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NUMERICAL ANALYSES OF THE INFLUENCE OF STRUCTURAL SLENDERNESS ON THE SEISMIC RESPONSE OF SINGLE AND CLUSTERED STRUTCURES

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Abstract. *The seismic design of structures generally considers a fixed base assumption, thus neglecting interaction with the supporting soil. The main structural property considered is usually the fundamental period. However, when the influence of soil-foundation-structure interaction (SFSI) is taken into account, other parameters such as structural slenderness, may play an important role in the response. Current design codes, (e.g. FEMA-440 and FEMA-450), assume that SFSI always has beneficial effects in the form of a reduction in the fundamental period spectral acceleration or base shear. This assumption has been studied and discussed by several authors. Additionally, in major urban areas structures are generally closely adjacent, and this situation is more complex than that of a structure whose response may be considered independent of all others. This study sets-out to improve the understanding of the behaviour of a clustered structure-soil-structure system. A 2D numerical model is used to simulate the behaviour of single and multiple structures on sand considering a range of slenderness ratios. Linear single degree-of-freedom (SDOF) structures and nonlinear soil are considered. The role of key parameters, e.g. effective building period and slenderness ratio of the structure-foundation system, will be elucidated.*

1 INTRODUCTION

A common practice in structural design is to neglect the influence of foundation soil by assuming a fixed base condition. Also, the natural period of the fixed base structure, T, is usually considered as the main design parameter. Furthermore, when soil-foundation-structure interaction (SFSI) is considered, the possible effects are generally assumed beneficial (e.g. reducing the spectral acceleration or the base shear). The effects of SFSI have been discussed by e.g. Mylonakis and Gazetas [1] who presented a study showing an increase of seismic demand due to SFSI for certain soil conditions. The influence of structural slenderness has also been highlighted when SFSI is considered in the structural response [2]. Karaca and Turkeli [3] identified the relevance of the slenderness on the response of reinforced concrete chimneys. The increasing lack of space, especially in dense urban areas, has made the interaction between adjacent structures an active research field in the last decades. The concept of structure-soil-structure interaction (SSSI) was introduced e.g by Luco and Contesse [4] and Chouw and Schmid [5,6]. A literature review about SSSI was presented e.g by Lou, et al. [7]. However, most of the advances in SSSI are achieved with analytical solutions for simplified problems based on an assumption of linearity for the different components of the system (i.e. soil and structure). It is well known that an assumption of linear behaviour for soil is valid only for a very small range of deformation, which is clearly not the case in the seismic response..

The National Earthquake Hazards Reduction program (NEHRP) [8] developed guidelines to consider the influence of SFSI on structural design. This NEHRP publication highlights the limited application of SFSI and describes the effects in common engineering practice, while also summarising several methods presented in other codes and guidelines.

One of the methodologies is presented by FEMA-440 [9]. This guideline divides SFSI into the effects of the fundamental period ($\tilde{T}$) and the damping of the soil-structure system. Based on the foundation damping (β_{f}) a modified damping ratio (β_0) is proposed for the computation of the response spectrum. The design response spectrum is calculated with the damping ratio β_0. Other approach is presented by FEMA-450 [10]. This methodology considers a reduction of the base shear. The final outcome as to beneficial or detrimental effect of SFSI depends of the combined effect of the two factors: (1) increase in damping due to SFSI system and (2) period elongation of the SFSI system (Figure 1). It is possible for a structure with a fundamental fixed-base period on the ascending branch of the response spectrum to have an increase system spectral acceleration. This can be seen in the left most part of Figure 1. The opposite can be seen, an overall decrease of the spectral acceleration, for a structure with a fixed-base period on the descending branch.

