, while the height of embedded concrete footing in a soil foundation is varied for each model, and the model was subjected to seismic loading. In this investigation, the numerical analysis was performed to provide a realistic understanding of a complex geotechnical engineering problem. The seismic vertical, horizontal, and differential displacements mechanisms of concrete footing are evaluated for all the models with attention to concrete footing-soil interaction. In the present work, the numerical analysis is unique, it is due to the development of cycling graphs by using ABAQUS, and the results exactly depict the seismic behavior of the models. The numerical results obtained from this study are compared with those that are available in the literature.

2. Problem Definition

At present investigation, the influence of concrete footing height embedded in the layered soil has been evaluated. The single concrete footing is placed on and inside soil foundation. The seismic behavior of concrete footing-soil interaction complicates; however, modeling concrete footing-soil interaction with using suitable techniques helps to realize this problem. It is assumed that the soil medium obeys the Mohr–Coulomb failure criterion and an associated flow rule, and this concept was applied in numerical analysis with considering mechanical properties of soil and concrete. The concrete footing and soil foundation are loaded simultaneously in one step in numerical analysis to have vertical and horizontal displacements simultaneously. The numerical analysis was performed to determine (i) seismic acceleration load response versus vertical displacement at the base of concrete footing, (ii) seismic acceleration load response versus stress and strain at the base of concrete footing, (iii) lateral displacement of concrete footing, and (iv) the stress-strain curve at the base of concrete footing. However, from the solution available in the literature is understood [10], lateral displacement of concrete footing reduces with increasing height of embedded concrete footing in the soil foundation. The results of numerical analysis influence soil-structure interaction. The suitable aspects in concrete footing-soil foundation design are well understood, and a valid analysis method is used in respect to literature analysis.

3. Modeling and Materials

The model is subjected to the realistic seismic load. The boundary condition, the nature of applied load, and mechanical properties of soil in all the models are assumed to be same. The mechanical properties of the materials and the seismic load are shown in Table 1 and Figures 1–3, respectively. In the present study, the earthquake data are collected from the United States Geological Survey (USGS) and Center for Engineering Strong Motion Data (CESMD). The earthquake data were recorded by Forca Canapine station, and this station is located in 11.7 km distance from the epicenter of the earthquake. The northern Norcia Italy earthquake has been occurred with 6.6 magnitudes, at the location of 42.85°N 13.09°E, and depth of 10.0 km, on 07 : 16 : 03 UTC, 30 Oct 2016. ABAQUS software has the ability to simulate the seismic acceleration load and apply realistic seismic load on the model in numerical analysis. The ABAQUS is based on the Lagrangian formulation. To simulate concrete footing-soil foundation interaction, the three different models are developed, and in each model, the level of embedment footing in soil is different. In the first model, the concrete footing is placed on soil foundation, and it is not embedded in the soil foundation. In the second model, half of the concrete footing is embedded in the soil foundation. In the third model, whole concrete footing is embedded in the soil foundation, and it is shown in Figure 4. The full height of the concrete footing is 30 cm. In the numerical simulation, the dimensions of concrete footing are 70 cm width ∗ 70 cm length ∗ 30 cm height. The dimensions of the soil foundation are 150 cm width ∗ 150 cm length ∗ 90 cm height. The ABAQUS has the ability to depict dynamic response at any part of a model. Depict dynamic response at a cross-section in a model is a new achievement in this research work, and it has not been reported in the literature previously. However, the seismic response between bases of concrete footing with soil foundation is not explained in the literature. The modeling of the three-dimensional concrete footing is important to capture the true seismic response under accurate boundary condition.

4. Numerical Analysis, Discussion, and Verification of the Results

The investigation on concrete footing-soil foundation interaction at the base of the concrete footing is essential for the analysis and design of infrastructure seismic stability. To analyze concrete footing-soil foundation interaction, an accurate model is made. This modeling is capable of simulating seismic concrete footing-soil foundation interaction at the base of the concrete footing. The model is able to capture the three-dimensional seismic response. The numerical results for seismic acceleration load response versus displacement at the base of a concrete footing, during concrete footing-soil foundation seismic interaction, have been provided in Figures 5–7. Due to the high variation of models of seismic response, different scales have been selected for graphs. The stiffness of the soil foundation is responsible for developing displacement. The level of loading, unloading, and reloading has been investigated for all the models. The seismic acceleration load response reached to zero in the unloading process, and in reloading, it increases up to the maximum level, and it is shown in Figures 5–7. When the model is subjected to seismic loading, unloading, and reloading in all the three phases of the loading mechanism, the displacement shows with different shapes. In the unloading phase, the displacement is zero, while in loading and reloading phases, the displacements reached the maximum level with two different directions. This displacement mechanism is developed due to the nature of the seismic load is applied to the model. The seismic loading is transferred to the bottom of the concrete footing, and it leads to seismic acceleration load response. The results of numerical simulation explained that the ABAQUS is able to compute nonlinear analysis. The seismic acceleration load response is distributed within the concrete footing base in contrast with the displacement pattern. The smaller seismic acceleration load response is observed with fully embedded concrete footing in the soil foundation. The differential displacement of the concrete footing was reduced with increasing depth of the concrete footing in the soil foundation. The seismic load acting at the base of a concrete footing was

Table 1: Soil and concrete mechanical properties [11, 12].

