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A study on the effects of vertical earthquake on horizontal and vertical acceleration of structures with underground stories based on a SSI 3D Model

Une étude sur les effets du tremblement de terre vertical sur l'accélération horizontale et verticale des structures avec des étages souterrains basée sur un modèle SSI 3D

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ABSTRACT: The ground motion measurements of past earthquakes have shown that the vertical acceleration could be as large as the horizontal acceleration. The vertical earthquake effect is typically considered to be less concerned than the horizontal earthquake effect. Moreover, seismic building codes rarely consider the vertical seismic effect in buildings. Most studies investigated the seismic behavior of structures and soils under only the horizontal earthquake effect and considered the vertical earthquake as a combination of the percentage of dead load and the horizontal earthquake based on seismic codes. To accurately perform the seismic evaluation of the structure and soil, it is required to perform time-history analysis by simultaneously applying the three earthquake components due to the complex dynamic behavior of the soil-structure interaction (SSI). This study performs the direct three-dimensional simulation of the soil and structure in ABAQUS in order to investigate the vertical earthquake effects on the horizontal and vertical accelerations. The peak horizontal acceleration (PHA) and peak vertical acceleration (PVA) and vertical acceleration of the cantilever element (i.e., the top story) in a 13-story structure with four underground stories were compared with and without the vertical earthquake component for three records. The results showed that PHA and PVA in the stories increased when the vertical earthquake effect was included. Moreover, it was found that the vertical earthquake effect increased PVA in the cantilever element of the model.

KEYWORDS: Vertical Earthquake Component, Soil-structure Interaction, Time-history Analysis, ABAQUS, Peak Horizontal Acceleration

1 INTRODUCTION

When an earthquake occurs, seismic waves are propagated by the earthquake source and move through the ground surface in different manners. These waves induce vibration and surface waves for a certain period once they reach the ground surface and these waves are damped slowly on the surface. The intensity and duration of surface vibrations in a given site are dependent on not only the earthquake magnitude and depth of focus but also site properties and soil layer (Kramer 1996). Structure-influencing vibrations are a function of several parameters, such as the earthquake source, travel path effects, site effects, and soil-structure interaction (SSI) effects, as shown in Figure 1. (Stewart et al. 1998). As a result, it is necessary to consider SSI to estimate the realistic structural response (Venanzi et al. 2014). SSI dynamic analysis studies mostly employed two-dimensional finite element models. In this case, the effects of three-dimensional seismic excitation characteristics would not be reflected (Yue et al. 2009). Moreover, some previous studies in the seismic analysis of SSI using three-dimensional models reported significantly more complex and difficult results than two-dimensional models (Vicencio and Alexander 2020).

Researchers found that the vertical-to-horizontal acceleration ratio was lower for longer periods compared to short periods (Bozorgnia and Niazi 1993). Researchers used to believe the horizontal earthquake component to be adequate in the seismic analysis of structures for a long time. However, the reports of destructive earthquakes and near-fault earthquake research revealed that the vertical earthquake component should be included along with the horizontal earthquake component in many cases (Papazoglou and Elnashai 1996). Moreover, previous studies on the 1994 Northridge earthquake investigated the vertical motion spectrum records and found that the vertical

motion response spectrum ratio was dependent on the earthquake intensity, earthquake time, and the distance of the site from the earthquake source. They concluded that the vertical-to-horizontal acceleration ratio (which has recently been used in codes) was underestimated for structures with short periods and conservative for structures with long periods (Bozorgnia and Campbell 2004).

