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Influence of Kinematic Interaction Effects on Earthquake Structure Response: Analysis of These Effects in the Colombia Earthquake of November 15, 2004

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INFLUENCE OF KINEMATIC INTERACTION EFFECTS ON EARTHQUAKE STRUCTURE RESPONSE: ANALYSIS OF THESE EFFECTS IN THE COLOMBIA EARTHQUAKE OF NOVEMBER 15, 2004

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ABSTRACT

Many authors have considered the kinematic interaction effects as favorable for seismic response of structures. However, this assumption is not always correct, because for some combinations of soil dynamic properties, foundation geometry and structural configuration, the kinematic interaction effects can lead to unfavorable performance of structures during earthquake. Therefore, the kinematic interaction effects increase or decrease the effective excitation that acts on the foundation base, in terms of their translation and rotation components. In this paper the role of kinematic interaction effects is analyzed for plate foundation embedded in different layered soil profiles, using recorded motions and several foundation geometries. Evaluations are carried out using a proposed analytical methodology based on Iguchi´s approach (Iguchi, M., 1982).

These analyses are focused to identify key parameters that control kinematic interaction effects, in order to point out specific conditions of foundation and soil profile properties which, if those effects are neglected, it may lead to erroneous conclusions in the assessment of seismic performance of structures.

In addition, this paper presents the application of the proposed methodology for the analysis of the kinematic interaction effects on damage caused in some buildings in the city of Cali, Colombia, by the earthquake occurred in the Pacific region of this country in November 15, 2004.

Conclusions of this work show the marked influence of foundation geometry and dynamic soil profiles on kinematic interaction effects. These results point out that as stiffness of soil profile decreases, translation components of effective excitation on the foundation base increase for high frequencies and they can reach values greater than those of free-field motion. On the other hand, the study shows that as foundation burial depth increases, the rotation components of the effective excitation on the foundation base increases in such way, that these components can get the control of seismic performance of high structures. Conclusions of this paper stand out the importance of kinematic interaction effects on soil-foundation-structure interaction analysis.

INTRODUCTION

The earthquake structure response depends basically on regional seismic hazard, earthquake ground response and structural vulnerability. The analysis of earthquake ground response supplies information about amplification characteristics of soil profiles in free-field conditions, i.e. this analysis estimates the ground motion without the influence of any structure. The free-field conditions correspond to motions without the incidence of structural vibrations. The earthquake structure response results from the interactions among three linked systems: The structure, the foundation and the soil profile beneath and around the foundation. An analysis of soil-foundation-structure interaction (SFSI) studies the combined response of these systems to an input motion in free-field conditions.

The phenomenon of SFSI includes a set of kinematic and inertial effects produced in structure, foundation and soil as a result of the flexibility of the soil profile to the earthquake excitation. The SFSI effects modify not only the dynamic response of the structure, but also the characteristics of earthquake ground motion near the foundation.

The kinematic effects allow the estimation of the differences between the effective earthquake excitation on the foundation base and the motion in free field. The kinematic effects are caused as a consequence of the foundation stiffness, which avoids its adjustment to the soil strains generated by the motion in free-field, and causes diffraction of waves which modifies the ground motion near the foundation.

The effects of kinematic interaction modify the free-field motion. The free-field motion is transformed into an effective excitation composed by translation and rotation components. In general, the translation component is lesser than the free-field motion, due to the spatial variation of the ground motion beneath and around the foundation is averaged as a result of the foundation stiffness. The rotation components appear because the foundation stiffness avoids the foundation follow the translation movements of the surrounding soil.

Generally, many authors consider that it is suitable to neglect the kinematic interaction effects, i.e. it is suggested to carry out only the analysis of inertial interaction. When the kinematic interaction is neglected, it is assumed that the effective earthquake excitation on the base of the foundation is equal to the free-field excitation, which only has translation components.

In general, the assumption of neglecting the kinematic interaction is due to these effects tend to reduce the translation of the foundation. Despite these effects generate rotation of the structure, which is not present in the free-field excitation, it has been considered that in the most of the cases it is more unfavorable the free-field motion than the effective excitation obtained from a kinematic interaction analysis.

However, the validity of this hypothesis depends markedly on the dynamic properties of the soil profile and the foundation geometry. The analysis of kinematic interaction allows the estimation of an effective excitation of the foundation composed by translations and rotations. In general, kinematic interaction decreases translation components, but in some cases it can increase these components. On the other hand, it is important to take into account that the rotation components generated by kinematic interaction in the foundation can increase markedly the structure displacements, which increases its earthquake damage (García, H. et al., 2000).

In this paper it is introduced a proposed methodology to evaluate kinematic interaction effects. This methodology is based on the Iguchi´s approach (Iguchi, M., 1982); it uses the transfer function concept to characterize these effects, according to the soil profile conditions and geometry foundation. This paper also presents the results of a parametric analysis carried out using the proposed methodology, which is addressed to identify the variables that control the effective earthquake excitation at the base of the foundation, associated with the soil-foundation kinematic interaction effects.

The influence of the kinematic interaction in the earthquake ground response depends on the foundation geometry and the properties of the soil profile.

Usually, the analysis of kinematic interaction effects is not carried out, because it implies to adopt finite element methods or other complex techniques, which implies requirements such as very detailed data of the system soil-foundation-structure, available time and technological resources to develop and analyze the corresponding model. Therefore, this kind of methods are only feasible for the study of special structures. Conversely, the proposed methodology is easy to apply in the most practical cases, it supplies a simplified and precise procedure, that provides useful data about the cases in which it is fundamental to consider kinematic interaction effects in the earthquake structure response.

METHODOLOGY TO ANALYZE KINEMATIC INTERACTION EFFECTS SOIL-FOUNDATION

The estimation of kinematic interaction effects is represented through the effective earthquake excitation on the base of the foundation, associated with a given earthquake motion. The effective excitation results from the superposition of the free-field motion and the diffracted field by the foundation. This depends on the foundation characteristics, soil profile conditions, incidence angle and type of seismic waves.