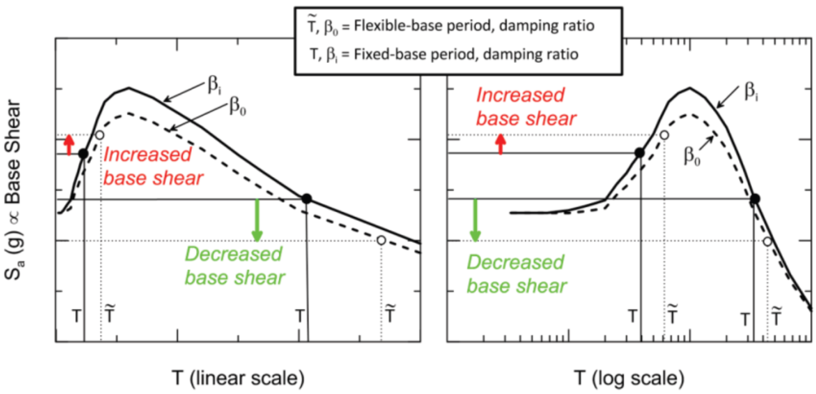


Figure 1: SFSI effects on spectral acceleration and base shear [5]

In previous studies the incorporation of the site-specific frequency content of the ground excitation, structural slenderness and the presence of the adjacent structures is hardly considered. This paper presents the results of the preliminary work to elucidate the consequence of structural slenderness λ and closely adjacent structures. λ is the ratio of the structural height (see Table 2) to the footing width of 6 m.

2 METHODOLOGY

2.1 FEM model

The finite element (FE) software GEFDyn [11,12] was used for all the studies performed. A 2D model and a plane-strain approach were utilised. A 30 m height soil profile was considered. Beneath the soil a 5 m thick layer of bedrock was assumed. Paraxial elements [13] were used at the lateral boundaries of each model. Those elements allow entry of the incident wave and, at the same time, satisfies radiation damping. The width of each model was selected to minimise the influence of the lateral boundaries. Figure 2 shows the FE model for 2 closely adjacent structures. When a single structure is considered it is located at the centre of the model to avoid asymmetry effects.

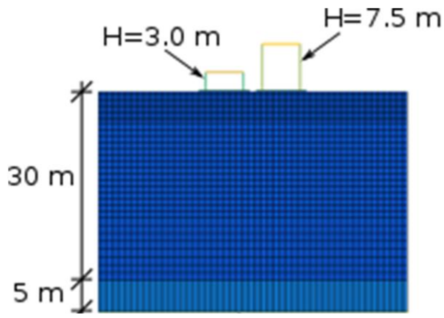


Figure 2: FE model considering adjacent structures

2.2 Soil parameters

The elasto-plastic multi-mechanism model developed at Ecole Centrale Paris (ECP) also known as Hujeux or ECP's model was used to represent the soil behaviour.

The following are the main hypotheses of the soil model:

- The model considers small deformations. The total deformation can be divided into elastic and plastic contributions.
- The formulation is based on the principle of effective stress.
- Isotropic behaviour is assumed for the elastic response.
- Shear behaviour is represented by three bi-dimensional mechanisms, each using a Mohr-Coulomb failure criterion.

Table 1shows some of the selected soil parameters. Refer to Aubry et al. [11] and Hujeux [12] for further information about the ECP's constitutive model.

Elasticity		**Critical state and plasticity**	
K_{ref} [MPa]	444	ϕ'_{pp} [°]	31
G_{ref} [MPa]	222	β [°]	43
n_e	0.40	d	3.5

		b	0.20
		p'_{co} [MPa]	-1.8
Flow rule and isotropic hardening		**Threshold domains**	
ψ [°]	31	r^{ela}	5.0×10^{-3}
a_{cyc}	1.0×10^{-4}	r^{ela}_{iso}	1.0×10^{-3}
a_m	4.0×10^{-3}	r^{hys}	3.0×10^{-2}
c	6.0×10^{-2}	r^{mob}	0.80
c_{cyc}	3.0×10^{-2}		
m	1.0		

Table 1: Soil parameters

The soil parameters utilised represent Toyoura sand with a relative density D_r = 37%.

