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Received on: 08/04/2019
Accepted on: 24/08/2019
Published online: 25/12/2019

Numerical Analysis on Seismic Response of Multi-Stories Reinforced Concrete Buildings Under the Effect of Infinite Boundary of Soil-Structure Interaction

Abstract- *The damage caused by large earthquakes is not only due to structures but also due to the soil failure, where the dynamic response varies considerably from the fixed base state because of the interaction between the ground and the structure. The main objective of this paper is to study the effect of the infinitely extended soil on the dynamic response of the structure. A three-dimensional dynamic analysis of reinforced concrete building considering the effect of soil-structure interaction is performed. Building with a different number of stories rest on soil with various characteristics have been taken into consideration. For simulation of wave propagation due to far-field effects, coupled finite-infinite elements is presented for modeling the soil. The infinite boundary provides a powerful tool for dealing with wave propagation problems. The analysis is performed through a finite element method which is implemented in ABAQUS program. An earthquake load is applied in the horizontal direction with various boundary conditions such as; free, and infinite boundary. The effect of boundary on the dynamic response of structure are investigated. The significant difference in dynamic response is observed when infinite boundaries are used, especially in the case of soft soil, where the existence of infinite elements leads to absorption of energy and thus greatly reduce the lateral displacement of the structure.*

Keywords- Soil-Structure Interaction, SSI, Seismic Soil-Structure Interaction

How to cite this article: Q.A. Hasan, S.F. Al-Wakel and Z.R. Zaidan, "Numerical Analysis on Seismic Response of Multi-Stories Reinforced Concrete Buildings Under the Effect of Infinite Boundary of Soil-Structure Interaction," Engineering and Technology Journal, Vol. 37, Part A, No. 12, pp. 516-521, 2019.

1. Introduction

Earthquake is the most disastrous and unpredictable phenomenon of nature. The total destruction of buildings from earthquake leads to the need for investigation to find reasons. The causes of the damages in the past caused by strong earthquakes were not only due to structural damage, but, some of them, due to the soil failure. Some examples can be mentioned here. The 1985 Mexico earthquake, where observed a failure in partial bearing capacity of foundation soil which caused the damages on 10-12 stories buildings [1]. The overturning and collapse of Hanshin expressway are observed in the 1995 Kobe earthquake due to the increase in natural time period with the effects of interaction [2]. The Chile earthquake in 2010 caused the damage of non-structure elements such as construction services, despite of the good behavior of buildings, where observed large amplification of vibration with soft soils caused more severe damage to buried services and building [3]. The most important causes of building defects are the soil, because of its importance in carrying the foundations, which is the cornerstone of the building, and may result from the movement of any part of the foundations of the building distort the building. The analysis of structures subjected to earthquake, it is usually assumed that the base of structure is fixed to simplify the mathematical problem but, in some cases, buildings construct in areas with geotechnical conditions unsuitable for earthquakes. This assumption leads to gross error in assessment of overall response under dynamic loads [4]. The soil-structure interaction is a process in which the movement of the structure affects the soil response and soil response affects the movement of structure, this process is called soil structure interaction [5]. In this paper seismic analysis was done by finite element method for soil-structure interaction. Three different soil types were considered as the hypothetical site soil for the study of the effect of soil properties on the seismic response of the soil-structure system. In order to simulate three-dimensional finite element model, ABAQUS program was used for whole project including the building structure and the local soil. The simulated buildings are three dimensional 10 and 15-storey buildings. The earthquake is selected from actual ground motion. This search was performed in order to investigate

https://doi.org/10.30684/etj.37.12A.4
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the time displacement history response of the buildings subjected to this actual earthquake.

2. The Geometry and Properties of Structure and Soil

The soil-structure system consists of soil, foundation and structure. An earthquake induced acceleration at the level of the bedrock as shown in Figure 1. The dynamic equation of motion of the soil and structure system can be written as [6].

