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INFLUENCE OF LIFT-OFF PHENOMENA ON SEISMIC RESPONSE OF MULTI-STORY BUILDINGS

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SUMMARY

During strong earthquake motions, the structures may be subjected to lateral forces that can bring them to the point in which partial separation of the base of the structure from the foundation soil, then tipping and finally overturning may occur. In addition, the structure itself changes properties during the dynamic excitations due to damage or reduction of the lateral stiffness. In this study, the dynamic behavior of a multi-story building is examined by comparing the structural response, with or without lift-off, varying the parameters related to structural shape and vertical stiffness of foundation soil. The building structure is modeled as a MDoF system, represented by a finite rotation model, which takes into account P-Δ effect. In the finite rotational model, the shear force is a function of the rotational angle at each level. Therefore, analyzing the variation of the rotational angles, one can obtain the magnitude of the shear force acting on the height of the structure. It is observed that in the case of the structure for which the lift-off is allowed, shear forces induced by the earthquake motion, are reduced in comparison to those when lift-off is prevented. Although it cannot be said that the lift-off phenomenon reduces the rotational angles in all analytical cases, we can conclude that, generally, it is benefic to consider its effects.

INTRODUCTION

For engineering purposes, it is often assumed that the foundation soil is very stiff and the soil–structure interaction is not taken into consideration. In reality, the structure interacts with the soil, leading to soil deformations that produce an alteration of the motions [Clough and Penzien, 1998], [Gao, Kwok and Samali, 1997]. Evidence that lift-off phenomena of the base of the structure from its foundation occurred during strong earthquakes has been observed in many situations. For example, during the Arvin-Tehachapi, California earthquake, July 1952, several slender petroleum-cracking towers stretched their anchor bolts and rocked back and forth on their foundations [Housner, 1956].

The first analytical investigations of the effects of lift-off phenomena on the earthquake response of a flexible structure idealized the structure as a SDoF oscillator [Meek, 1975]. Later, same author extended his study to multistory, braced-core buildings [Meek, 1978]. It was concluded that partial separation of the base of the structure from the foundation soil leads to reduction in the structural deformation. Other studies have shown that the foundation mat of slender structures has a greater tendency to uplift [Chopra and Yim, 1985]. In addition, it was concluded that for flexible structures, the uplift increases the rotational angle of the foundation mat, but the effects on the structural deflections and the resulting stresses in the structure are not clear [Psycharis, 1983].

Examination of real structures after large earthquakes showed that it is possible to obtain a reduction in the structural damage if the foundation is allowed to lift-off. After the Kobe earthquake in January 1995, it was

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reported that several buildings, located in areas where extensive damage occurred, had survived the earthquake with minor structural damage because lift-off occurred [Hayashi, 1996].

The objective of this paper is to investigate the effect of lift-off phenomena on the dynamic response of flexible structures allowed to lift-off.

SOIL-STRUCTURE SYSTEM

The soil-structure system used in this study is shown in Figure 1. This system consists of two components: a MDoF elastic structure, represented by a finite rotation model; a representation of the foundation soil, modeled by two spring and dashpots. These components are described as follows:

MODEL OF THE STRUCTURE

The mass of each story is considered concentrated at the level of the slab that has a rectangular shape of width L and behaves as a rigid body. The geometrical characteristics of each level i are defined by the story mass, m_i, the moment of inertia of the mass with respect to its centroidal axes, I_i, and the height of the story, r_i. The model has bending springs at both ends of each column, and the columns can rotate up to collapse. The deformation of level i is denoted by a finite rotational angle ϕ_i. Therefore, the model is called *finite rotation model*. In this model, each level has a single degree of freedom and it is possible to input earthquake motions on horizontal and vertical directions simultaneously and to consider P-Δ effect.