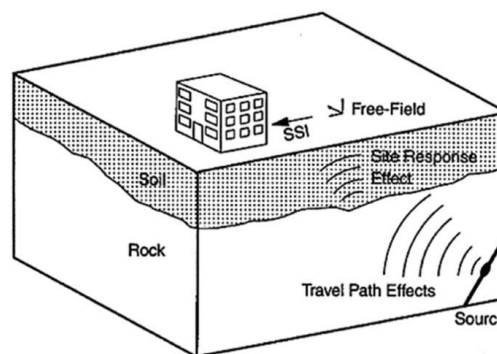


Figure 1. Structure-influencing vibrations

Most studies on the seismic analysis of SSI applied the horizontal earthquake component, and the effect of the vertical earthquake component on the structural response was considered as a fraction of the dead and live loads. A few studies investigated the vertical earthquake effect in interaction models on structural accelerations. The present study investigates the vertical earthquake effect on the peak horizontal acceleration (PHA) and peak vertical acceleration (PVA) and vertical acceleration of the cantilever elements in a real-life urban structure with a complex

geometry in two models: (1) with the vertical earthquake component (model 1) and (2) without the vertical earthquake component (model 2). For this purpose, the dynamic time-history analyses of the three-dimensional models were carried out in ABAQUS.

2 MATERIALS AND METHODS

2.1 Geotechnical parameter of the site soil

To determine the soil parameters using the geotechnical reports of in-site borehole logs, field and laboratory examinations were employed to complement the calculations. Since geotechnical parameters are associated with the corrected SPT-N value, experimental relations were used to obtain the friction angle and soil density, as shown in Table 1. (Sabatini et al. 2002). After analyzing the field and laboratory results based on the geotechnical reports of the case study structure, the soil specifications were obtained, as shown in Table 2.

Table 1. Corrected SPT-N Value in site

Soil Classification (USCS)	N _(SPT)
SC	40
CL	42

Table 2. Properties of soil layers in the model

Soil Type	Depth (m)	Density (kg/m ³)	Poisson's Ratio	Friction angle	Cohesion (kPa)
SC	0-46	1986	0.25	30.93	7.3
CL	46-60	2040	0.3	29	19.6

Since the elasticity modulus of the soil is a function of stress (Brinkgreve et al. 2010), the modulus of elasticity was calculated based on Eq. 1 (Geo studio Ltd 2008).

$$E = E_i \left(\frac{\sigma}{P_a} \right)^m \quad (1)$$

where

E = elastic modulus

E_i = the modulus of elasticity t acquired by the SPT test

P_a = atmosphere pressure, equal to 100kpa

σ = mean stress

m = based on Table 3.

Table 3. m ratio values (Duncan 1980)

Soil Classification	m ratio values
SC	0.5
CL	0.2

As the top-down construction method was employed, the unloading modulus of elasticity was used in static analysis. Furthermore, based on the in-site geophysical experiments, the dynamic shear modulus of the soil was calculated to perform the seismic analysis of the SSI model based on Eq. 2 (Kramer 1996).

$$G_{max} = \rho v_s^2 \quad (2)$$

The G/G_{max} ratio was assumed to be 0.4 to reduce the stiffness of the soil (Yeganeh et al. 2015). Moreover, the Mohr-Coulomb plasticity constitutive model was employed to simulate soil behavior. The damping of the soil was determined to be 3.3%

based on the ASCE 41-17 (ASCE/SEI 41-17 2017) and ASCE 7-16 (ASCE/SEI 7-16 2017) Codes.

2.2 Modeling of the structure

The structure had thirteen stories, including four underground stories, in Mashhad, Iran. The structural system of the model consisted of a steel joint frame and concrete shear walls to resist seismic loads. Figure 2. shows the locations of the columns and shear walls. European standard IPE sections were applied to the beams, while box sections were used for the columns in the steel joint frame, as shown in Figure 3. The Rayleigh damping model was used to include structural damping, and the damping ratio was assumed to be 5% (Bazaz et al. 2021; FEMA 1997).