Soil type	Modulus elasticity, E (MPa)	Poisson's ratio, ν	Friction angle, ϕ (degree)	Dilatancy angle, ψ (degree)	Cohesion, c (kPa)	Unit weight, γ (kN/m^3)	Ref.
Soil	5	0.36	35	20	20	12.2	[11]
Concrete	49195	0.24	—	—	—	24.405	[12]

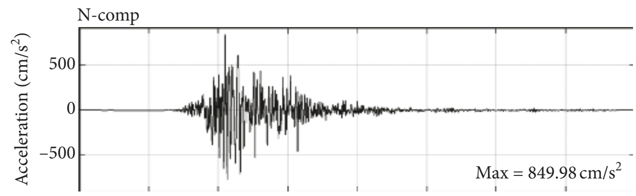


Figure 1: Acceleration history, northern Norcia Italy earthquake of 30 Oct 2016 [13].

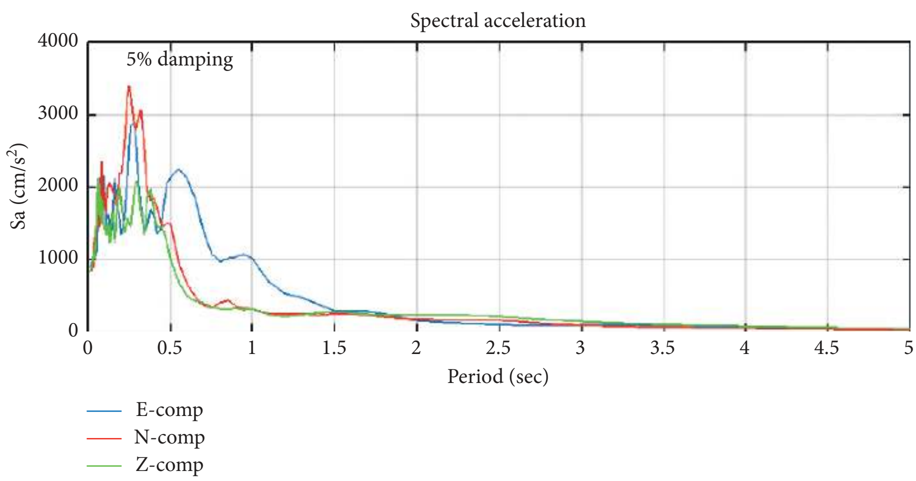


Figure 2: Spectral acceleration history, northern Norcia Italy earthquake of 30 Oct 2016 [13].

developing differential displacement with different mechanisms and magnitudes. The seismic load plays a crucial role in developing the ground displacement mechanism, and it has a direct relationship with damage caused by an earthquake. The failure of concrete footing due to high differential displacement is more possible if the concrete footing is placed over the soil foundation. With embedment of concrete footing in the soil foundation, the failure of concrete footing due to differential displacement was reduced.

The numerical results for seismic acceleration load response versus strain at the base of a concrete footing during concrete footing-soil foundation have seismic interaction which is shown in Figures 8–10. The strain level of a model is evaluated with respect to seismic acceleration load response. With the reduction of strain, the stiffness of soil increases and damping ratio decreases; all of this process directly is depend on seismic acceleration load response. The cyclic strength of soils is determined numerically with a focus on the propagation of seismic waves, considering small strain and inelastic behavior of soil foundation at beneath of concrete footing. The permanent deformation and reduction strength of soil foundation are expecting in the first model when the concrete footing is placed over the soil foundation and concrete footing is not embedded in the soil foundation. On the contrary, with the half and full embedded concrete footing in the soil foundation, the possibility for permanent deformation and reduction strength of the soil foundation is reduced significantly. The location of the embedment concrete footing in the soil foundation governs seismic energy dissipation. The strain rate sensitivity is analyzed by evaluating seismic acceleration load response, and it supports in understanding differential displacement of the concrete footing.

The numerical results for shear stress versus shear strain at the base of a concrete footing, during concrete footing-soil foundation interaction, are shown in Figures 11–13. The graphs show, with increased depth of embedment concrete footing in the soil foundation, the shear stress and shear strain were reduced, and they behave smoother with smaller magnitude. It can understand that, with increasing embedment of concrete footing in the soil foundation, the vibration of the concrete footing is significantly reduced. The results show that the stress buildup strain energy in the base of the concrete footing leads to releasing the strain energy in the form of vibration and causes deformation of the model. After applied seismic load on the model, the concrete footing