This methodology uses a simplified approach with simple mathematic expressions, which estimates the effective earthquake excitation on the foundation base, using a weighted average of displacements and stresses in the soil-foundation interface. As shown in Figure 1, the foundation base and the foundation walls are in contact witch the soil. The effective earthquake excitation is estimated based on the free-field earthquake motion or input ground motion, and it is expressed in terms of the translation component (U_o), in the axis-Y direction, and the rotation component (ϕ_o) around the axis-X direction, according to the convention of axis pointed out in the Figure 1.

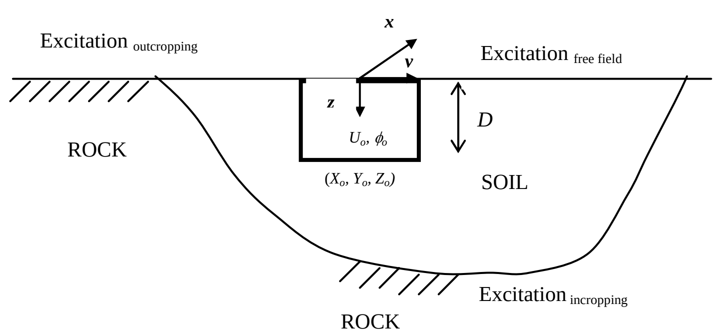

Figure 1. Configuration of rock, soil profile, foundation and possible location of the input ground motion for the kinematic interaction analysis.

The proposed methodology for the evaluation of kinematic interaction effects includes the following:

Hypothesis

This methodology assumes the foundation with no mass and perfectly rigid.

The foundation base rests on a elastic half-space, and is subjected to the incidence of vertical seismic waves.

Input data

Record of the input ground motion in terms of the history of accelerations.

Location of the input ground motion.

Properties and geometry of the soil profile:
- Number of strata until the bedrock
- Thickness of each soil stratum
- Unitary weight of each soil stratum
- Shear wave velocity of each soil stratum
- Unitary weight of the bedrock
- Shear wave velocity of the bedrock

Foundation geometry
- Foundation burial depth (D)
- Foundation width (B)
- Foundation length (L)

Analysis and processing of the input ground motion

- Estimation of the Fourier transform of the input earthquake record, based on the history of acceleration.

- Analysis of earthquake ground motion, considering the dynamic response of the soil profile. This step is applicable for the cases where the input ground motion is located in the bedrock under the soil profile (incropping condition), or the input ground motion is located in the rock outcrop (outcropping condition).

Analysis of the soil profile

The analysis of soil-foundation kinematic interaction requires the estimation of equivalent dynamic properties of the soil profile, such as the shear modulus (*G*), the damping ratio and the average shear wave velocity.

The evaluation of equivalent dynamic properties of the soil profile was carried out using a finite element method. This method was proposed by Lysmer and Waas (Lysmer y Waas, 1972), and is applicable for the analysis of stratified materials with a rigid base, which is excited through the propagation of horizontal shear waves. In this case the stratified material is the soil profile, and the rigid base is the bedrock. The application of this method requires to divide each stratum into several sub-strata. The thickness of each one and every sub-stratum (*h*) must be smaller than one fifth of the length (λ) of the shear wave in that sub-stratum. In this way, the number of sub-strata results greater than the number of original strata of the soil profile. Figure 2 illustrates the application of this method through the division of a soil profile, composed by three strata, into 17 sub-strata.

If the soil profile is divided into N strata, and it is assumed the variation of the eigenfunctions is linear, it is possible to obtain a problem of eingenvalues and eigenvector of order N, described by the Equation (1).

$$\left([K_s] - w_i^2 [M_s]\right)\{W_i\} = \{0\} \tag{1}$$

Where,

w_i: Natural frequency corresponding to the natural mode of vibration *i* of the soil profile.

$\{W_i\}$: Natural mode of vibration *i* of the soil profile. This is a eigenvector of order N, according to Equation 2.

$$\{W_i\} = \begin{Bmatrix} W_1 \\ W_2 \\ W_3 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ W_N \end{Bmatrix} \tag{2}$$

Where,

$W_1, W_2, \ldots, W_N$: Modal displacements of the nodes $Z_1, Z_2, \ldots, Z_N$.

$[K_S]$: Stiffness matrix of the soil profile (order N x N).

$[M_S]$: Mass matrix of the soil profile (order N x N).

The stiffness and mass matrices of soil profile are assembled as follow:

- Calculation of the stiffness $[K_i]$ and mass $[M_i]$ matrices of the stratum *i*, using the Equations (3) y (4).

$$[K_i] = \frac{G_i}{H_i}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{3}$$

$$[M_i] = \frac{\gamma_i h_i}{g}\begin{bmatrix} 1/3 & 1/6 \\ 1/6 & 1/3 \end{bmatrix} \tag{4}$$

Where,

h_i: Thickness of soil stratum *i*.

G_i: Shear modulus of soil stratum *i*.

γ_i: Unitary weight of soil stratum *i*.

- The assembly of the mass and stiffness matrices is carried out according to procedure shown in Figures 3 and 4. The elements out of the block defined in Figures 3 and 4 are equal to zero. The elements that superimpose in the block must be summed. The elements that locate out of the matrix are not used.

- Estimation of the frequencies and modes of vibration of the soil profile. These data are useful to determine the fundamental period of vibration, shear modulus and shear wave velocity of the soil profile.