A preliminary linear analysis was conducted for a soil column in the free field. A natural period of 0.46 s was obtained for the soil based on the ratio of the acceleration at the top to the acceleration at the base of the column in the frequency domain. A small amplitude input was used to guarantee linear behaviour of the soil. Considering the approximate expression presented in Equation (1) the shear wave velocity is $V_s = 260\, m/s$. Thus, the soil can be considered as medium-dense.

$$T_s \approx 4H/V_s \tag{1}$$

2.3 Structural models

The structures studied were single degree-of-freedom (SDOF) systems represented in 2D by elastic frame elements (2 m span) with two columns and a top beam. Three natural periods were selected. For each natural period a 3 m and 7.5 m high model was considered. All the seismic mass was concentrated in the top beam. To avoid differences in the confining stress in the foundation sand under the structure, the same mass (50 tonne) was considered for all models. The foundation was considered to be a massless beam of 6 m length. No uplift of the structural foundation was allowed at the soil-foundation interface. Table 2 shows some of the selected parameters for the SDOF structural models.

Structure	Height (m)	Columns (cm x cm)	Beam (cm x cm)	Natural period (s)
$T_{long} - L_1$	3.0	22×22	20×30	0.78
$T_{long} - L_2$	7.5	52×52	20×30	0.78
$T_{mid} - L_1$	3.0	28×28	30×45	0.44
$T_{mid} - L_2$	7.5	67×67	30×45	0.44
$T_{short} - L_1$	3.0	33×33	35×52.5	0.32
$T_{short} - L_2$	7.5	78×78	35×52.5	0.32

Table 2: Structural models parameters

2.4 Ground motion

Local site effects were directly included in the numerical model. The ground motion recorded on bedrock was used as the input motion. For all the analyses the strong motion recorded at the Gilroy station during the 1989 Loma Prieta Earthquake was utilised. A total duration of 10 s of the main shock was used (Figure 3).

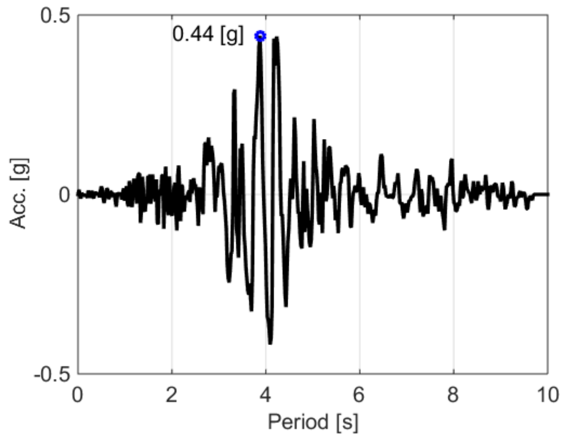


Figure 3: Ground motion (Loma Prieta, 1989)

3 RESULTS AND DISCUSSION

3.1 Stand-alone structures

The acceleration and displacement at the top of each model was calculated and the ratios of the maximum value to the maximum obtained for a free-field condition are presented for acceleration and displacement in Figure 4 and Figure 5, respectively as a function of the ratio of the natural period (T_{str}) of the SDOF to the natural period (T_{site}) of a 1D column of soil.

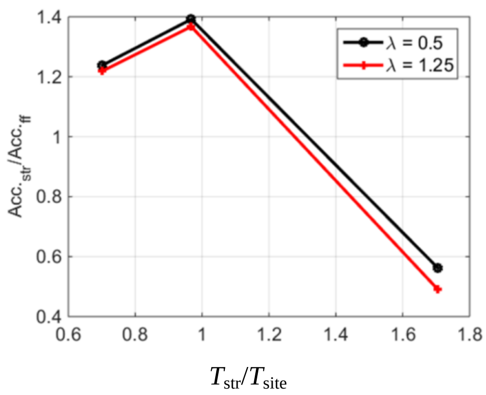


Figure 4: Ratio of maximum acceleration beneath the structure to the maximum on free-field

Regarding the maximum acceleration, the effect of slenderness is shown to be of minimal importance over the period range employed in this study. A higher slenderness ratio tends to give a marginally lower maximum acceleration for the same period.