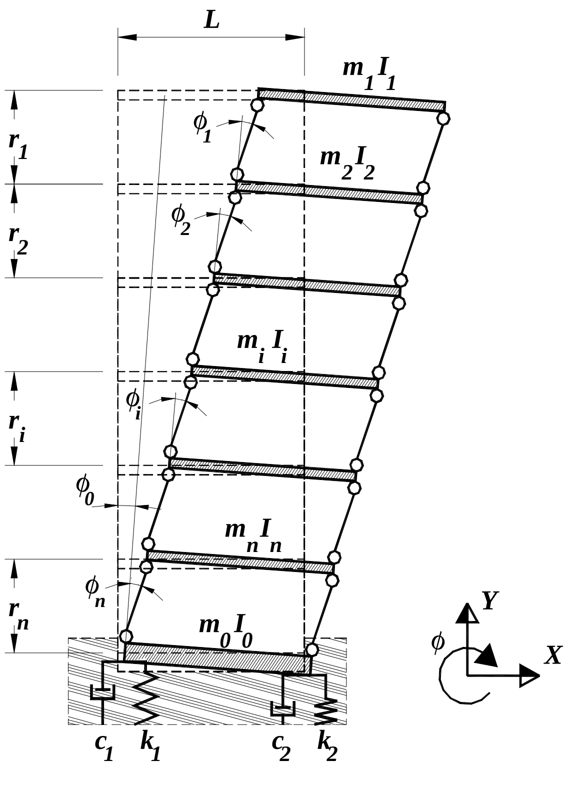

Figure 1: Soil-Structure System

MODEL OF THE FOUNDATION SOIL

The flexibility and damping of the supporting soil is represented by two spring-dashpots elements located at both edges of the foundation mat. The foundation mat is idealized as a rigid rectangular plate and it is assumed that horizontal slippage between the mat and supporting elements is restricted. The stiffness coefficients, k_1, k_2, and damping coefficients, c_1, c_2, of the foundation model are assumed to be constant, independent of displacement, amplitude or excitation frequency. The foundation mat rests on the two spring-dashpots elements only through gravity and is not bonded to these supporting elements. Thus, a supporting element can provide a compression reaction force to the foundation mat, but not a tension reaction force.

The deformed shape of the structure, at any time, can be defined by the angle of rotation at each level, ϕ_i, the foundation mat rotation, ϕ_0, and vertical displacement, y_0, at the gravity center of the foundation mat.

Equations of motion

The equations governing the motion of the structure can be derived considering the equilibrium of the moment at each story, the moment and vertical equilibrium of forces acting on the entire system. The relative displacements of the i-th level, x_i, y_i, in X and Y directions are expressed by next equations:

$$x_i = r_i \sin\phi_i' + r_{i+1}\sin\phi_{i+1}' + \ldots + r_n \sin\phi_n' = \sum_{j=i}^{n} r_j \sin\phi_j' \tag{1}$$

$$y_i = r_i \cos\phi_i' + r_{i+1}\cos\phi_{i+1}' + \ldots + r_n \cos\phi_n' + y_0 = \sum_{j=i}^{n} r_j \cos\phi_j' + y_0 \tag{2}$$

where

$$\phi_i' = \phi_i + \phi_0$$

Therefore inertia forces acting on the i-th level, H_i, V_i, in X and Y directions are:

$$H_i = -m_i\left\{\ddot{X}_g + \sum_{j=i}^{n}\left(\ddot{\phi}_j' r_j \cos\phi_j' - \left(\dot{\phi}_j'\right)^2 r_j \sin\phi_j'\right)\right\} \tag{3}$$

$$V_i = -m_i\left\{\left(g + \ddot{Y}_g\right) - \sum_{j=i}^{n}\left(\ddot{\phi}_j' r_j \sin\phi_j' + \left(\dot{\phi}_j'\right)^2 r_j \cos\phi_j'\right) + \ddot{y}_0\right\} \tag{4}$$

where $\ddot{X}_g$ and $\ddot{Y}_g$ are accelerations of ground motion, in X and Y directions, respectively.