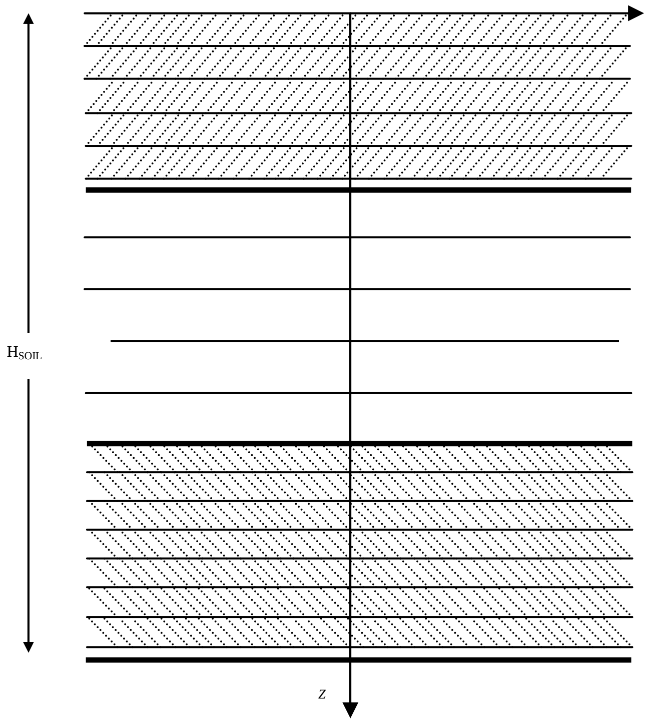

Figure 2. illustrative example of the division of a soil profile, composed by 3 strata, into 17 sub-strata.

Estimation of the effective earthquake excitation in the foundation

The estimation of the translation (U_o) and rotation (ϕ_o) components of the foundation in the frequency domain is deduced in the section 1.4.2, taking into account the mathematical expressions presented in the following numerals.

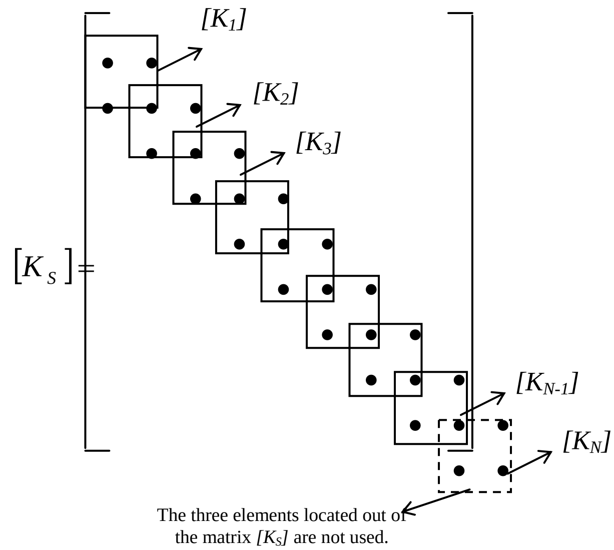

Figure 3. Assembly of the stiffness matrix of the soil profile [K_S].

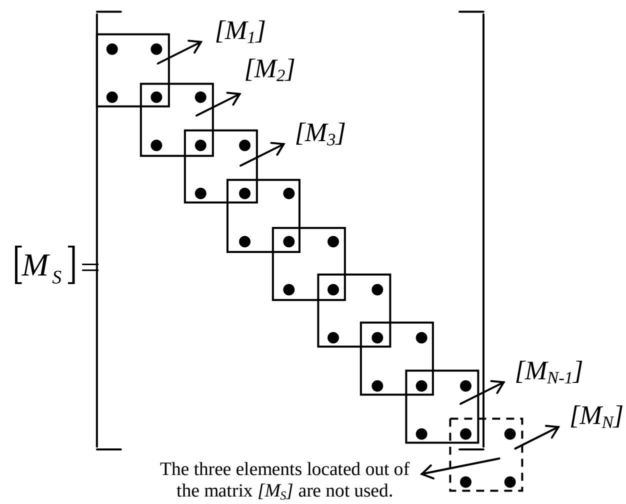

Figure 4. Assembly of the mass matrix of the soil profile [M_S].

Iguchi´s approach

The Iguchi´s approach is based on the weighting average of free-field displacements and stresses on the soil-foundation interface. It proposes the estimation of the effective earthquake excitation on the foundation base, at the reference point (X_o,Y_o,Z_o), through the Equation (5).

$$U_o = H^{-1}\iint A^T U_g dS + K^{-1}\iiint A^T T_g dS \qquad (5)$$

Where,

S: Interface between soil and foundation, which includes the base and walls of the foundation.

U_o: Vector of free-field displacements in the interface (S) between the foundation and the soil, according to Equation (6).

$$U_o = \begin{bmatrix} U_{ox} \\ U_{oy} \\ U_{oz} \\ \phi_{ox} \\ \phi_{oy} \\ \phi_{oz} \end{bmatrix} \qquad (6)$$

A: Transformation matrix of rigid-body motion, according to Equation (7).

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 & Z - Z_o & Y_0 - Y \\ 0 & 1 & 0 & Z_o - Z & 0 & X - X_o \\ 0 & 0 & 1 & Y - Y_o & X_o - X & 0 \end{bmatrix}$$

$$H = \iint A^T A dS$$

The integration equations (5) y (8) considers the total soil-foundation interface (S).

U_g: Free-field earthquake motion, represented by the translation components in the X, Y y Z directions (Equation 9).

$$U_g = \begin{bmatrix} U_{gx} \\ U_{gy} \\ U_{gz} \end{bmatrix}$$

K: Matrix of dynamic stiffness of the foundation, composed by the impedance functions of the soil.