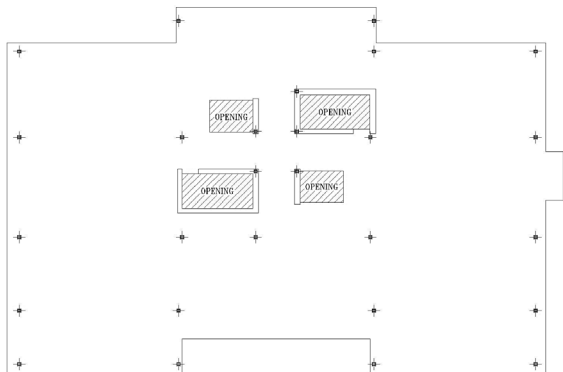


Figure 2. Placement plan of shear walls and columns

Table 4. General characteristics of steel and concrete

Material	Modulus of elasticity (Pa)	Poisson's Ratio	Density (kg/m ³)
Steel	2.10×10^{11}	0.3	7826
Concrete	2.56×10^{10}	0.2	2500

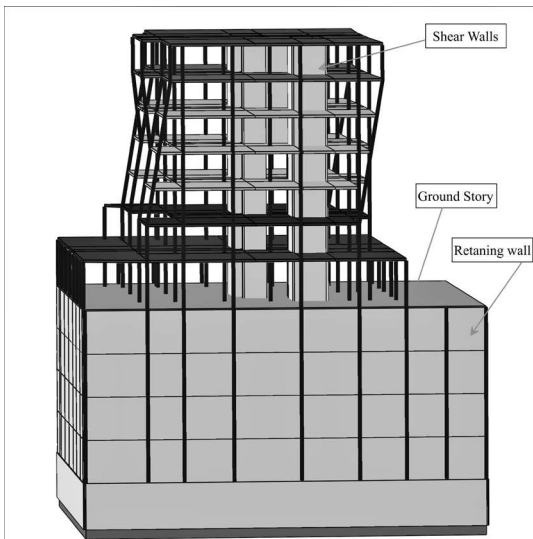


Figure 3. ABAQUS model of the structures

2.3 Modeling of SSI

To model the SSI, the direct three-dimension modeling method was employed in ABAQUS. Soil modeling requires the proper selection of dimensions to reflect the structure and site vibration effects in the equations and minimize the effects of the borders

on the output. Different references suggest that the model's dimensions are selected to be 3-5 times larger than the structure size, and the soil depth is considered to be at least 30 m. Therefore, a model size of 250 m and a model height of 60 m were applied, as shown in Figure 4. (Briaud and Lim 1997; Far et al. 2010).

During an earthquake, there is a possibility of slips between the joint surfaces of the soil and the foundation and retaining wall. In order to model the contact surfaces of soil, foundation, and retaining wall in Abaqus software, the contact interaction property of the type of surface-to-surface contact that has contact behavior (friction) has been used. (ABAQUS 2014; Khazaei and Amiri 2017).