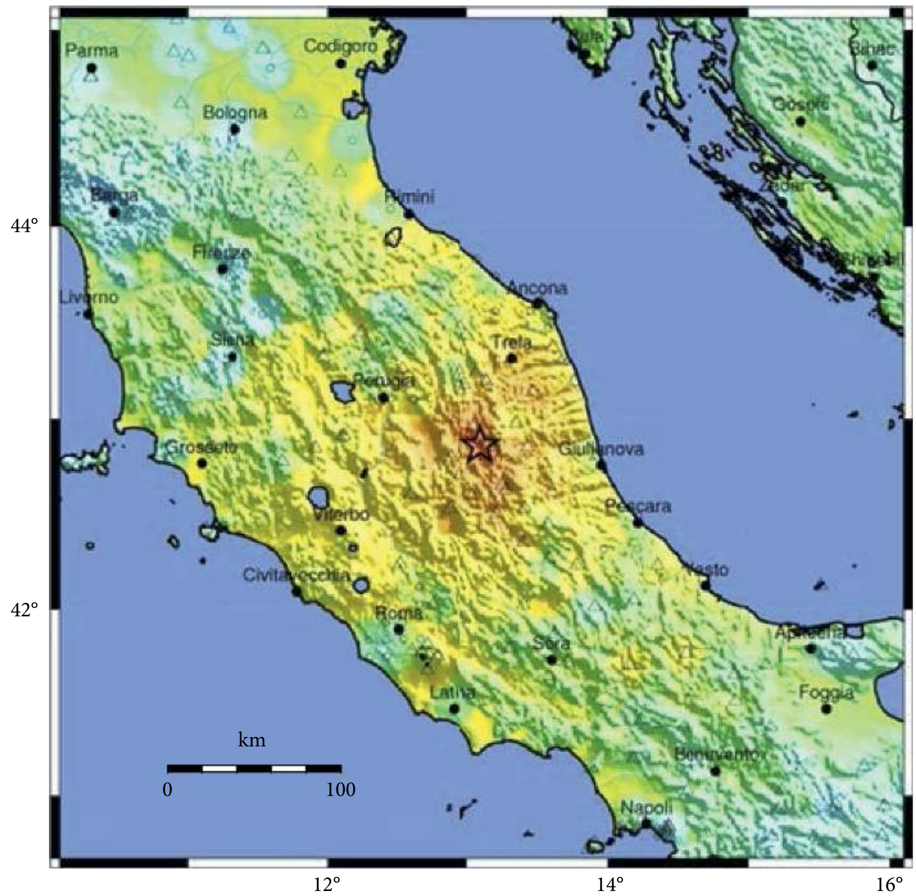
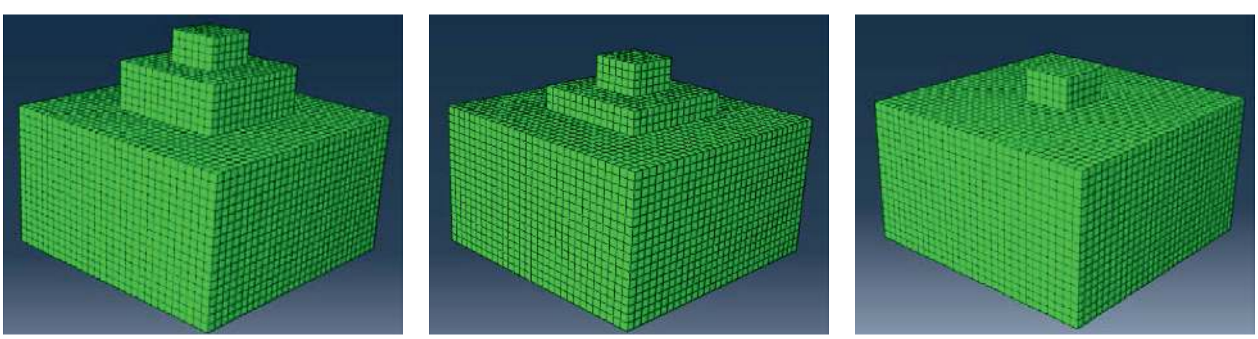


Figure 3: ShakeMap, northern Norcia Italy earthquake of 30 Oct 2016 [13].



(a) (b) (c)

Figure 4: Concrete footing-soil models. (a) Footing not embedded. (b) Half of the footing is embedded. (c) Full of the footing is embedded.

is displaced. The level of the concrete footing displacement depends on the level of releasing strain energy and strength of soil foundation. If the strength of soil foundation is the same in all the models, the strain energy plays important role in the displacement of the concrete footing. On the contrary, the level of strain energy depending on the location of the concrete footing is embedded in the soil foundation. Each model is capable to produce different amounts of strain energy after seismic loading is applied to the model. The geometry of the model is a factor in the production level of strain energy. It can be understood that the concrete footing geomorphology has an important function in releasing strain energy, and it influences on earthquake zone differently. However, the stability of a structure is different at any location when the structure is subjected to seismic loading. If two structures with the same strength and geometry are located nearby, but in distance between the two structures, the geomorphology changes significantly, the structure seismic response is too different. The level of strain energy is influenced on the variability damping ratio of a model. With fully embedment concrete footing in the soil foundation, the damping ratio and natural frequency are reduced. The lateral

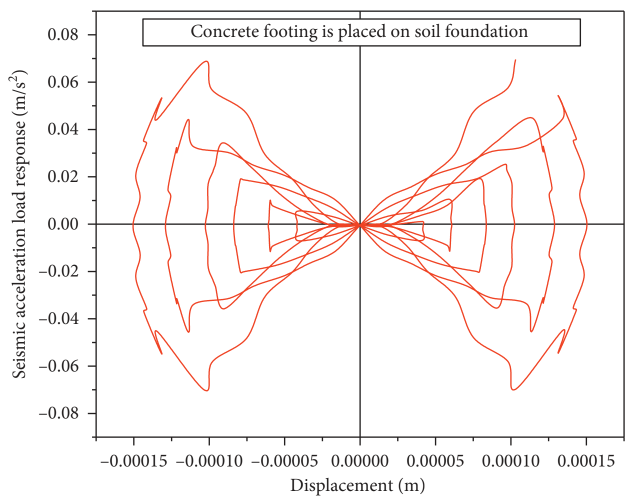


FIGURE 5: Seismic acceleration load response vs displacement at the base of a concrete footing, during concrete footing-soil foundation interaction.