T_g: Free-field shear stress vector in the interface between the foundation and the soil (S), according to Equation (10).

$$T_g = \begin{bmatrix} G \dfrac{dU_g}{dx} \\ G \dfrac{dU_g}{dy} \\ G \dfrac{dU_g}{dz} \end{bmatrix} \qquad (10)$$

<u>Proposed methodology</u>

The deduction of mathematical expressions of the proposed methodology is based on the estimation of the earthquake motion in the reference point (X_o,Y_o,Z_o), located in the central point of the foundation base (Figure 1), in terms of the translation component (U_o) in the axis-Y direction, and the rotation component (ϕ_o) around the axis-X direction in the domains of frequency and time.

Considering these two components, the free-field displacement vector in the soil-foundation interface of the Equation (6) is transformed in the Equation (11).

(7)

$$U_o = \begin{bmatrix} 0 \\ U_{oy} \\ 0 \\ \phi_{ox} \\ 0 \\ 0 \end{bmatrix} \qquad (11)$$

(8)

The transformation matrix of rigid body (A) expressed through the Equation (3) is transformed in the Equation (12), taking into account the location of the reference point (X_o,Y_o,Z_o) on the foundation base respect to the origin (X, Y, Z) in the Figure 1 (where X=X_o and Y=Y_o).

$$A = \begin{bmatrix} 1 & (Z_o - Z) \end{bmatrix} \qquad (12)$$

(9)

In addition, the proposed methodology is based on the analysis of vertical incidence of seismic shear waves at the depth Z. For this reason, the translation vector of free-field motion of Equation (5) is transformed into the vector of Equation (13).

$$U_g = \begin{bmatrix} 0 \\ U_{gy}(z) \\ 0 \end{bmatrix} \qquad (13)$$

Therefore, the shear stresses in the soil-foundation interface that have influence on the effective earthquake excitation correspond to those associated with the product between the shear modulus and the shear deformation in the axis-Z direction. For this reason, the vector of free-field shear stresses of Equation (6) is converted into that expressed through the Equation (14).

The Equation (15) is obtained from replacing the Equations (11) to (14) in the Equation (5), which estimates the effective earthquake excitation in terms of the translation component in the axis-Y direction, and the rotation component around the axis-X direction, in the point (X_o,Y_o,Z_o) on the foundation base.

$$T_g = \begin{bmatrix} 0 \\ 0 \\ \left(G \dfrac{dU_g}{dz} \right) \end{bmatrix} \tag{14}$$

$$\begin{bmatrix} U_{oy} \\ \phi_{ox} \end{bmatrix} = \frac{12 \cdot \ddot{U}_{rb}}{(3 \cdot A_P - 4 \cdot A_T) w^2 \cdot Cos(K_s \cdot H_s)} \begin{bmatrix} \dfrac{1}{3}\left(\dfrac{Sen(K_s \cdot D)}{K_s} \cdot P_B + Cos(K_s \cdot D) A_B \right) - \dfrac{1}{2D} \dfrac{P_B}{K_s^{\,2}} (1 - Cos(K_s \cdot D)) \\ \dfrac{1}{3}\left(\dfrac{Sen(K_s \cdot D)}{K_s} \cdot P_B + Cos(K_s \cdot D) A_B \right) - \dfrac{1}{2D} \dfrac{P_B}{K_s^{\,2}} (1 - Cos(K_s \cdot D)) \end{bmatrix}$$

$$+ K^{-1} \frac{G \cdot \ddot{U}_{rb}}{w^2 \cdot Cos(K_s \cdot H_s)} \begin{bmatrix} P_B \cdot (1 - Cos(K_s \cdot D)) + K_s (Sen(K_s \cdot D)) \cdot A_B \\ P_B \left(D - \dfrac{Sen(K_s \cdot D)}{K_s} \right) \end{bmatrix} \tag{15}$$

Where,

D: Burial depth of the foundation, which is illustrated in Figures 1 and 5.

L: Length of the foundation base (Figure 5).

B: Width of the foundation base (Figure 5).

H_S: Total thickness of the soil profile until the bedrock.

A_P: Area of the foundation walls, according to Equation (16a).

$$A_P = P_B \cdot D = (2B + 2L) \cdot D \tag{16a}$$

A_B: Area of the foundation base, according to Equation (16b).

$$A_B = B \cdot L \tag{16b}$$

A_T: Total area of the foundation, which is expressed through the Equation (16c).

$$A_T = A_P + A_B \tag{16c}$$

$$K_S^{\,2} = \frac{w^2}{V_s^{\,2} \cdot (1 + 2 \cdot \xi \cdot i)} \tag{17}$$

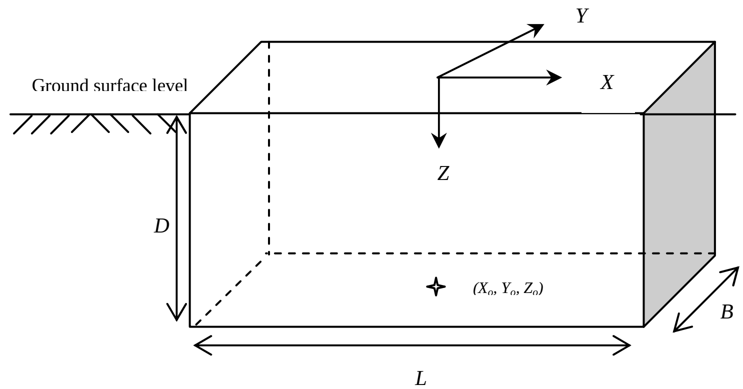

Figure 5. Variables of geometry and location of the reference point for the analysis of the effective earthquake excitation on the foundation base.

The Equation (15) is the simple expression of the proposed method to estimate the effective earthquake excitation in terms of the translation component in the axis-*Y* direction, and the rotation component around the axis-*X* direction.

The variables involved in the Equation (15) were studied through a parametric analysis for different conditions of soil profile properties and foundation geometry, in order to identify those that control the variation of the effective earthquake excitation on the foundation base respect to the free-field excitation. The results of this parametric analysis are presented in numeral 2 of this paper.