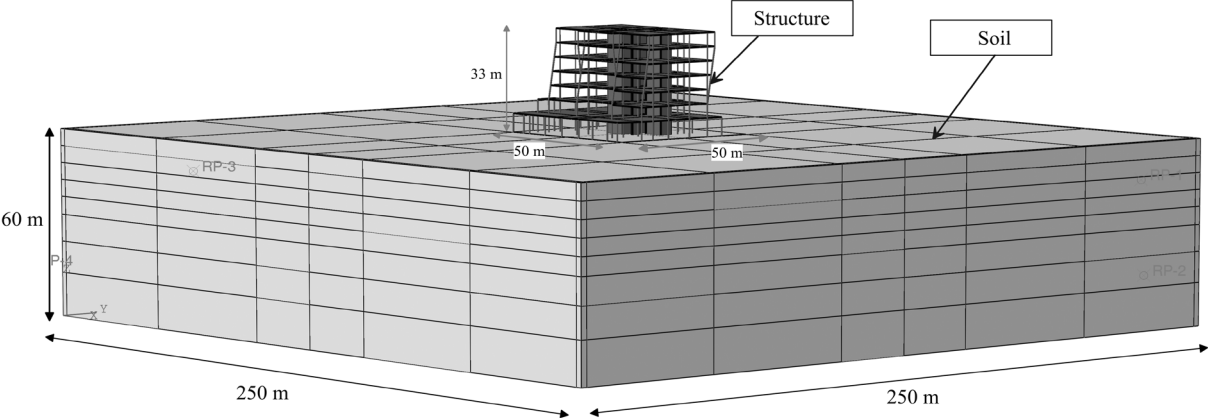


Figure 4. Structure model considering SSI in Abaqus software

2.4 Determination of records to the base of the numerical model

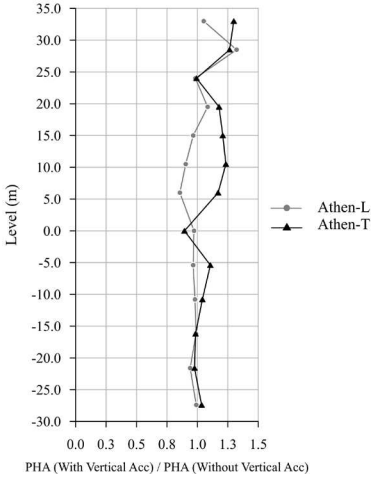
According to the seismic microzonation studies of Mashhad, three records (see Table 5) with a return period of 500 years were provided for the design basic level that its occurrence probability or larger earthquakes would be smaller than 10% in the 50 years of the building's lifetime (Moghaddas 2009).

Table 5. Selected acceleration records

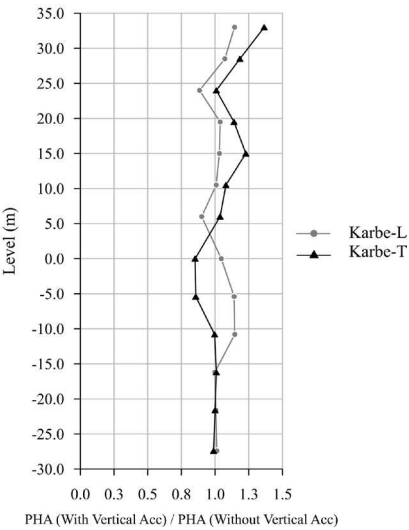
Earthquake	Magnitude (M)	PHA Longitudinal (g)	PHA Transverse (g)	PVA Vertical (g)
Kojur-Firoozabad, Iran (poul)	6.4	0.27	0.28	0.17
Karehbass, Iran (Karbe)	6.3	0.275	0.278	0.121
Athens, Greece	5.9	0.224	0.253	0.134

3 RESULTS AND DISCUSSION

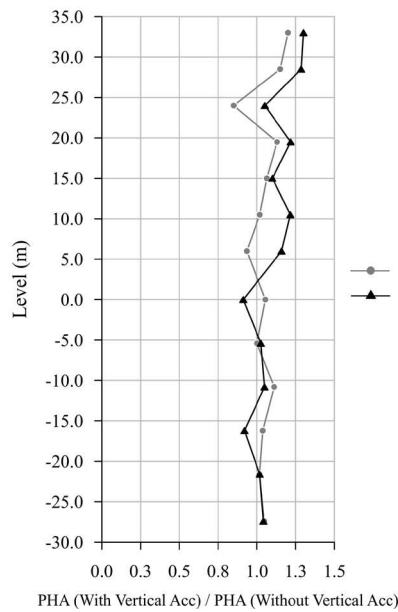
The vertical earthquake component effect has generally been considered to be less concerned than the horizontal earthquake effect since the vertical earthquake is mistakenly believed to be lower than the horizontal earthquake and buildings are assumed to have higher vertical stiffness than horizontal stiffness. However, research has shown that the vertical earthquake component effect is significant in structures constructed in high-risk zones. Figure 5. compares the vertical earthquake effect on PHA when the vertical earthquake component is considered (Model 1) to the case where the vertical earthquake component is not applied (Model 2) for the three records. Furthermore, it was found in this project that the vertical accelerations of the stories induced by the horizontal earthquake were calculated when the vertical earthquake component was not included in the model (Mohammadyar and Akhtarpour 2021). Figure 6. shows the PVA ratio of Model (1) to Model (2) for the three records.



