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NUMERICAL ANALYSES OF INTERACTION BETWEEN ADJACENT STRUCTURES ON LIQUEFIED SOIL

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Abstract

In all major earthquakes, structures in the proximity of rivers and coastal plains, are often affected by substantial excess pore-water pressure which may lead to soil liquefaction. The excess pore-water pressure will lead to soil softening and change in structural response. However, in the few cases where soil-structure interaction is considered during the analysis process almost always a linear model of the soil and structure is employed. While this model is simple and therefore convenient, the analyses are a poor representation of real soil behaviour. Additionally, in major urban areas most structures are closely adjacent. Therefore, the situation is more complex than free-field condition or just a stand-alone structure. The analysis of a single structure cannot capture the major characteristics of the seismic response of closely adjacent structures. In this work an elasto-plastic multi-mechanism model was used to represent soil behaviour. A coupled solid-liquid phase formulation was utilised. A single degree-of-freedom structure was employed using frame elements. At this stage, a linear structure and nonlinear soil are considered. The coupled soil-structure model is used to simulate the behaviour of single and adjacent structures on sand under conditions of substantial excess pore-water pressure. The analyses show lower settlement under free-field conditions than that evident in the presence of a structure. Also, lower settlement (but higher than the free-field case) was observed for closely adjacent structures compared with the case of an isolated structure. A higher increment in pore-water pressure (but a lower pore-water pressure build-up ratio) beneath structures was also observed. Differences in the response spectrum were evident between an isolated structure and a structure closely adjacent to a rigid block.

Keywords: Structure-soil-structure interaction; liquefaction; adjacent structures; numerical modelling

1 Introduction

Building damage associated with soil liquefaction has been widely documented, e.g. Cubrinovski, et al. [1] reported a total of about 15,000 residential properties damaged across the Christchurch CBD during the 2010 Canterbury (New Zealand) earthquake. The authors related the damage mainly to soil failures (mostly related to liquefaction) instead of inertial loading due to ground shaking. The above highlights the importance of the correct understanding of soil behaviour when liquefaction occurs. Two particular cases were presented by Cubrinovski, et al. [1]. First, a complex of three nearly identical buildings was studied. The buildings were three-storey structures with a garage at the ground floor supported by shallow foundations. Despite the proximity, buildings suffered different damage levels. Second, the performance of The Christchurch Town Hall for Performing Arts (a complex of adjacent structures) was documented. The structures are also supported on shallow foundations. An air bridge that connects the complex with the Christchurch Convention Centre separated from the building. The conclusion reached was that the distortion in the base of one of the buildings displaced the outer walls creating this separation. However, no common trends were found for the settlement and tilting of the structures. Based on these observations, the influence of buildings appears to be a key factor in the magnitude of permanent settlement and other design parameters.

One of the first observations of field interaction between buildings and the surrounding soil was made by Jennings [2]. The author forced the Milikan library building into free vibration and measured the magnitude of stationary waves corresponding with the natural frequency of the building around the base of the building. Also, the influence of a building on the increment of pore water pressure was presented by Rollins and Seed [3]. In addition, Tokimatsu et al. [4] studied the effect of liquefaction on several buildings during the 1990 Luzon (Philippines) earthquake and found that the settlement of a building tends to increase with increasing number of stories. Based on evidence form the 1999 Kocaeli (Turkish) earthquake Sancio et al. [5] obtained similar conclusions. However, Sancio et al. [5] remarked that the settlement of a building's is also affected by a large number of other variables that are difficult to assess independently.

Soil-foundation-structure interaction with an isolated structure (SFSI) has been widely studied during the last few decades. An overview of different analytical design methods considering SFSI was presented by Stewart et al. [6]. The same year the authors presented a summary of some recommendations based on empirical findings [7]. Most of the actual design methods represent the effects of SFSI as a fundamental period lengthening. This methodology usually gives a beneficial effect of SFSI. However this assumption was questioned by Mylonakis and Gazetas [8], reaffirming the complexity of the phenomenon. Additionally, when multiple structures are considered, the phenomenon becomes a dynamic cross interaction between the structures and the surrounding soil. The concept of Structure-Soil-Structure Interaction (SSSI) was introduced by Luco and Contesse [9] to identify this phenomenon. A complete literature review about the state of the art of SSSI was presented by Lou et al. [10].