RESULTS OF PARAMETRIC ANALYSIS

The parametric analysis was carried out for a foundation composed by a plate and four walls in contact with different soil profiles. The properties of the soil profiles used for this analysis are presented in the Tables 1 to 3.

The results of the parametric analysis are presented in terms of the ratio between the effective earthquake excitation on the foundation base and the free-field earthquake motion, for the components of translation and rotation. The Figures 6 to 12 relate the transfer function of translation (FTUocs) and rotation (Ftfiocs) components, with the normalized angular frequency. These figures compare the tendency of transfer functions for different soil profiles and burial depth of the foundations. These figures also illustrate the variables with major incidence on the kinematic interaction effects.

The normalized angular frequencies, etah and etar, relate the angular frequency, the equivalent circular radius of the foundation surface, and the shear wave velocity of the soil profile, according to Equations (18) and (19).

$$etah = etar = \frac{\omega Rm}{Vs} \quad (18)$$

$$Rm = \left(\frac{A_B}{\pi}\right)^{1/2} \quad (19)$$

Table 1.Properties of type 1 and type 2 soil profiles.

Stratum	Thickness (m)	Unit weight of soil (ton/m^3)	Vs (m/s) Soil profile 1	Vs (m/s) Soil profile 2
1	2.0	1.70	150	150
2	2.0	1.70	150	150
3	2.0	1.70	150	150
4	2.0	1.70	800	200
5	2.0	1.70	800	200
6	2.0	1.70	800	200
7	2.0	1.70	800	200
8	2.0	1.70	800	200
9	2.0	1.70	800	200
10	2.0	1.70	800	200
11	2.0	1.70	900	
12	2.0	1.70	900	
13	2.0	1.70	900	
14	2.0	1.70	900	
15	2.0	1.70	900	
Roca		2.20	1500	1500
Damping ratio of soil (ζ_s)			0.05	0.05
Equivalent shear wave velocity of soil (m/s)			648.7	196.9
Natural period of vibration of the soil profile (s)			0.19	0.41

Based on the results of the parametric analysis, the variables with major incidence on the effective earthquake excitation are discussed below.

Table 2. Properties of type 3 soil profile.

Stratum	Thickness (m)	Unit weight of soil (ton/m^3)	Vs (m/s) Soil profile 3
1	2.0	1.60	80
2	2.0	1.60	100
3	3.0	1.70	120
4	2.0	1.70	100
5	3.0	1.70	200
6	3.0	1.80	100
7	2.0	1.80	150
8	3.0	1.80	250
Roca		2.20	1500
Damping ratio of soil (ζ_s)			0.02
Equivalent shear wave velocity of soil (m/s)			142.7
Natural period of vibration of the soil profile (s)			0.56

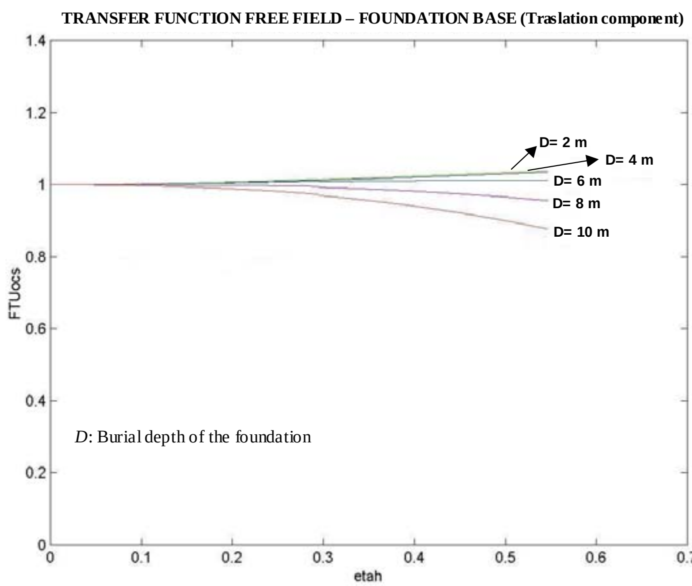

Figure 6. Transfer function of the translation component with the normalized frequency for the type 1 soil profile, width and length foundation 10 m, and burial depths of the foundation 2 m, 4 m, 6m, 8m y 10 m.

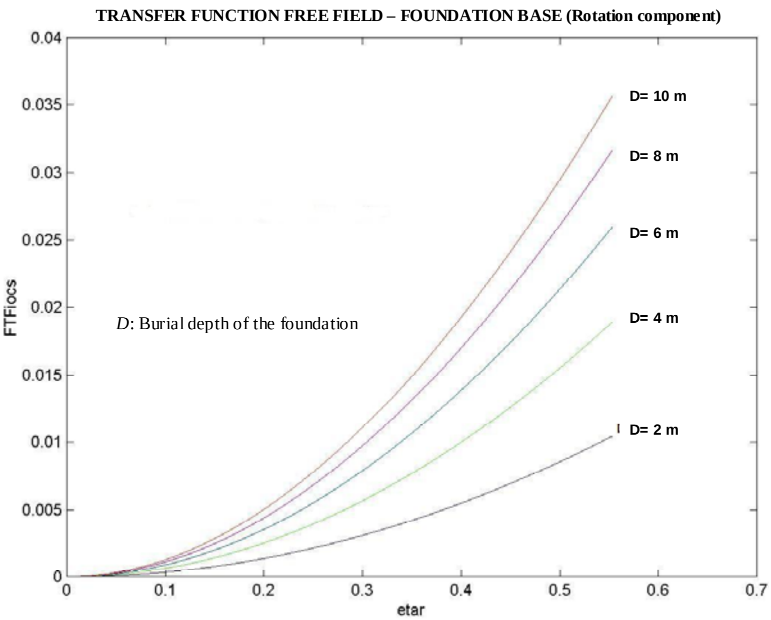

Figure 7. Transfer function of the rotation component with the normalized frequency for the type 1 soil profile, width and length foundation 10 m, and burial depths of the foundation 2 m, 4 m, 6m, 8m y 10 m.