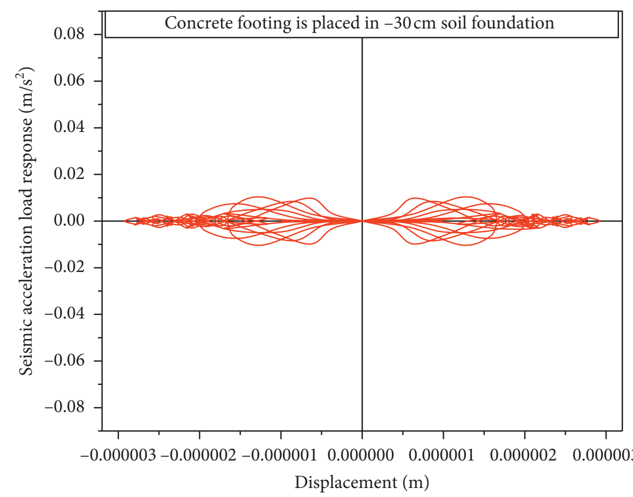


FIGURE 7: Seismic acceleration load response vs displacement at the base of a concrete footing, during concrete footing-soil foundation interaction.

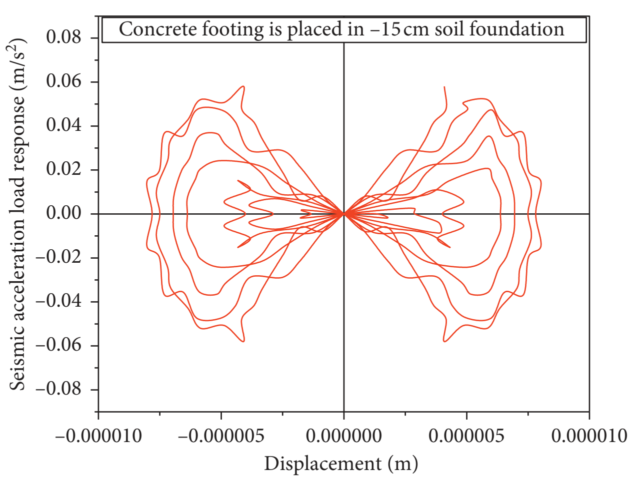


FIGURE 6: Seismic acceleration load response vs displacement at the base of a concrete footing, during concrete footing-soil foundation interaction.

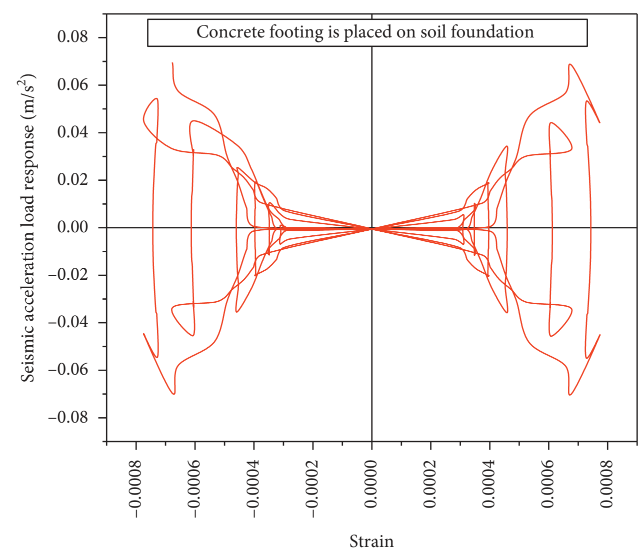


FIGURE 8: Seismic acceleration load response vs strain at the base of a concrete footing, during concrete footing-soil foundation interaction.

strength of the concrete footing increases with full embedment of the concrete footing in the soil. It is due to the strain energy distributed. In the model fully embedded with concrete footing in the soil foundation, the shape of the strain energy is converted from point loading to distribute loading, while the magnitude of strain energy does not change. The shape of the strain energy has a direct relationship with a vertical and horizontal displacement of the concrete footing.

Seismic acceleration load response versus stress at the base of a concrete footing during concrete footing-soil foundation interaction is shown in Figures 14–16. The seismic acceleration load response changes with the distribution of vertical and horizontal seismic stresses are applied to the whole model, and this phenomenon is shown in Figures 14–16. It is based on elastic soil interaction with solid concrete footing. The minimum level of stress is developed in a fully embedded concrete footing in the soil foundation.