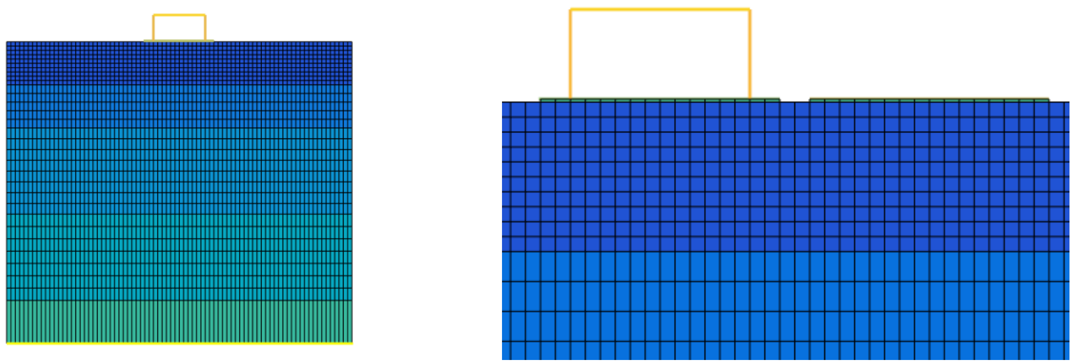
Recent research by Lopez-Caballero and Modaressi [11] represents significant progress in the numerical analysis field. The authors analysed the beneficial or detrimental effects of SFSI. The researchers concluded that the pore-water pressure profile at the end of the earthquake is affected by the presence of a structure. According to the authors the influence of a structure appears to be depend on the frequency of both the structure and the input excitation. However, no extended numerical analysis on adjacent structures on liquefiable soil has been conducted.

The evidence presented in the literature supports the idea that liquefaction needs to be considered as an integral part of the design process, instead of an independent hazard represented by an uncoupled calculation of settlement or some other parameter. The main objective of this study was to evaluate the interaction between multiple structures and the foundation soil subjected to liquefaction. A numerical approach considering a 2D fully coupled non-linear numerical model based on a plane-strain approach was used. A single degree-of-freedom (SDOF) structure, a rigid block and the free-field were considered.

2 Methodology

Finite element (FE) models were generated for each case using the software GEFDyn [12, 13]. A 30 m soil profile was considered for each analysis. Beneath the bottom soil layer a 5 m thick layer of elastic bedrock was assumed. Paraxial elements [14] were used at the base of each model which allows incorporation of the incident waves and, at the same time, satisfies the radiation condition. The width of each model was selected to reduce the influence of the lateral boundary conditions.

The SDOF structure was constructed using 2D frame elements. A soil column with no structure was studied to simulate the free-field condition. A stand-alone structure on soil and a structure adjacent to a rigid block were analysed. For all the studies the water table was considered to be at surface level. Figure 1 shows the stand-alone configuration (Fig. 1-a) and a zoom-in of the structure adjacent to the rigid block in Fig. 1-b.



a. Stand-alone structure   b. Structure adjacent to rigid block

Fig. 1 – Different configurations studied

Local site effects were included directly in the numerical model, thus a ground motion recorded on bedrock was used as the input motion. For all the analyses the record of acceleration of the Gilroy station in the 1989 Loma Prieta, M_w = 6.9, earthquake was utilised. A total duration of 10 seconds of the main shock was considered (Fig. 2).

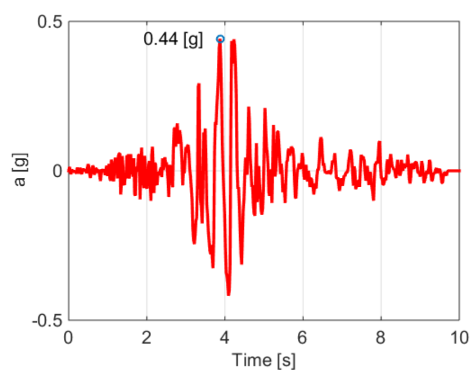


Fig. 2 – Ground motion (Gilroy station, Loma Prieta, 1989)

2.1 Structural models

A single degree-of-freedom (SDOF) structure was studied. The model comprised of two columns and a top beam. All the structural elements were considered elastic. A total mass of 50 tonne was distributed at the top beam. 3.0 m height and 6.0 m width, were considered for the frame. The selected mass produced a bearing pressure close to 70 kPa. Each model contained an 8 m long foundation beam. Table 1 summarises the properties of the structural model.