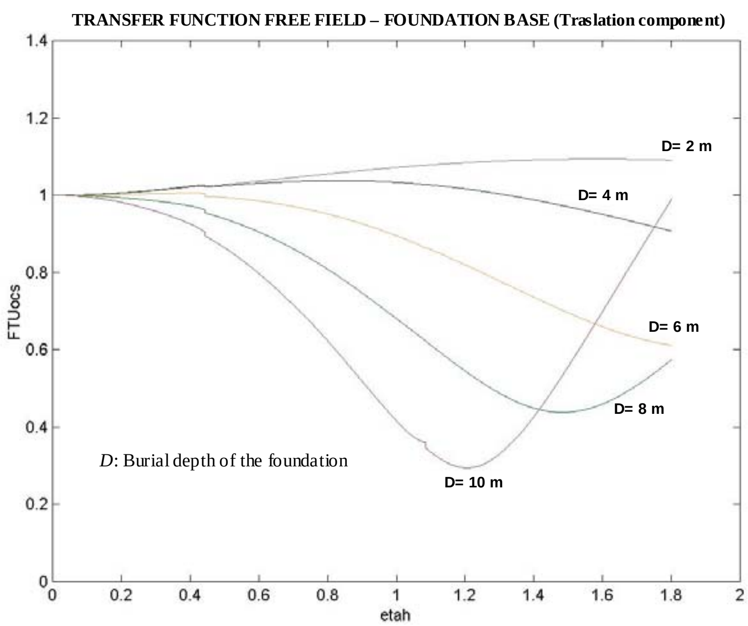

Figure 8. Transfer function of the translation component with the normalized frequency for the type 2 soil profile, width and length foundation 10 m, and burial depths of the foundation 2 m, 4 m, 6m, 8m y 10 m.

Table 3. Properties of type 4 soil profile.

Stratum	Thickness (m)	Unit weight of soil (ton/m^3)	Vs (m/s) Soil profile 4
1	2.0	1.70	60
2	2.0	1.70	60
3	2.0	1.70	60
4	2.0	1.70	60
5	2.0	1.70	60
6	2.0	1.70	60
7	2.0	1.70	60
8	2.0	1.70	60
9	2.0	1.70	60
10	2.0	1.70	60
11	2.0	1.70	60
12	2.0	1.70	60
13	2.0	1.70	60
14	2.0	1.70	60
15	2.0	1.70	60
16	2.0	1.70	60
17	2.0	1.70	60
18	2.0	1.70	60
19	2.0	1.70	60
20	2.0	1.70	60
21	2.0	1.70	60
22	2.0	1.70	110
23	2.0	1.70	110
24	2.0	1.70	110
25	2.0	1.70	110
26	2.0	1.70	110
27	2.0	1.70	110
28	2.0	1.70	110
Roca		1.70	1500
Damping ratio of soil (ζ_s)			0.05
Equivalent shear wave velocity of soil (m/s)			72.7
Natural period of vibration of the soil profile (s)			3.08

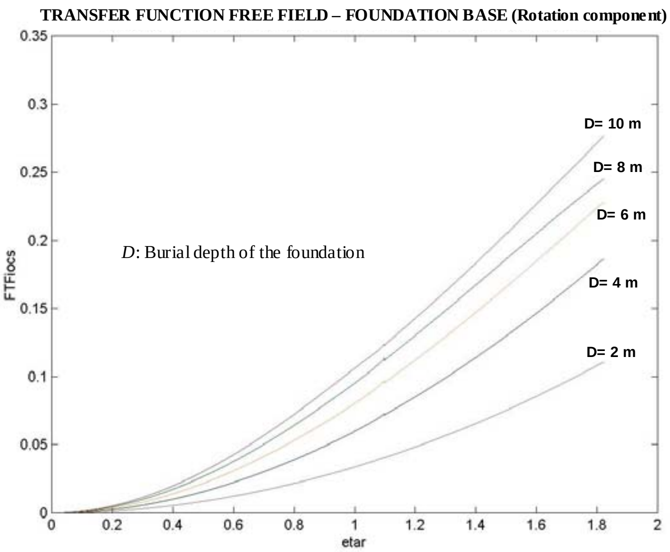

Figure 9. Transfer function of the rotation component with the normalized frequency for the type 2 soil profile, width and length foundation 10 m, and burial depths of the foundation 2 m, 4 m, 6m, 8m y 10 m.

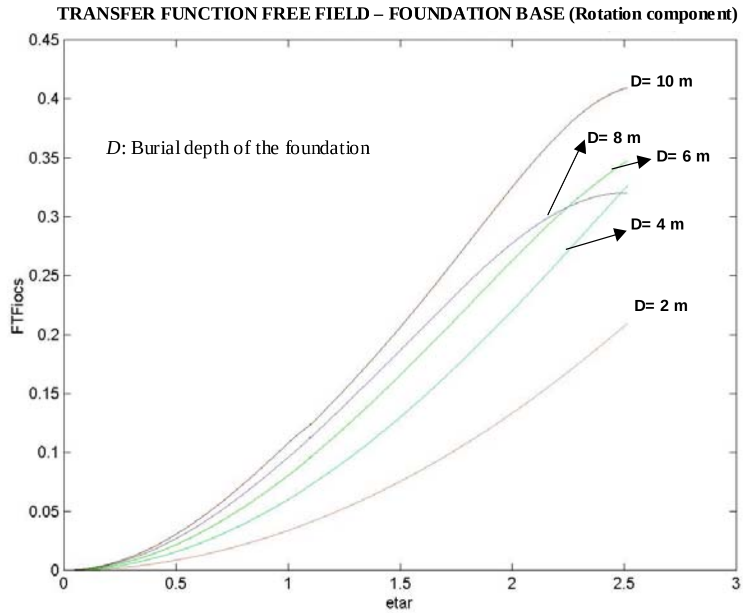

Figure 11. Transfer function of the rotation component with the normalized frequency for the type 3 soil profile, width and length foundation 10 m, and burial depths of the foundation 2 m, 4 m, 6m, 8m y 10 m.