One can make the moment equilibrium at i-th level using the following equation:

$$\left(\sum_{j=1}^{i} H_j\right) r_i \cos\phi_i' - \left(\sum_{j=1}^{i} V_j\right) r_i \sin\phi_i' - C_i\dot{\phi}' - M_i(\phi_i) = 0 \tag{5}$$

where C_i, $M_i(\phi_i)$, represents the damping coefficient and the rotational bending moment, respectively, at the i-th level.

The upward reaction forces on the foundation, R_1, R_2, of the two supporting elements acting at the edges of the foundation mat, and the restoring moment, M_f, with respect to the gravity center of the foundation mat have the following expressions:

$$R_1 = -k_1\left(y_0 + \frac{L}{2}\sin\phi_0\right) - c_1\left(\dot{y}_0 + \dot{\phi}_0 \frac{L}{2}\cos\phi_0\right)$$

$$R_2 = -k_2\left(y_0 - \frac{L}{2}\sin\phi_0\right) - c_2\left(\dot{y}_0 - \dot{\phi}_0 \frac{L}{2}\cos\phi_0\right) \tag{6}$$

$$M_f = (R_2 - R_1)\frac{L}{2}\cos\phi_0 \tag{7}$$

Equations (6) and (7) are valid during the time when the full length of the foundation is in contact with the foundation soil. When lift-off phenomena occurs at one edge of the foundation mat, the corresponding supporting element will no longer provide any reaction until the contact is reestablished.

From the moment equilibrium of the whole structure with respect to the gravity center of the foundation mat, one can obtain the following expression:

$$I_M\ddot{\phi}_0 - \sum_{j=1}^{n} H_i \sum_{k=j}^{n} r_k \cos\phi_k' + \sum_{j=1}^{n} V_i \sum_{k=j}^{n} r_k \sin\phi_k' + M_f = 0 \tag{8}$$

(9)

where

$$I_M = I_0 + \sum_{k=1}^{n}\left\{ I_k + m_k\left(\sum_{j=k}^{n} r_j \cos\phi_j\right)^2 \right\} \tag{10}$$

From the equilibrium of the forces acting on the vertical direction, the following expression can be obtained:

$$\sum_{i=1}^{n} V_i + R_1 + R_2 - m_0\left\{\ddot{y}_0 + \left(\ddot{Y}_g + g\right)\right\} = 0 \tag{11}$$

Equations (5), (9) and (11) define the motion of the structure and foundation system. The computer program was developed based on these equations.

ANALYTICAL PROCEDURE

The maximum shear force acting at the *i*-th level can be expressed as follows:

$$F_i = \frac{k_i \phi_{i\max}}{r_i} \tag{12}$$

where k_i represents the stiffness and $\phi_{i\max}$ the maximum angle of rotation reached during the earthquake, at *i*-th level.

In order to investigate the influence of lift-off phenomena on the response of the structure, we define the *response ratio*. The *response ratio* is the ratio of maximum rotational angle when lift-off phenomena can occur and the maximum rotational angle when the foundation mat is bonded to the supporting elements (without lift-off). A response ratio smaller than 1 implies that the lift-off phenomena reduces the angles of rotation. This is equivalent to a reduction in the shear forces. For additional information about the structural response, we define an other non-dimensional index: the *contact ratio*, expressed by the ratio between the minimum contact length of the foundation mat with the supporting soil and the total length of the foundation mat. The contact length depends on the vertical displacement and the rotational angle of the foundation mat.

The influence of lift-off phenomena is studied by comparing the structural response in both cases, with or without lift-off, varying the following parameters related to structural shape and vertical stiffness of the foundation soil.

Parameters of the structure involve the number of levels, *N*, and the *aspect ratio*, *H/L*. Three cases were considered regarding the number of levels: *N*= 5, 10 and 15. For each case, the aspect ratio varies from 1 to 10. For easiness of calculation, each level is considered to have the same mass, m_i, and height, r_i=4.00 m. The mass of each level is calculated using a uniformly distributed mass of 1.5 t/m^2, and 2.0 t/m^2 in the case of the foundation mat, respectively. The stiffness distribution of the structure is assumed so that the first mode shape is inverted triangular. The damping ratio of the first mode is assumed 5%, and the damping matrix is proportional to the stiffness matrix.