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{a\}\ddot{u}_g + \{F_v\} \quad (1)$$

where $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are the nodal accelerations, velocity and displacements, with respect to the underlying soil foundation, respectively. $[M]$, $[C]$ and $[K]$ are the mass, damping, and stiffness matrices of the structure, respectively. $\{\ddot{u}_g\}$ is the earthquake induced acceleration at the level of the bedrock. For example, if only the horizontal acceleration is considered, then {a} $=[1, 0, 1, 0, \ldots. 1, 0]^T$. {Fv} is the force vector corresponding to the viscous boundaries. This vector is nonzero only when there is a difference between the motion on the near side of the artificial boundary and the motion in the free field.

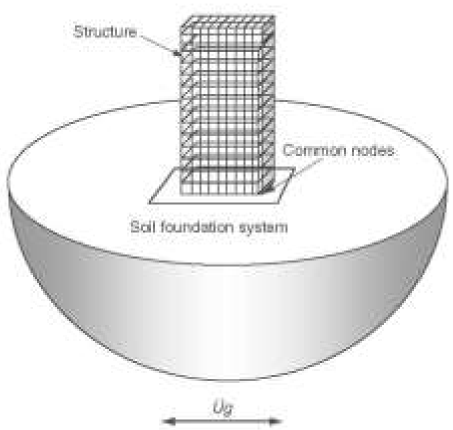


Figure 1: Infinite boundary of soil-structure system.

To study the effect of soil-structure interaction (SSI), a three-dimensional concrete structure with raft footing resting on a homogeneous soil is considered. Simulated buildings are 10 and 15 story. The building consists of 3 bays in X-and Z-direction. The bay length was 4m in each direction. The story height was 3m. Cross-sections of the columns were selected identical for each of five-sequential stories and the dimensions of the cross-section of the columns were reduced 5cm in every five-story. The buildings are modeled with (80 × 80) cm columns for the first five stores. The beam length is 4 m and the cross-section is assumed to be (65×65) cm for the first five story reduced 5cm in every five story. The values of dead load and imposed action is 2 kPa, which are applied as uniformly distributed loads according to AS1170.4 (2007). SAP2000 V14 has been utilized for the structural design purpose. The details of the buildings were according to the research [7].

The modulus of elasticity of concrete (E) was calculated accordance with clause 3.1.2.a of Australian Standard for Concrete Structures [8] as follows:

$$E = (\rho)^{1.5}\, X(0.043\sqrt{f\acute{c}}\ ) \quad (2)$$

A dry soil is used in this study. The simulated bounded soil is considered to be rectangular shaped with dimensions of 60 m length, 32 m width and 30 m depth. The geometry of soil is according to the research [7]. The slab thickness is 0.25 m. The effect of soil properties is also investigated by considering three types of soil according to the research [9]. The foundation is modeled as a square foundation with dimensions of 1meters in depth, and 14 meters in length and width. The building is considered to be located in seismic zone [7]. Damping Ratio for soils are 5% .The properties of structure and soil are shown in Tables 1 and 2, respectively.

Table 1. Properties of structure [7]

The Properties	Value
Density of Concrete (kg/m³)	2400
Damping Ratio	0.05
Modulus of elasticity (MPa)	28600
Poisson's ratio	0.3
f́c (MPa)	32
Yield stress (MPa)	25

Table 2: The property of soils [9]

Type of soil	Density (kg/m³)	Young's modulus (Pa)	Poisson's ratio
Firm	2064	5.68×10^9	0.35
Medium	1864	3.61×10^8	0.3
Loose	1667	3.45×10^7	0.25

4. Modeling of soil-structure system

I. Type of Element

A three-dimensional 8-noded hexahedral (brick) element with 6 degrees of freedom in each node (translations and rotation in X, Y and Z-directions) named (C3D8R) are utilized for modeling soil and raft foundation with reduced integration to prevent the shear locking effect.

This elements has the ability to represent material and geometrical nonlinearities and also large deformations. Reduced integration reduces the requirements of higher order solids.

In order to model beam and column, a 2-noded beam element with 6 degrees of freedom in each node (translations in X, Y and Z directions of global coordinates system) are used. A 4-noded thin shell element with reduced integration are used to model slab.