Table 1 – Properties of structural model

Geometry		
Height (H)	[m]	3.0
Span (L)	[m]	6.0
Foundation (B)	[m]	8.0
Columns		
Height (h)	[m]	0.25
Width (b)	[m]	0.25
Beams		
Height (h)(*)	[m]	0.375
Width (b)	[m]	0.25
Mass density (ρ)	[kg/m3]	8.89×10^4
Fundamental frequency	[Hz]	1.77
Fundamental period	[s]	0.56

(*) Corresponds to the dimension out of plane, i.e. normal to the direction of the shaking.

The response of a rigid block was also analysed as a possible simplification of the structure. The rigid block has the same mass as the SDOF structure but distributed at the foundation level with no additional structural elements.

2.2 Cases studied

The following is a summary of the different models and configurations utilised.

- *Free-field condition (soil column)*
  A soil column with no structure on the surface was modelled to represent the free-field (FF) condition.

- *Stand-alone structure*
  The structure was studied alone at the top of the soil profile.

- *Structure adjacent to a rigid block*
  The structure was studied adjacent to a rigid block with the same mass. A distance of 1 m between the bases of the structures was considered.

2.3 Soil constitutive model

The elastoplastic multi-mechanism model developed at Ecole Centrale Paris (ECP), also known as the Hujeux model, was used to represent the soil behaviour. The parameters utilised in the solution were adapted from Lopez-Caballero and Modaressi [11, 15]. Four sets of parameters were selected for different depths. Table 2 shows some of the selected parameters for each layer. The ECP model was written in terms of effective stress and based on a Coulomb-type failure criterion. It considers three plane-strain deviatoric plastic deformation mechanisms and in addition an isotropic deformation. Refer to Aubry et al. [16] and Hujeux [17] for further information about the ECP constitutive model.

Table 2 – Properties of each soil layer

Parameter	0 – 5 m	5 – 10 m	10 – 20 m	20 – 30 m
Elasticity				
ρ_s [MPa]	2700	2700	2700	2700
n_0	0.35	0.35	0.35	0.35
Elasticity				
K_{ref} [MPa]	628	628	628	444
G_{ref} [MPa]	290	290	290	222
n_e	0.5	0.5	0.5	0.4
Critical state and plasticity				
ϕ'_{pp} [º]	30	30	30	31
β [º]	33	33	33	43
d	2.0	2.0	2.0	3.5
b	0.2	0.2	0.2	0.2
p'_{co} [MPa]	0.04	0.06	0.15	1.8

Where, ρ_s is the density of the soil particles and n_0 is the initial porosity. Hence, the material density (for a saturated soil) can be obtained by $\rho = \rho_s(1 - n_0) + \rho_w n_0$. Where ρ_w is the pore-fluid density.

3 Stand-alone structure (SFSI)

One of the important characteristics of liquefaction is the inducement of settlement. Fig. 3 shows the settlement of the free field and that under the centre of the rigid block and a structure with a natural frequency of 1.77 Hz. Both, the rigid block and the structure have a bearing pressure of 70 kPa. The FF condition (blue line), rigid block (dashed red line) and the structure (black dotted line) are presented.

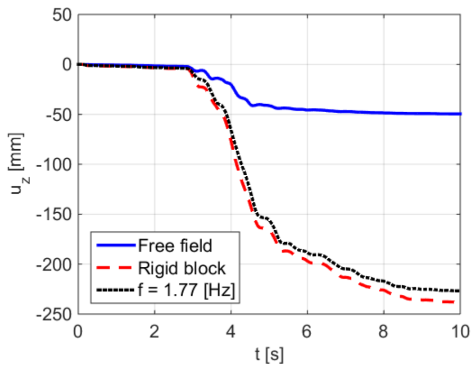


Fig. 3 – Settlement under the structure

Higher values of settlement can be seen beneath a structure compared to free-field. The settlement of the rigid block is very similar to that of the structure.

Another important feature is the possible influence of structures on the pore-water pressure build-up. Fig. 4 shows the pore-water pressure increment at the end of the ground motion. The results for the FF condition (blue line), under the centre of the rigid block (dashed red line) and under the centre of the structure (dotted black line) are presented. The initial effective vertical stresses for free-field condition is also presented (grey line).