The numerical results for lateral displacement of a concrete footing with considering concrete footing-soil foundation seismic interaction are illustrated in Figure 17. Figure 17 shows that the lateral displacement is reduced with an increase in the concrete footing embedment level in the soil foundation. It is required to indicate that the level of the embedded concrete footing in soil foundation directly affects on concrete footing differential displacement magnitude and mechanism. The mechanism of lateral displacement is not linear in all the models. In all the three models, the magnitude of the displacement drops to zero, during the direction of seismic loading is changed. The seismic loading has three steps: loading, unloading, and reloading. In unloading steps, the load reached zero. The results of numerical simulation have good agreement with the concept of

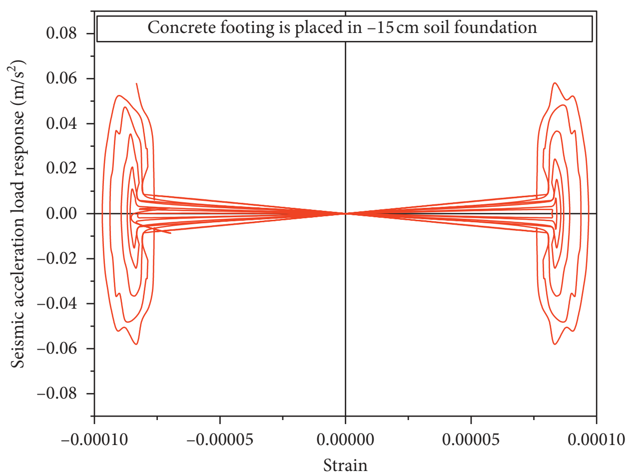


Figure 9: Seismic acceleration load response vs strain at the base of a concrete footing, during concrete footing-soil foundation interaction.

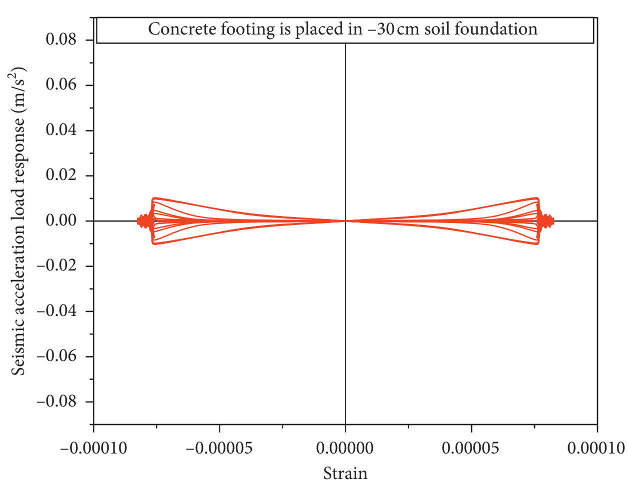


Figure 10: Seismic acceleration load response vs strain at the base of a concrete footing, during concrete footing-soil foundation interaction.

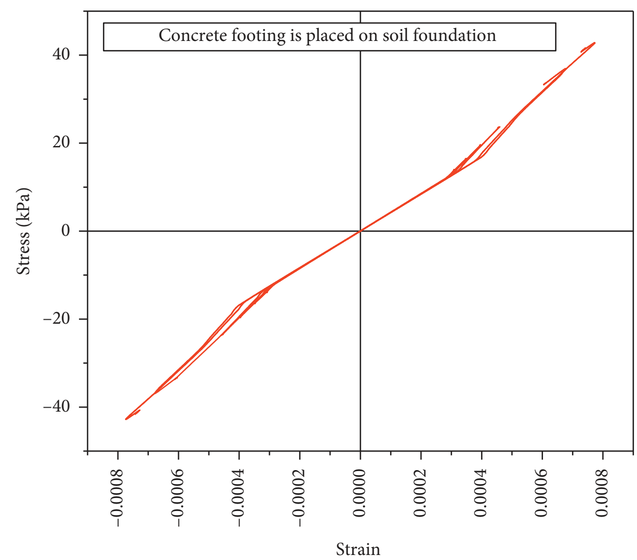


Figure 11: Shear stress vs shear strain at the base of a concrete footing, during concrete footing-soil foundation interaction.

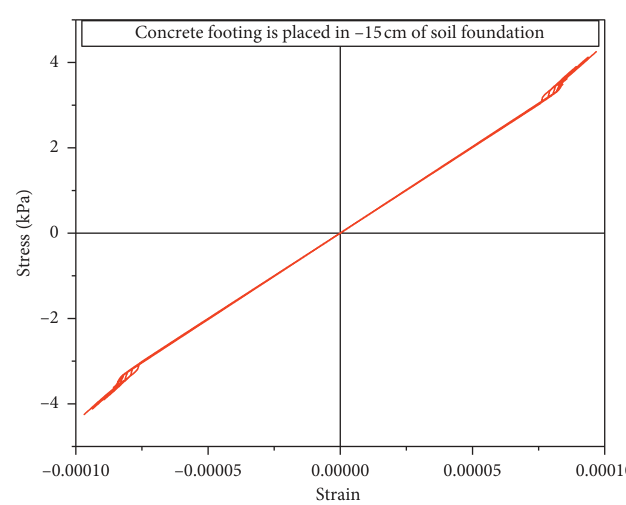


Figure 12: Shear stress vs shear strain at the base of a concrete footing, during concrete footing-soil foundation interaction.

seismic loading nature. The lateral displacement changes (i) with smooth movement at the base of the concrete footing and (ii) marginally smaller than for fully embedded concrete footing. However, due to the faster release of the lateral loading to zero, for a fully embedded concrete footing in soil foundation, the value of loading frequency is reduced, and less shaking has been observed at the model with fully embedded concrete footings in soil foundation. The magnitude and mechanism of lateral displacement change with respect to the location of a concrete footing is embedded in the soil foundation.