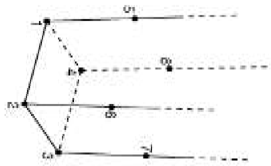
II. Infinite element

Finite element method that used to simulate soil-structure interaction model, where the soil medium is cut along certain boundaries. So as to restrain reflection of the earthquake waves from the sides of the cut soil, and to take into account the extension of the soil an infinite boundary is considered, Infinite elements boundary are important for problems of boundary value, where they are used in undetermined area, or problems in which the surrounding medium is large compared to the area of interest, which are usually used in conjunction with finite elements, that can have a linear behavior only and which provide stiffness in static solid continuum analyses and provide "quiet" boundaries to the finite element model in dynamic analyses. A solid section definition is used to define the properties of infinite elements.

The infinite element is like the finite element in formulation as well as the mapping of the domain. Infinite elements have absorbing properties which can be used in time domain. The peripheral of the finite elements (element type: C3D8R), has been surrounded by infinite element (element type: CIN3D8) which is implemented in ABAQUS program as shown in Figure 2.

The values of boundary damping are built into the infinite elements in ABAQUS program. During the dynamic response, analysis following static preload, the traction provided by the infinite elements to the boundary of the finite element mesh consists of the constant stress obtained from the static response with the quiet boundary damping stress added. Since the elements have no stiffness during dynamic analysis, they allow a net rigid body motion to occur, which is usually not a significant effect. The peripheral of the finite element (C3D8R) has been surrounded by infinite elements (CIN3D8).

The soil-foundation-structure system with finite and without infinite boundary are shown in Figures 3 and 4, respectively.



Finite element Infinite element

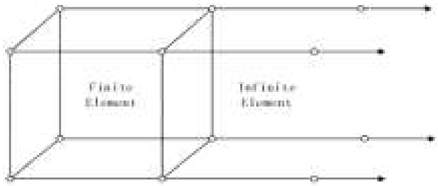


Figure 2: The infinite element.

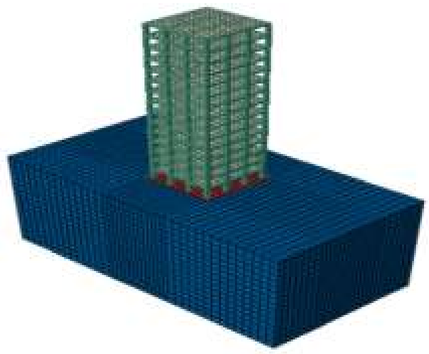


Figure 3: Soil structure system with finite boundary.

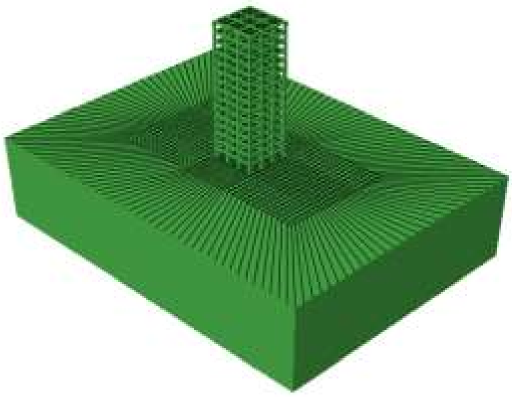


Figure 4: soil structure system with infinite boundary.

5. Earthquake

Romania's 1977 Vrancea Earthquake N-S is applied on the models. The time-acceleration history of the earthquake is shown in Figure 5, the active seismic excitation time is about 35 seconds.

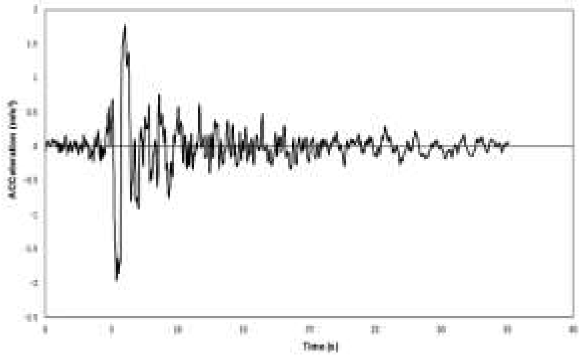


Figure 5: Time-acceleration history of Earthquake Accelerograms (Inculet, 2016)

5. Verify and Discussion the Results of Analysis

During the earthquake, the seismic response of a system of soil-structure is influenced by several factors including the soil type, structure's height and its materials' properties and soil-structure interaction. In order to consider how the dynamic response of the structure is influenced by the infinite boundary of soil, three different types of soil were modeled as firm, medium and loose soil. The analysis is performed on structure with 10 and 15 story with three different types of soil to study the effect of soil-structure interaction and height of structure on the amplitude of displacement of the soil-foundation-structure system.