As to the parameters regarding the foundation, only the stiffness of the soil is considered significant for this study. The stiffness of the soil is taken into consideration by the frequency ratio, β.

$$\beta = \frac{\omega_\upsilon}{\omega} \tag{13}$$

where ω is the natural frequency of the system in the horizontal vibration, supported by a foundation with infinite stiffness, and ω_v is the vertical vibration frequency of the system with the supporting elements bonded to it.

$$\omega_\upsilon = \sqrt{\frac{k_1 + k_2}{\left(\sum_{i=1}^{n} m_i + m_0\right)}} \tag{14}$$

In this study, β takes three values: 4, 8, and 12, each corresponds to the case when the soil is soft, medium and hard, respectively. The damping coefficients of the two supporting elements are selected so that the damping ratio in vertical vibration of the system with its foundation mat bonded to the supporting elements to be 40%. For simplicity, the elastic and damping coefficients of the two supporting elements were considered equal, i.e., $k_1=k_2=k$ and $c_1=c_2=c$, respectively.

Table 1 presents the input ground motions used in this study. For the purpose of this paper, only the component with the larger peak acceleration is used, although all records have two horizontal components.

Table 1: Input Ground Motions

Earthquake record (year)	Component	Max. Acceleration (cm/s^2)	Max. Velocity (cm/s)
El Centro (1940)	NS	341.7	33.5
	UD	206.3	12.6
Kobe JMA (1995)	NS	818.0	90.2
	UD	332.2	39.9
Mexico SCT (1985)	EW	167.9	60.5
	UD	35.7	9.0

ANALYTICAL RESULTS

Influence of vertical stiffness of the soil on the vibration period

In order to study the effect of vertical stiffness of the soil on the vibration period of the structure, we investigate the variation of the ratio T_C/T for the case when β varies from 4 to 12. T represents the natural vibration period of the structure when it is rigidly supported and T_C when is flexibly supported. In Figure 2, the variation of this ratio in relation with β, is presented for three aspect ratios: H/L=5,10 and 15, respectively, when N=10. It can be seen that the vibration period elongates when the slenderness of the structure increases. In addition, from the asymptotic shape of these curves it can be assumed that after a certain value of β, the ratio is insignificantly affected by the increase in vertical stiffness of the soil.

Influence of Structure Shape

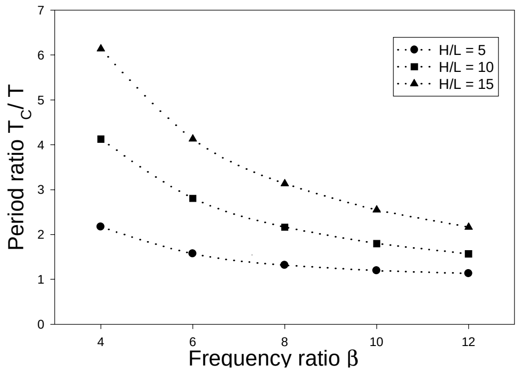

Figure 2: Variation of period ratio, *N*=10

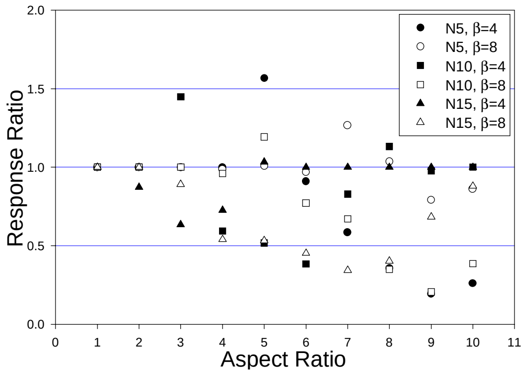

Figure 3: Response ratio for β=4 and β=8, Mexico

For all cases, the response ratio for each level was analyzed. It was found that, generally, the response ratio has a similar pattern for each level. Thus, hereafter, the average value of the response ratios at all levels is considered for discussion.