(a) Athens earthquake



(b) Karbe earthquake



(c) 2004 Poul earthquake

Figure 5. Ratio of PHA of Model 1 to Model 2 under (a) Athens earthquake, (b) Karbe earthquake, and (c) 2004 Poul earthquake

As can be seen from Figure 5, the consideration of the vertical earthquake effect in the dynamic analyses significantly increased PHA (by up to 30% at positive levels). Moreover, the vertical earthquake effect on PHA was not significant at levels below Ground since the structure had high stiffness. According to Figure 6., the exclusion of the vertical earthquake component in the dynamic analyses had a significant effect on PVA; the inclusion of the vertical earthquake component increased to about 2.5 times the amount of PVA. Although Code 2800 suggests that it is not necessary to consider the vertical earthquake component, the analysis of the structures without the vertical earthquake effect may be inadequate for structures in zones of relatively high risk (Standard Code 2800).

Table 6. shows the vertical acceleration ratio of the cantilever elements of the top story. As can be seen, the consideration of the vertical earthquake component increases the vertical acceleration.

Table 6. Comparison of cantilever vertical acceleration under the vertical earthquake effect

Earthquake	Vertical Acc (Model 1) (g)	Vertical Acc (Model 2) (g)	Increase %
Kojur-Firoozabad, Iran (poul)	4.8 m/s ²	3.32 m/s ²	44.5 %
Karehbas, Iran (Karbe)	3.78 m/s ²	2.41 m/s ²	56.8 %
Athens, Greece	4.95 m/s ²	3.03 m/s ²	63.3 %

4 CONCLUSIONS

A small number of studies have been done, in the field of three-dimensional time-history analyses of SSI in urban structures with concrete shear walls and deep excavation, so that three earthquake components are applied to it simultaneously. Therefore, this paper evaluated the vertical earthquake effect on the PHA and PVA and the vertical acceleration of the cantilever elements of a structure with complex geometry in ABAQUS. The

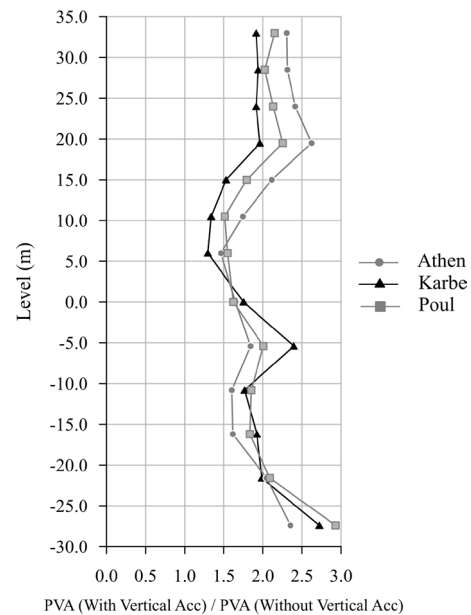


Figure 6. Ratio of PVA of Model 1 to Model 2 under (a) Athens earthquake, (b) Karbe earthquake, and (c) 2004 Poul earthquake

results showed that the consideration of the vertical earthquake component (i.e., applying the three earthquake components to the model simultaneously) increased PHA, PVA, and the vertical acceleration of the cantilever elements (at the top story). Hence, in this case, it can be said that the assumptions of the seismic building codes are somewhat inadequate. It is recommended that the three earthquake components are considered simultaneously in the time-history analysis of SSI.

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