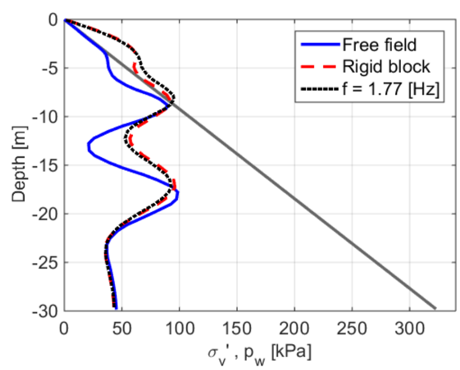


Fig. 4 – Excess pore-water pressure at the termination of the excitation

Fig. 4 shows a higher increment of pore-water pressure when a structure (or rigid block) is considered. This difference (i.e. the influence of the structure) largely disappears at approximately 20 m depth. This result is +consistent with the area of influence of a static load on the surface proposed in the literature (2 to 3 times the foundation width).

However, when a structure is considered the vertical effective stress also increases. Therefore, further analyses were conducted to assess the liquefaction hazard. Fig. 5 shows the time history of excess pore water pressure build-up at 2 m (Fig. 5-a) and 5 m depth (Fig. 5-b). Results for free-field (blue solid line), beneath the centre of the rigid block (dashed red line) and beneath the centre of the structure's foundation (dotted black line) are presented.

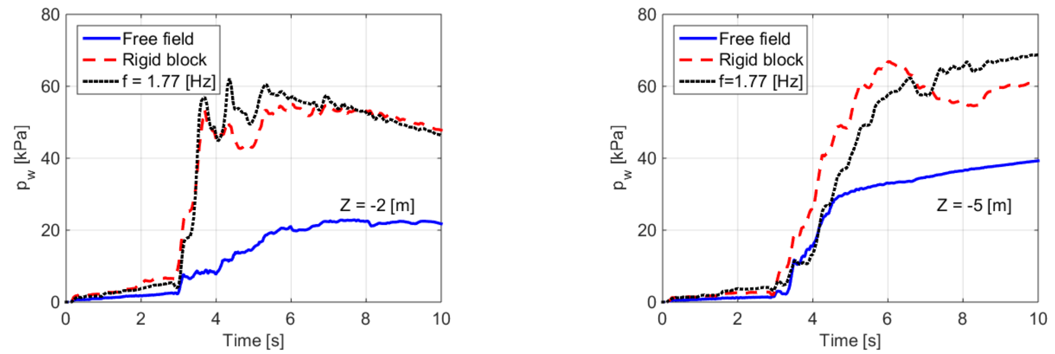


Fig. 5 – Excess pore water pressure build-up under the centre of the structure

To assess the liquefaction triggering the ratio between the pore pressure build-up to the initial vertical effective stress at the same depth is defined as follows (Eq. 1).

$$r_u(z,t) = \frac{\Delta p(z,t)}{\sigma\prime(z,t=0)} \quad (1)$$

Where, $\Delta p(z,t)$ is the excess pore pressure for a depth (z) in the model; and, $\sigma'(z,t=0)$ corresponds to the initial vertical effective stress (t=0) for the same depth. A value of $r_u(z,t) = 1$ indicates liquefaction triggering. Fig. 6 shows the development of r_u at 2 m (Fig. 6-a) and 5 m depth (Fig. 6-b).

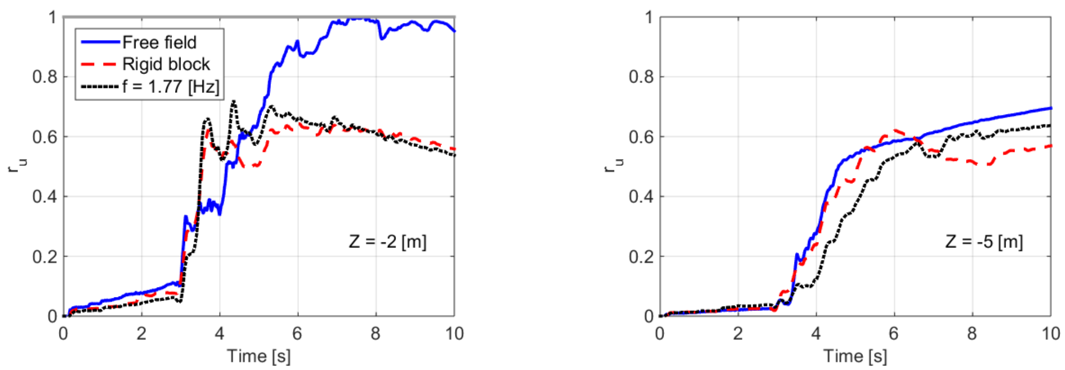


Fig. 6 – r_u beneath the centre of the structure at different depths

Higher values of r_u can be seen on FF condition compared with the soil beneath the structure at a depth of 2 m below the foundation. For a depth of 5 m this influence is much reduced.