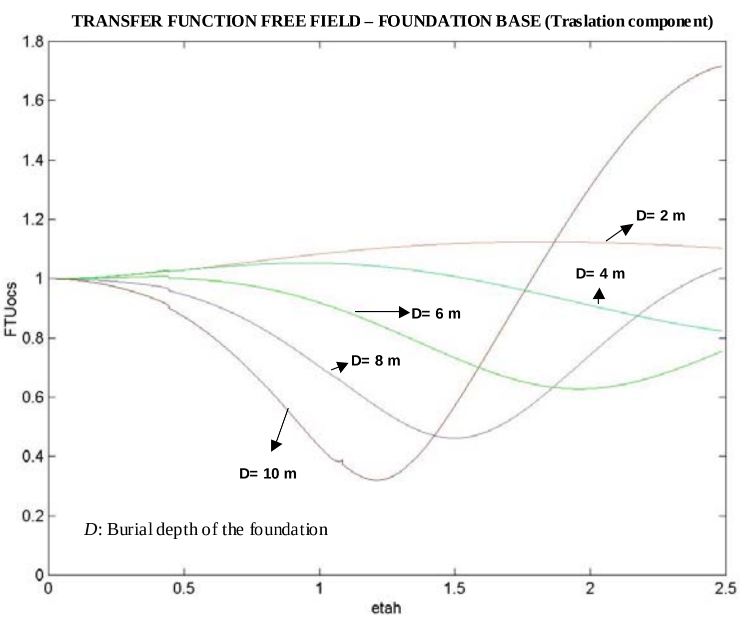

Figure 10. Transfer function of the translation component with the normalized frequency for the type 3 soil profile, width and length foundation 10 m, and burial depths of the foundation 2 m, 4 m, 6m, 8m y 10 m.

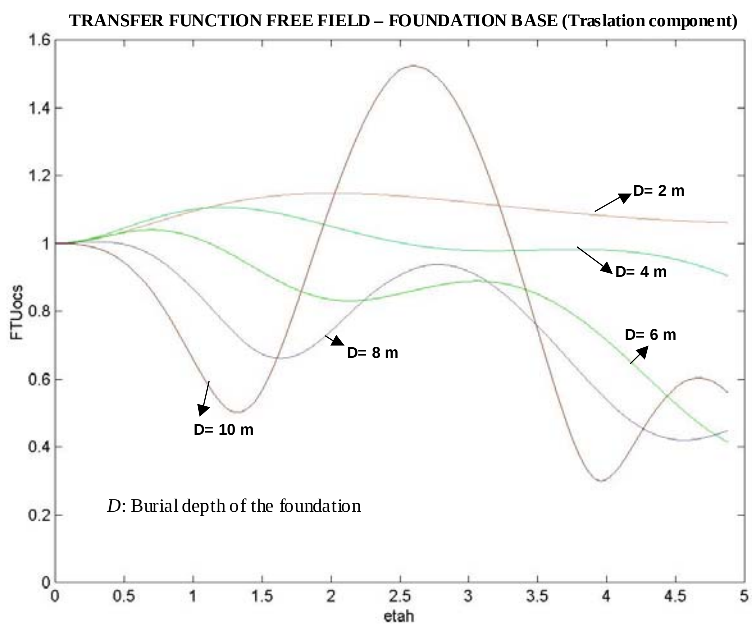

Figure 12. Transfer function of the translation component with the normalized frequency for the type 4 soil profile, width and length foundation 10 m, and burial depths of the foundation 2 m, 4 m, 6m, 8m y 10 m.

Boundary conditions of the foundation geometry and the soil profile stiffness

The translation component of the effective earthquake excitation for plate foundation, with burial depth bigger than its width, resting on soft soil profile, is characterized by modal shapes of displacement greater than free-field motions. Examples of this condition are illustrated in Figures 10 and 12, for type 3 and type 4 soil profiles. In addition, for cases where the dimensions of the base foundation are bigger than their burial depth, there is a lesser difference between the displacement at the ground surface and the displacement at the base foundation level, which implies a smaller translation component (U_o). This condition is easily inferred from the analysis of the Equation (15).

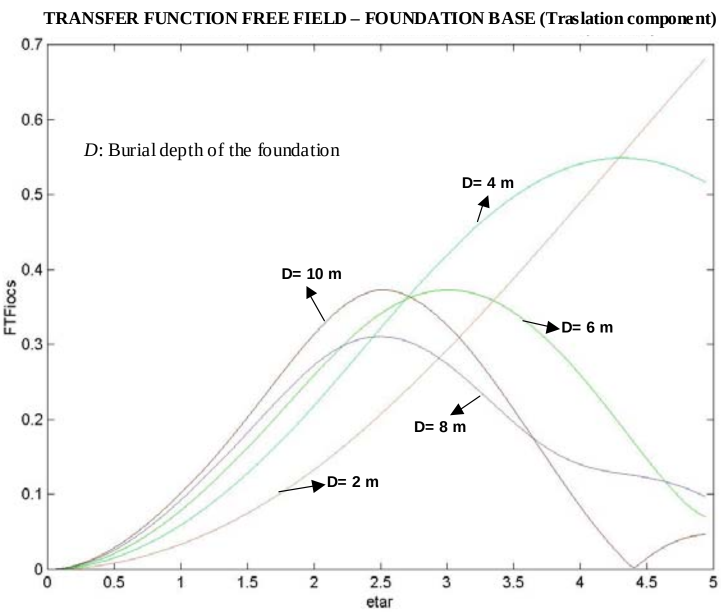

Figure 13. Transfer function of the rotation component with the normalized frequency for the type 4 soil profile, width and length foundation 10 m, and burial depths of the foundation 2 m, 4 m, 6m, 8m y 10 m.