For Mexico earthquake, Figure 3 shows the response ratio variation for all structural shapes in the cases when β=4 and β=8. If β=4, for small height structures having large aspect ratio, the response ratio is smaller than 1. As the total height of the structure increases, the decrease of the response ratio shifts to the structures with smaller aspect ratio. When β=8, if the total height of the structure increases, the response ratio smaller than 1 extends also to the structures having small aspect ratios.

In the case of El Centro earthquake, Figure 4 presents the response ratio variation for all structural shapes, when β=4 and β=12. For structures with small height, the response ratio is smaller than 1 for all aspect ratios. For structures with medium height, when aspect ratio has a large value and β=12, the response ratio becomes grater than 1.

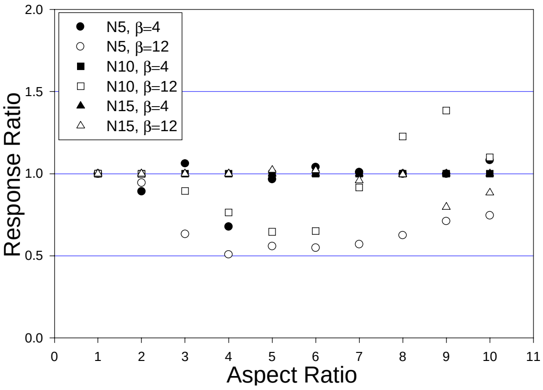

Figure 4: Response ratio for β=4 and β=12, El Centro

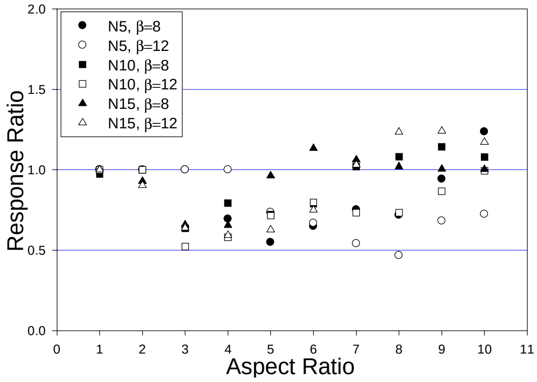

Figure 5: Response ratio for β=8 and β=12, Kobe

Figure 5 shows the response ratio variation for all structural shapes, in the cases when β=8 and β=12, and the structure is subjected to Kobe earthquake. When β=8 for all aspect ratios of small height structures, except *H/L*=10, the response ratio is equal to 1 or smaller. With the increase of the height, the response ratio decreases only for structures with aspect ratio from 1 to 6. For the case when β=12, for large aspect ratio and height, the response ratio is grater than 1.

For all the cases presented which are not covered by the above, the response ratio is smaller than 1 or is almost equal to it.

Influence of Foundation

Observing the response ratio plots for all cases analyzed, the influence of the soil stiffness can be presented as follows:

- In the case of Mexico earthquake input ground motion, for slender structures it was observed that the response ratio value increases for small height structures and decreases for medium and large height structures with the increase of soil stiffness.
- When El Centro earthquake input ground motion was used, it was found that with the increase of β value the number of cases when the response ratio is smaller than 1 increases.
- For Kobe earthquake input ground motion, an effect similar to El Centro earthquake was observed.

Figures 6a and 6b present the maximum angle of rotation at each level for all input ground motions, in the case of a structure having *N*=15 and *H/L*=6, for β=8 and β=12 respectively. It can be observed that for both cases, with lift-off or without, a hard soil (β=12) increases the maximum rotational angle at all levels for all input ground motions. In addition, the maximum rotational angles in the case of El Centro earthquake are small in comparison to Mexico and Kobe cases, and the lift-off reduces the response ratio in the case of Kobe earthquake.