Finally, Fig. 7 shows the response spectrum obtained from the acceleration recorded on surface for the FF (blue line); the acceleration under the rigid block (dashed red line); and the acceleration beneath the structure (black dotted line).

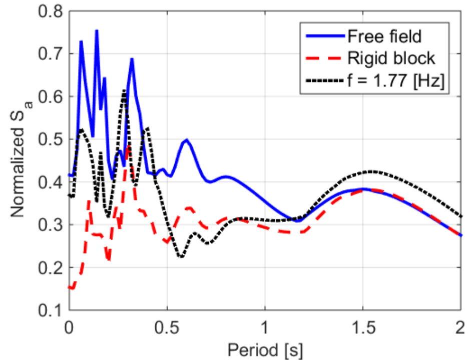


Fig. 7 – Response spectra

Lower values of response can be observed when a rigid block is considered. For short periodss, the free-field condition presents the highest response. For periods longer than 1.5 s the rigid block shows a similar response to the free-field case. However, the structure experienced higher response at periods longer than 1.5 s.

4 Adjacent structures (SSSI)

The structure was placed closely adjacent to the rigid block. A distance of 1 m between foundations was modelled.

Fig. 8 shows the settlement for free-field (blue line), beneath the stand-alone structure (dashed red line) and beneath the structure when closely adjacent to the rigid block (dotted black line). A lower settlement for the structure when adjacent to the rigid block is evident compared to the stand-alone case.

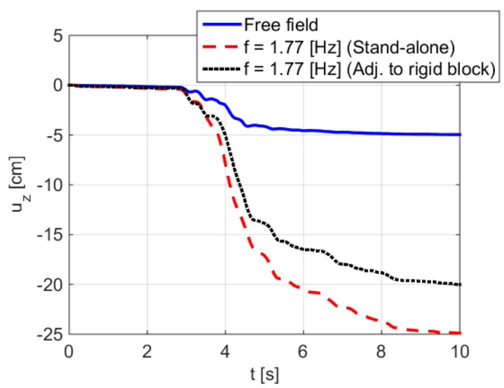


Fig. 8 – Settlement of FF, and structure

Fig. 9 shows the horizontal separation between the base of the structure and the rigid mass. The separation of the structures increases with seismic loading. This increasing separation has been observations in the studies of Hayden et al. [18] based on centrifuge testing.

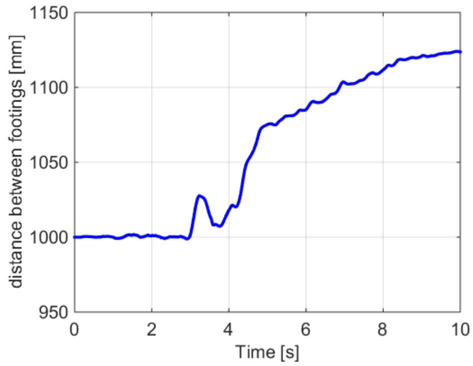


Fig. 9 – Horizontal separation of the structure base and the rigid block

5 Conclusions

A 2D fully coupled nonlinear numerical model, based on a plane-strain approach was used to study the liquefaction potential and seismic response of a body of sand. The study included the effects of the seismic response of a structure mounted on the surface. By way of comparison the response of the same structure when closely adjacent to a rigid block was also determined.

The study shows that the free-field condition underestimates the final settlement compared with the settlement beneath a stand-alone structure and a structure closely adjacent to a rigid surface mounted block. However, the settlement when the structure and the rigid block are closely adjacent is lower than the case of a stand-alone configuration. However, further research is necessary to assess the possible influence of the period of the structure on the settlement.

The excess pore-water pressure was greater when a structure was mounted on the surface, however, the pore-water pressure ratio was lower compared with free field case. Thus, liquefaction is less likely to happen beneath a structure compared with free-field condition. This may be due to the increase in the initial mean effective stress beneath the structure.

The influence of a structure on the surface acceleration spectra was found to be beneficial for periods lower than 1.5 s and detrimental for higher values.

Finally, the horizontal separation of closely adjacent structures was found to increase with seismic motion. This supports previous conclusions from in-situ and laboratory observations. This is important when adjacent buildings are connected above ground.

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7 Copyrights

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