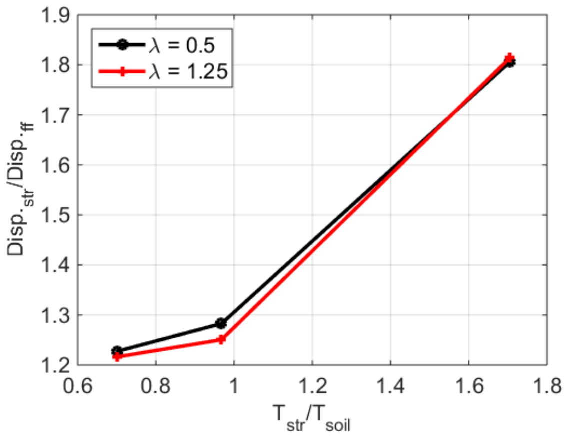
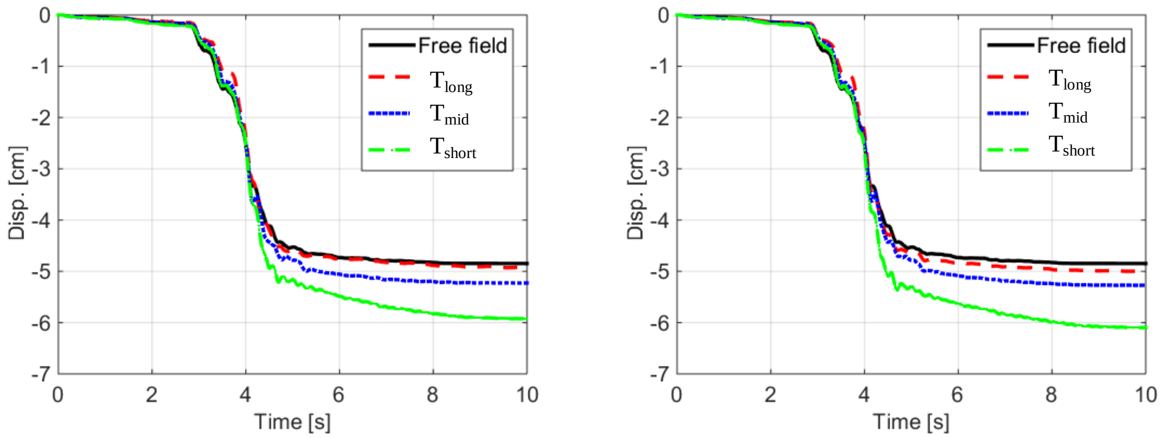


Figure 5: Ratio of maximum displacement beneath the structure to the maximum on free-field

The effects of slenderness on the maximum horizontal displacement are shown to be small for structures with a natural period close to the natural period of the site. Otherwise, slenderness has very little effect for the three structures considered.

The settlement beneath the structure was also studied. Figure 6 shows the results for the different single structures .



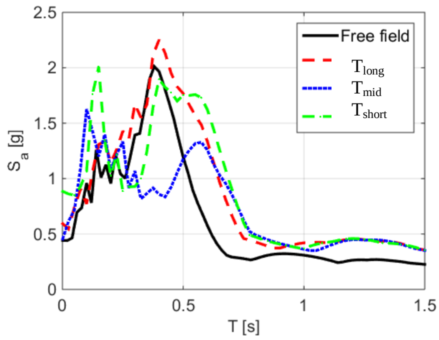
a. Lower slenderness models ($\lambda = 0.5$)

b. Higher slenderness models ($\lambda = 1.5$)

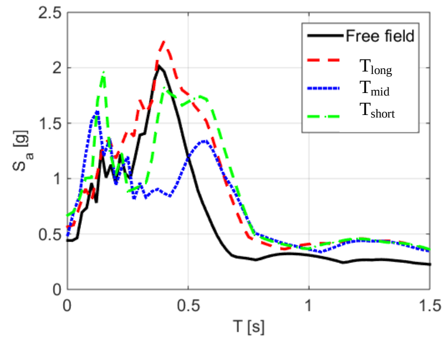
Figure 6: Settlement beneath the structure (alone on soil)

A similar trend is shown in Figure 6 for the settlement for both slenderness ratios. However, the lower period structures encountered higher settlement. The slenderness ratio has almost no effect. Thus, in the cases considered the natural period of the structure is more important than the slenderness ratio.