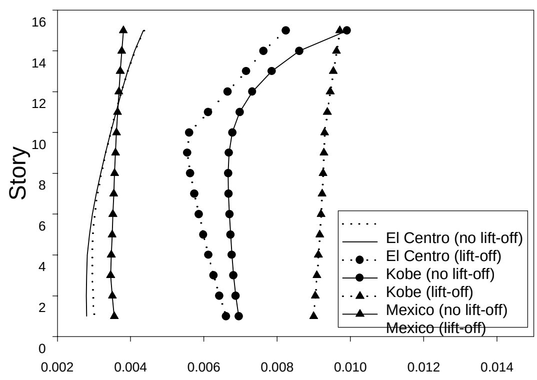

Figure 6a: Maximum rotational angle, β=8, *N*=15

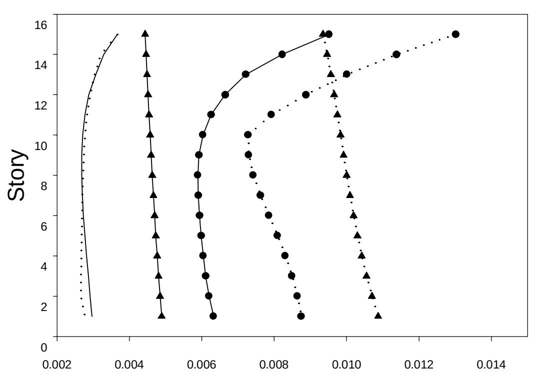

Figure 6b: Maximum rotational angle, β=12, *N*=15

Figures 7 and 8 present the contact ratio versus response ratio for a structure having *N*=10 subjected to Kobe earthquake and *N*=15 subjected to El Centro earthquake, respectively.

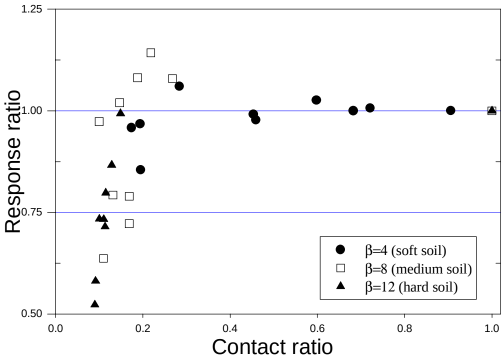

Figure 7: Contact ratio, *N*=10, Kobe

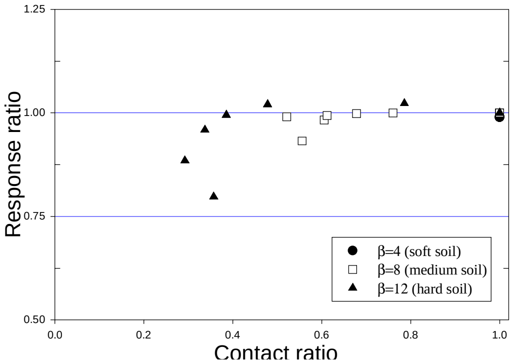

Figure 8: Contact ratio, *N*=15, El Centro

It can be observed that for a hard soil, the contact ratio decreases. Similar plots were obtained for all the other cases analyzed. Generally, it was noticed that the smallest response ratio is obtained for the stiffer soil.

Figures 9 and 10 present the time-history of base rotational angle for a structure with *N*=10, *H/L*=5, for Kobe earthquake when β=4 and β=8, respectively. Again, it can be observed that the rotational angle increases with β. In addition, with the increase of β the occurrence of lift-off phenomena increases also. This can be explained by the fact that in static stage, when β=8 the sinking of the structure in the supporting soil is smaller than in the case when β=4, and the structure needs less displacement on vertical direction in order to initiate the lift-off. Consequently, the structures need to reach a smaller rotational angle for lift-off initiation.