Soft soil profiles

The results of parametric analysis point out the marked influence of the soil profile properties on the effective earthquake excitation at the foundation base. The differences between the free-field excitation and the foundation base excitation increase, as the soil profile stiffness decreases.

This condition shows the importance of kinematic interaction analysis in soft soil profiles. For this kind of soil profiles, the translation component of the effective earthquake excitation at the foundation base may be bigger or smaller than the free-field motion, depending on the frequency.

Variations of the translation component of the effective excitation for soft soil conditions are illustrated in Figures 10 and 12. Variations on the rotation component of the effective excitation for soft soil condition are shown in Figures 11 and 13. The importance of the rotation component increases as the soil profile stiffness decreases.

Foundation geometry

The translation component of the effective excitation at the base foundation level decreases, as the burial depth increases. This is illustrated by the Figures 6 and 8.

In addition, the rotation component of the effective excitation at the base foundation level increases as the burial depth increases. A major burial depth of the foundation is obtained in case of structures with basements below the ground surface level. When this foundation rests on soft soils, the rotation components of the effective excitation might result critical. This condition is shown in Figures 7, 9, 11 and 13.

CASE STUDY: COLOMBIA EARTHQUAKE OF NOVEMBER 15, 2004

On November 15, 2004, it occurred an earthquake of magnitude (M_w) 7.2, at a depth of 15 km, in the Colombian Pacific Ocean (OSSO, 2004 and Velásquez, A. et al, 2005). The city of Cali is located at a distance of 180 km from the epicenter of this earthquake. For this reason, records of this ground motion in the city of Cali show higher amplitudes for an interval of periods between 1,2 to 1,5 s (Velásquez, A. et al, 2005).

Several buildings located at the south of the city of Cali suffered mainly non-structural damage, however, in some cases there was some structural damages as well. These structures were located in a particular zone characterized by soft soil profiles, named “Canaveralejo deposits”, according to the studies of geotechnical zonification of this city (OSSO, 2004). This soil profile presents amplification effects for a range of vibration periods between 0,8 and 1,5 s (Rosales, C. et al , 2005).

In general, damaged structures in this city corresponded to buildings with more than 8 floors. These buildings had at least one or two levels of basements. In the Figure 14 a histogram of the number of floors of the affected buildings is shown.

These damages might be associated with several conditions such as:

- High amplitudes of the earthquake that arrived to the city for long vibration periods, because of the great distance between the epicenter and the city.
- The properties of earthquake ground response of the typical soil profiles in the Canaveralejo zone, which are characterized by seismic amplification for long vibration periods.

In addition, the results of parametric analysis of kinematic interaction effects presented above, point out the great importance of the kinematic interaction effects for the specific case of soft soil profiles. In this earthquake, the damaged buildings presented a combination of two variables, which correspond to those identified in the parametric analysis as controller of the kinematic interaction effects. The rotation component of the effective earthquake excitation might have played an important role in the displacement level that suffered the damaged buildings.

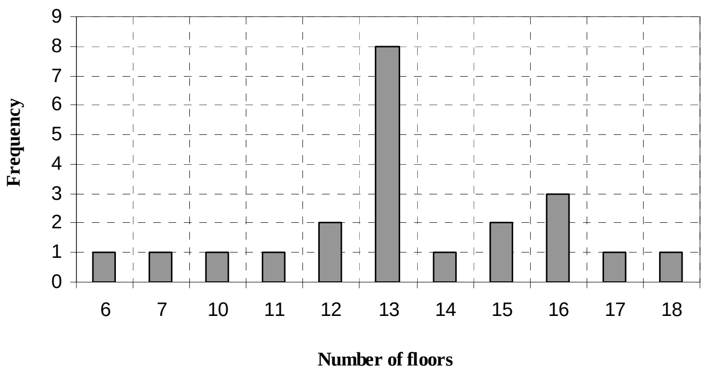

Figure 14. Frequency histogram of number of floors of damaged buildings in the city of Cali, by the earthquake of November 15, 2004.

Lessons of the earthquake of November, 2004 in the city of Cali, confirm considerations about the importance of studying the influence of kinematic interaction effects in the seismic performance of structures, according to the characteristics of the soil profile, foundation geometry and structural configuration.

CONCLUSIONS

The assumption of neglecting the kinematic interaction effects is not always conservative. The results of the analysis discussed in this paper show parameters that control the kinematic interaction effects, which show that some combinations of soil profile and geometry of superficial foundation require their evaluation.

This paper presents a simplified methodology to study kinematic interaction effects, which is applicable for superficial foundations. This methodology requires input data about the foundation geometry, the soil profile properties until the bedrock, the dynamic stiffness of the foundation, and the location of the input earthquake excitation (outcropping, incropping or free-field).

The soil profile stiffness has a deep influence on the kinematic interaction effects. In fact, the effective excitation at the foundation level increases as the soil profile stiffness decreases. The translation component can be bigger or smaller than that of free-field motion depending on the vibration frequency. Therefore, the effects on the structure will also depend on its natural frequency of vibration and its height.

The burial depth of the superficial foundation is another important variable on the effective excitation at the foundation level. The translation component decreases as the burial depth of the foundation increases, and the rotation component increases as the burial depth foundation increases.

The particular conditions of the damaged buildings in the city of Cali as a consequence of the November 2004 earthquake, match with some of the identified variables in the parametric analysis shown in this paper, which control the importance of kinematic interaction effects.

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