The influence of the structural slenderness and period on the response spectra of the acceleration beneath the structure are shown in Figure 7.



a. Lower slenderness models ($\lambda = 0.5$)



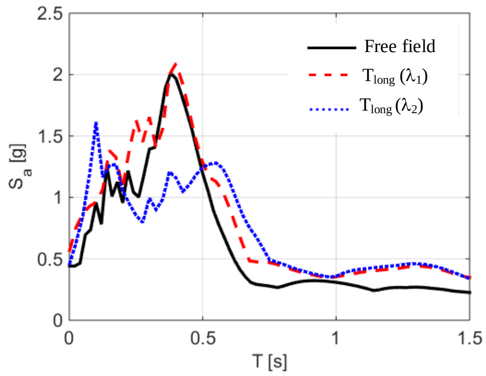
b. Higher slenderness models ($\lambda = 1.5$)

Figure 7: Response spectra for acceleration beneath the structure

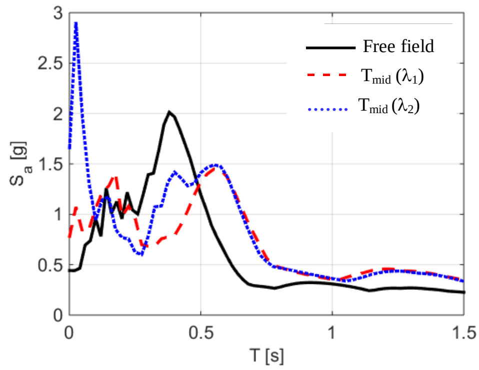
The obtained spectra were compared with the spectrum from free-field (black solid line). When stand-alone structures were tested the slenderness has very little influence.

3.2 Adjacent structures on soil

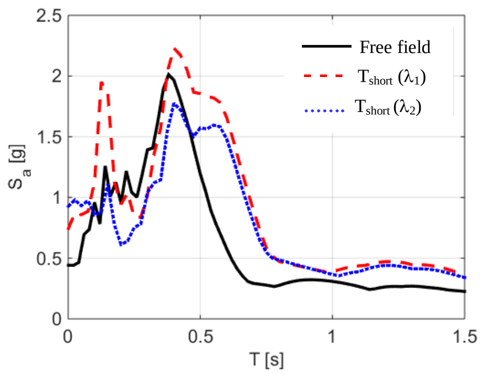
Each pair of structures with the same natural period but a different slenderness were tested with a one meter separation distance. In this case different response spectrum have been obtained beneath each structure (Figure 8). Again, the spectrum from free-field condition is also presented (black solid line).



a. High period structure (T_{long})



b. Intermediate period structure (T_{mid})



c. Low period structure (T_{short})

Figure 8: Effect of slenderness, structural period and an adjacent structure on the acceleration beneath the structure ($\lambda_1 = 0.5$ and $\lambda_2 = 1.5$)

Even though, no clear trends have been observed to define the influence of an adjacent structure there are significant differences between the spectra of the free field and the spectra beneath the structures. Differences can also be observed between the spectra of the soil beneath the two buildings. Further work is needed to clearify the observations.

4 CONCLUSIONS

FE models based on a 2D plain-strain approach were used to study the influence of slenderness on the structural response. The elasto-plastic multi-mechanism ECP constitutive model was used to represent the soil behaviour. Stand-alone structures and closely adjacent structures were considered. The influence of natural period, slenderness and an adjacent structure were studied.

In the cases considered the results for stand-alone structures show:

- The maximum displacement at the top of the structure increases with the natural period of the structure.
- Slenderness has marginal effect.
- Structures with the shortest period experienced the largest settlement. In contrast, for the highest slenderer ratio the permanent settlement was slightly bigger.

In the case of closely adjacent structures of equal period:

- Slenderness significantly effects the spectral acceleration for periods below 0.5 s.
- The natural period of the structures has a significant influence on SSSI.
- The free-field ground motions should not be used as a design structural excitation.

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