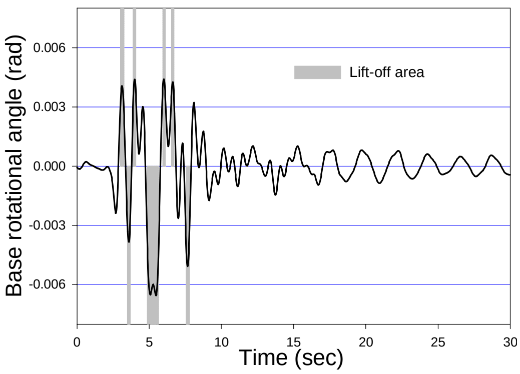

Figure 9: Base rotational angle, *N*=10, β=4, Kobe

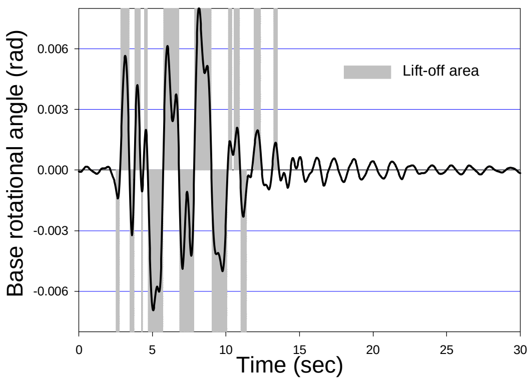

Figure 10: Base rotational angle, *N*=10, β=8, Kobe

Figure 11 presents the elastic base shear coefficient spectra of a structure having *H/L*=10 subjected to El Centro input ground motion when β value varies. It can be seen that in the case when lift-off is prevented, the decrease of β value produces a reduction of the base shear coefficient and in the case when lift-off is allowed, this reduction is smaller. The values of the base shear coefficient decrease in the case when lift-off is allowed in comparison to those when lift-off is prevented. Similar observations were made in the other cases that were analyzed.

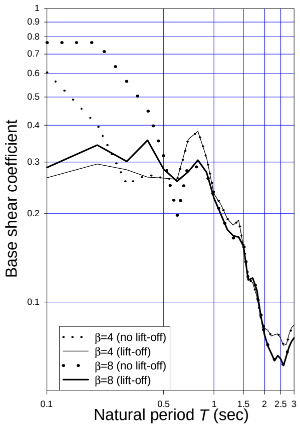

Figure 11: Base shear coefficient spectra, β=4, β=8, El Centro

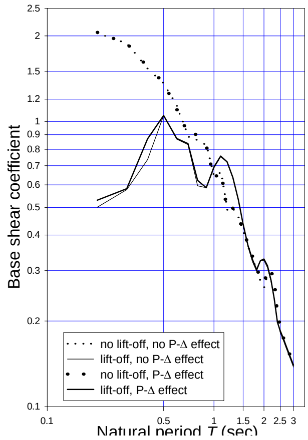

Figure 12: Base shear coefficient spectra, β=12, Kobe

The elastic base shear coefficient spectra of a structure having *H/L*=10, β=12, and subjected to Kobe earthquake input ground motion is displayed in Figure 12. In this case, the structure was analyzed with and without the P-Δ effect for the case when lift-off is prevented and for the case when lift-off is allowed. It can be noticed that there is no significant difference in the response spectra when P-Δ effect is considered, for both cases, with or without lift-off.

CONCLUSIONS

In order to study the effects of lift-off phenomena on the structural response to earthquake motions, a variety of plots were presented. The investigation of the presented data leads us to the following conclusions:

1. The natural vibration period of the structure on flexible base, after a certain value of frequency ratio, β, is insignificantly affected by the increase in vertical stiffness of the soil.
2. For all cases analyzed, it was found that the response ratio has similar pattern for each level and generally the smallest value was obtained for hard soil.
3. The values of the base shear coefficient spectra decrease in the case when lift-off is allowed in comparison to those when lift-off is prevented. In addition, there is no significant difference in the response spectra when P-Δ effect is considered, for both cases, with or without lift-off.
4. In the case of this study, the consideration of lift-off phenomena generally reduces the rotational angle, and consequently the shear forces acting along the height of the structure. This is based on the fact that unfavorable effects were observed for less than 10% of the 270 cases which were analyzed.

It was observed that the response of the structures having same parameters but subjected to different earthquakes is scattered. Therefore, further study is necessary in order to establish the effect that the type of earthquake has on the structural response of structures allowed to lift-off from the foundation soil.

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