The validation of SSI analysis through field data has been difficult, due to the lack of well-documented and instrumented structures subjected to earthquakes [11]. The suitable three-dimensional models have been made to explain the concrete footing-soil foundation interaction, during the model is subjected to realistic seismic loading. It is observed that the seismic loading response of each model, at any cross-section of concrete footing and soil foundation, is not the same. This phenomenon leads to the occurrence of different concrete footing-soil foundation interaction mechanisms horizontally and vertically. This phenomenon leads to the occurrence of different displacement mechanisms at each direction and cross-sections of the model, as shown in Figures 5–16. However, for studying the concrete footing differential displacement mechanism, the concrete footing-soil interaction at the base of the concrete footing have numerically been investigated. Figure 18 shows that the horizontal displacement resonance curves at the foundation bottom forced vibration test [10]. Figure 17 shows the lateral displacement for a concrete footing, during concrete footing-soil foundation interaction. Figure 18 shows the horizontal displacement resonance curves at foundation bottom, forced vibration test. In comparing the results of the numerical simulation with those that are reported in the

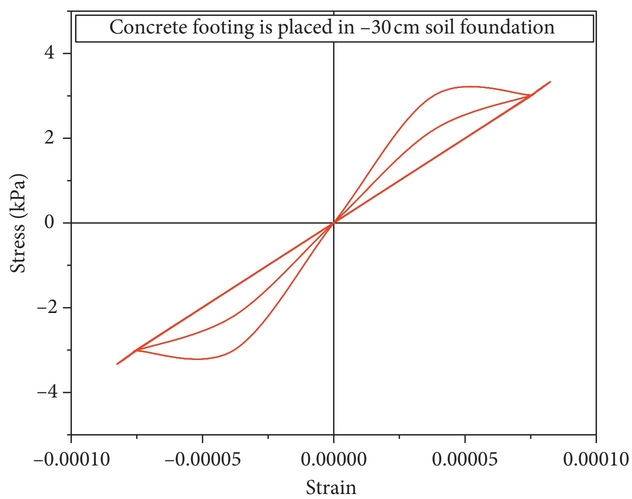


FIGURE 13: Shear stress vs shear strain at the base of a concrete footing, during concrete footing-soil foundation interaction.

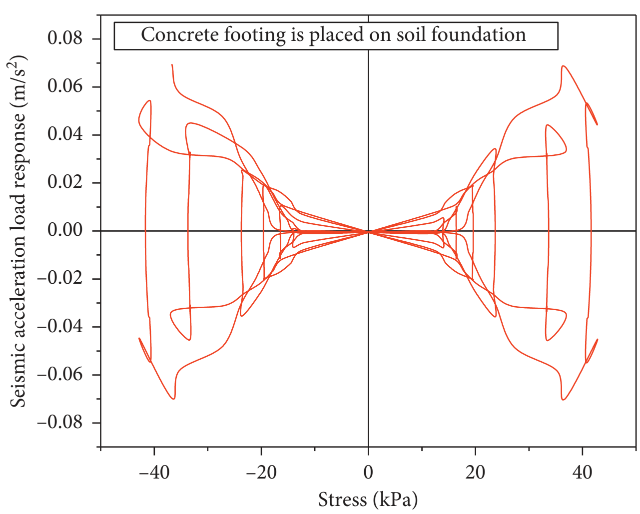


FIGURE 14: Seismic acceleration load response vs stress at the base of a concrete footing, during concrete footing-soil foundation interaction.

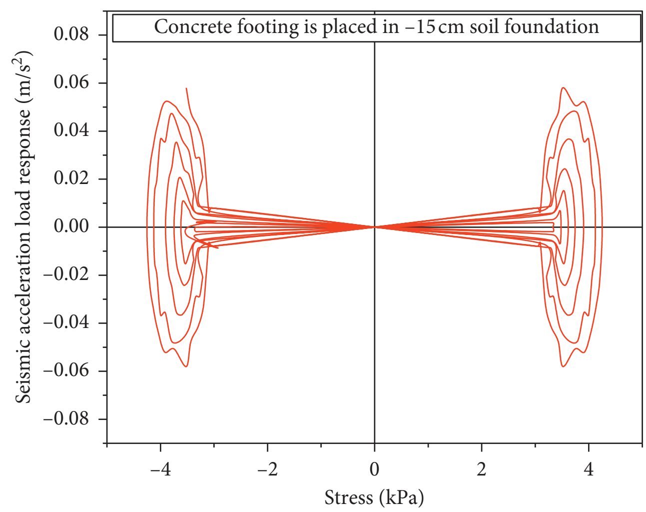


FIGURE 15: Seismic acceleration load response vs stress at the base of a concrete footing, during concrete footing-soil foundation interaction.