Figures 6 to 11 show the comparisons between the dynamic response of structure on soil simulated with finite and infinite boundary.

To verify the results, the dynamic response of the structures on three types of soil without infinite boundary of the present study is compared with the study of reference 9. Where, in both studies, the dynamic response of the structure on loose soil is more than in the case of firm or medium soils.

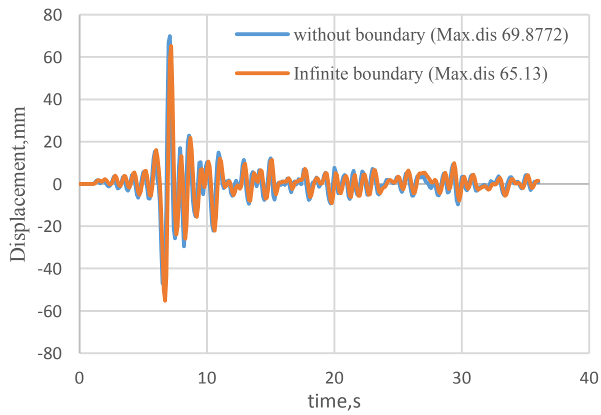


Figure 6: Time-Relative displacement history of 10-storey structure on medium soil under the effect of SSI with and without infinite boundary.

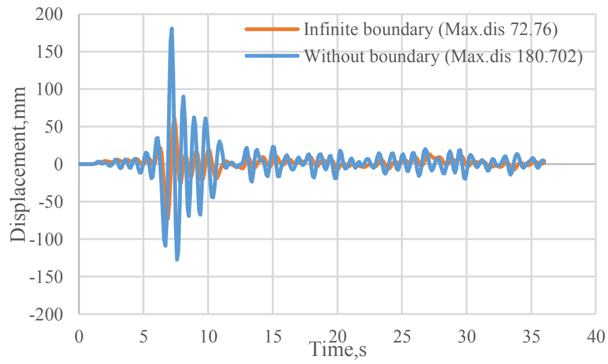


Figure 7: Time- Relative displacement history of 10-storey structure on medium soil under the effect of SSI with and without infinite boundary.

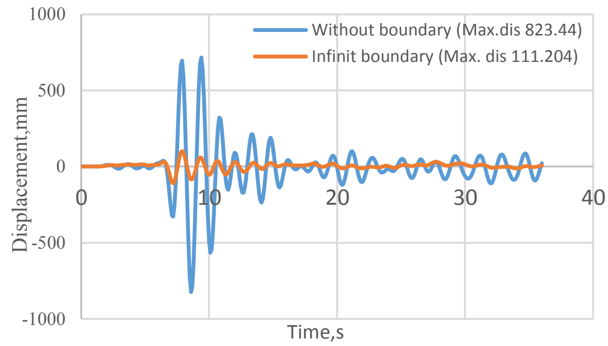


Figure 8: Time- Relative displacement history of 10-storey structure on loose soil under the effect of SSI with and without infinite boundary

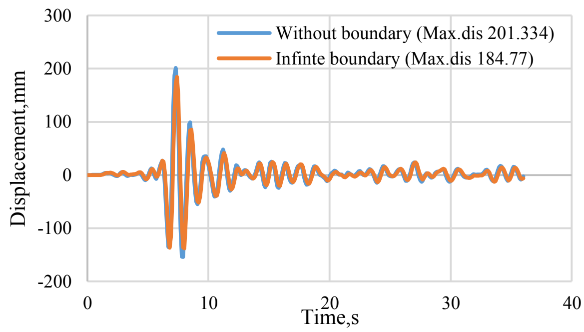


Figure 9: Time-Relative displacement history of 15-storey structure on firm soil under the effect of SSI with and without infinite boundary.