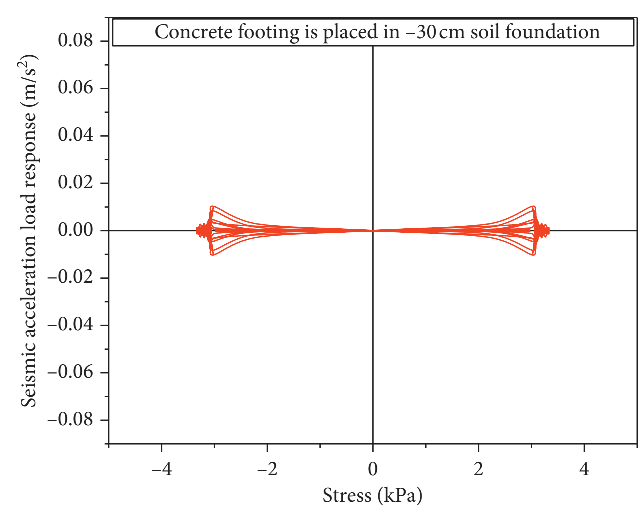
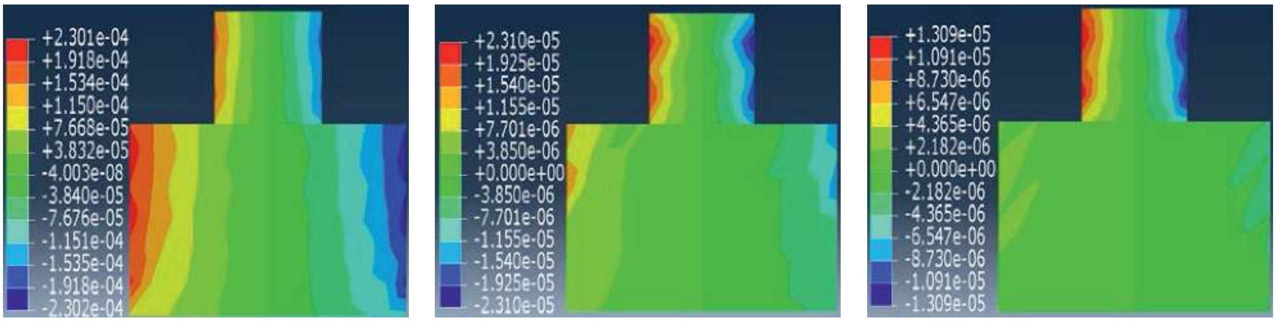


FIGURE 16: Seismic acceleration load response vs stress at the base of a concrete footing, during concrete footing-soil foundation interaction.

literature, it has been understood that the results of the numerical simulation are in good agreement with those that are reported in the literature. In this three-dimensional numerical simulation, the displacement mechanism at horizontally and vertically directions for all models plays a key role to explain the complexity of the concrete footing-soil interaction. The stability of concrete footing depends on the realistic result of the numerical analysis. The results of the present study demonstrate that the modeling of concrete footing-soil foundation interaction supports solving a geotechnical engineering problem is related to the differential displacement mechanism of the concrete footing. The results have shown that the model can capture the essential displacement mechanisms with considering both the vertical and horizontal deferential displacement of soil foundation.

In the load-strain mechanism, only the part of the strain energy corresponding to the linear elastic response is recovered [14]. On the contrary, the load transferring mechanism has been investigated using numerical analysis and experimental works with considering the strength of materials and shape of the modeling [15–18], and this phenomenon significantly influences on concrete footing-soil foundation interaction. But due to characteristics of soil during loading, unloading, and reloading process, and change compression loading to tensile loading in very short times, the crack on soil due to tensile loading and fatigue of soil cannot be explained same as which is presented in the literature, about crack and fatigue on metal [19–21]. The failure pattern and shear resistance of soil have been discussed using mathematical modeling techniques and numerical simulation [22–27], and the bearing capacity and effective stress have been changing with respect to soil foundation displacement. There are special techniques in numerical simulation [6, 14, 22, 26, 28].



(a) (b) (c)

Figure 17: Lateral displacement of a concrete footing, during concrete footing-soil foundation interaction. (a) Footing not embedded. (b) Half of the footing embedded. (c) Full of footing embedded.

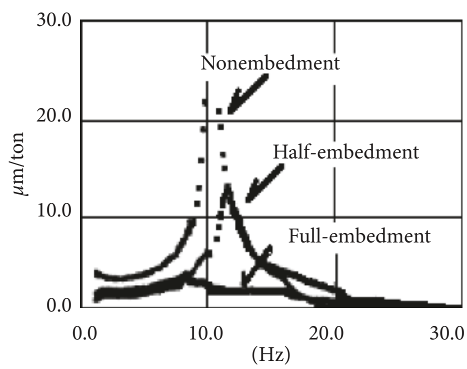


Figure 18: Comparison of displacement resonance at foundation bottom [10].

In the present study, cyclic graphs have been developed for understanding concrete footing displacement using ABAQUS which never has been reported in the literature.

5. Conclusion

In this study, a procedure for the 3D finite element analysis on the concrete footing-soil foundation model is made for understanding concrete footing-soil foundation seismic interaction. It has been attempted to simulate concrete footing-soil interaction during model that is subjected to realistic seismic loading. The results of the numerical analysis show that the height of concrete footing is embedded in the soil influences on seismic behavior of concrete footing and govern concrete footing-soil interaction, and it results in displacement magnitude and mechanism of the concrete footing.

(i) The acceleration seismic load response-strain and stress at the base of the concrete footing is changed in respect to concrete footing-soil interaction. The concrete footing-soil interaction is minimized deformation of soil and is enhanced concrete footing stability. The acceleration seismic load response at the base of concrete footing can be controlled with installing concrete footing in the appropriate location of the soil foundation.