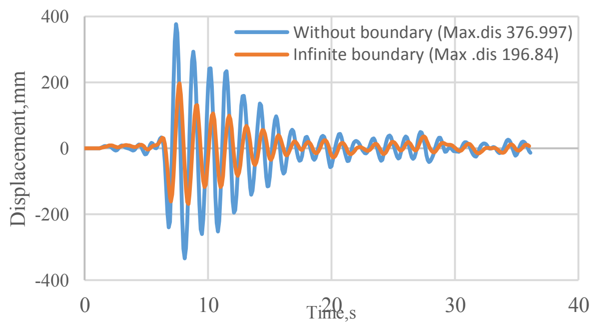


Figure 10: Time- Relative displacement history of 15-storey structure on medium soil under the effect of SSI with and without infinite boundary.

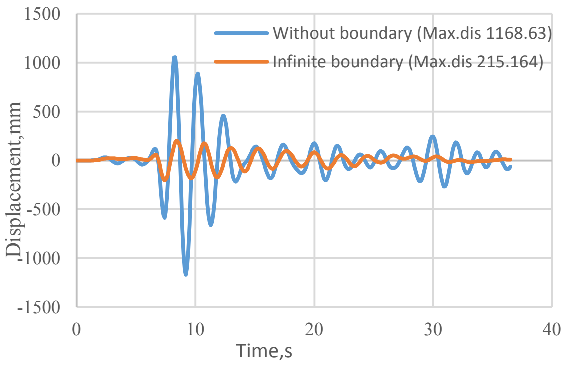


Figure 11: Time-Relative displacement history of 15-storey structure on loose soil under the effect of SSI with and without infinite boundary.

From the results it can be observed that, the maximum amplitude of displacement decreases in the case of simulate the infinite elements, compared with that results in the case of the finite media of soil. This behavior is due to the decay of the seismic waves with distance as a result of using the infinite boundary. Therefore, boundary conditions must be set around this discretized area in order to effectively simulate the effect of infinity dissipation, absorbing all energy that spreads out and does not allow any energy to return to the system. These boundary conditions are defined as transmitting boundaries (Wang et al., 2008).

Elementary boundaries are conditions of zero displacement. They reflect the impinging waves and do not absorb them, keeping the energy of the waves restricted inside the discretized region. If these boundaries are not placed far enough distant for intrinsic damping to damp out the waves before hitting the boundaries, they may cause an error in estimating the dynamic response.

In addition, it can be observed that the difference in the displacement increase with decreasing of soil stiffness. It is noted that there is no clear difference between the displacement of structure on soil simulated with finite and infinite boundary in the case of firm soil as shown in figure 6 and 9, while this difference increase with the decreasing of soil stiffness, where it can be noted a significant difference in the displacement of structures resting on loss soil as shown in figure 8 and figure 11. The effect of soil–structure interaction increase with the increasing the height of the structure, where it is can be observed that the maximum displacement were noted in 15-storey structures resting on loss soil.

This amplification of displacement may alter the level of performance of the structure. Thus, the infinite element boundary has a very important effect in soil structure interaction, the use of infinite boundaries to simulate the infinite media of soil in the dynamic analysis of a soil-foundation-structure system has a significant impact in reducing the displacement of structure due to wave propagation. This effect depends on the soil type where decreasing the stiffness of soil increases the effect, where there is a very large difference in the lateral displacement in soft soil condition.

6. Conclusions

In this work, a coupled computational method of finite and infinite elements is presented and applied in selected geotechnical problems. In order to numerically simulate geotechnical problems, the local region of interest was modeled by finite elements, which enable simulation of more complex geometries. On the other hand, the surrounding field of the domain has been considered by using infinite elements. By using the coupled finite-infinite elements approach, the number of nodes and elements has been reduced however, the accuracy of the results is not affected in the near field.

1. The infinite elements with added absorbing properties which have been proposed in this study, provide a very general and easy method to implement frame of infinite elements.
2. The result observed that the loss of infinite element led to very large displacements in loss soil and the variation of displacement decrease in the medium soil, while in the firm soil the difference is not noticeable.
3. The neglect of the infinite elements leads to very large displacements and this is not true for seismic design especially in loss soil.

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