(ii) The acceleration load response-displacement at the base of the concrete footing is not the same for all the three models.

(iii) The lateral and vertical displacements of the concrete footing are reduced with an increase in concrete footing embedment height in the soil.

(iv) The differential displacement of the concrete footing is reduced with an increase in concrete footing embedment height in the soil.

(v) After applying a seismic load to the model, the concrete footing is displaced, the level of displacement depending on the level of releasing strain energy. Each model is capable to produce different amounts of strain energy. The geometry of the model is a factor affecting on the level of the strain energy.

(vi) The results have good agreement with those that have been reported in the literature.

Data Availability

The data used in this paper have been collected from the literature, and the references that support the data used in numerical analysis are cited as [11–13]. The mechanical properties of materials used are those reported in the literature (Table 1). Figures 1–3 show the seismic load has been collected from the literature and applied in numerical simulation. In the present study, the earthquake data are collected from United States Geological Survey (USGS), Center for engineering strong motion data (CESMD). The earthquake data are used as reported by the Forca Canapine station; this station is located at 11.7 km distance from the epicenter of the earthquake. The northern Norcia Italy earthquake occurred with the magnitude of 6.6, at the location of 42.85°N and 13.09°E and depth of 10.0 km, on 07 : 16 : 03 UTC, 30 Oct 2016 (Figures 1–3). ABAQUS software has the ability to simulate seismic acceleration load and apply realistic seismic load on the model in numerical analysis.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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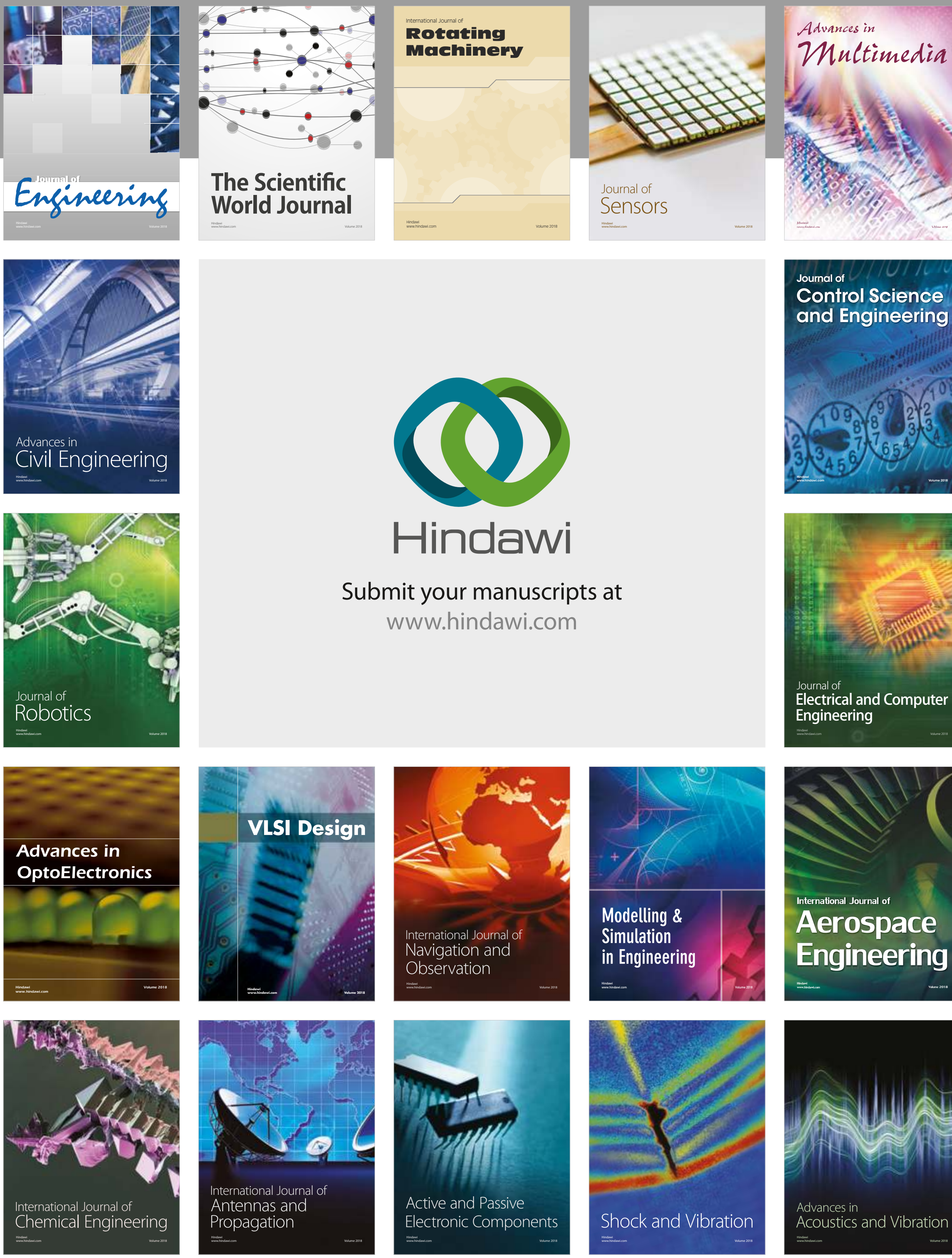
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