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IMPACT OF THE SOIL CONSTITUTIVE MODEL ON THE SEISMIC SOIL STRUCTURE RESPONSE

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ABSTRACT

It's well known that the soil behavior is highly dependent on the soil strain level. In the low frequency range, the soft soil behaviour may amplify significantly the ground motion. This paper includes a numerical study on the influence of the soil modeling on the seismic soil structure interaction for buildings. The analysis is conducted using a 3D numerical modeling that includes the soil layer close to the ground surface, the foundation and the superstructure. Numerical simulations are conducted with different soil constitutive modeling ranging from linear to equivalent linear model. Real ground motions records with different frequency content are used in the analysis. The results reveal that the soil-foundation structure interaction depends on several parameters such as the frequency content of the load, the load amplitude and the natural frequencies of the structure and the soil layer. Considering the non linear behavior of the soil add significant complexity to the problem, where careful analysis should be conducted for the soil structure response.

Keywords: Seismic; soil structure interaction; non linear, numerical

1. INTRODUCTION

For engineering practice, the seismic response of building structures is generally conducted assuming fixed based condition. However, the soil structure interaction (SSI) can have a significant effect on this response by modifying the free field soil movement and filtering the seismic motion applied at the foundation level.

At the soil foundation interface, several non linearities could occur including the geometrical non linearities such as the foundation uplift and the soil yielding at the vicinity of the foundation base. Indeed, the post-seismic observations clearly show a significant role of the surface soil characteristics on the recorded ground motion. Under severe earthquake, this non linearity may lead to a reduction in the dynamic amplification and a shift in the natural frequencies of the soil (Field et al. 1997, Yu et al. 1993). Several approaches have been proposed to model the non linear soil structure interaction. In particular, macro element based models have been developed (Cremer et al 2001, Grange et al 2009, Abboud 2017) and show promising capabilities. The impedance functions used in the macro-element could be determined from the charts proposed by Gazetas (1991). Such impedance function has been used by Khalil et al (2007) to represent the soil-structure interaction in order to assess the flexible base natural period of 3D framed structures. Note that these impedances depend on the foundation shape and the frequency content of the incident motion. For visco-elastic linear model, the resulting seismic motion at the top of a homogeneous soil layer has in general one dominant frequency. For a non linear soil behavior, this assumption is questionable and consequently the determination of the impedance

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function becomes more complicated. The direct method seems to be the more rigorous to analyze the soil structure interaction problems. The positive point in this method is its ability to deal with complexities in geometry and material properties, while the negative one is pointed out by the numerous inputs and outputs, in addition to complexity and time consumption (Yeganeh et al., 2015). A full 3D time history analysis has been conducted by Gullu et al. (2016) to study the Soil structure interaction problem of the historical masonry stone arch bridge (Mataracı Bridge, Trabzon). More recently, Amorosi et al. (2017) use the direct method to study a nuclear power plant taking in account the nonlinear soil behavior.

This paper presents an analysis of the influence of the soil modeling on the seismic soil structure interaction for buildings. The analysis is conducted using a 3D global numerical modeling. Different soil constitutive models are tested ranging from linear model that could be used at small amplitude, to non linear model at higher motion amplitude.

2. NUMERICAL MODEL

2.1 Problem under consideration

The reference case (Figure 1) consists in a one storey building modeled as a reinforced concrete frame resting on a homogeneous soil layer with a thickness of 15 m overlying rigid bedrock. The Young's modulus of the soil is assumed to increase with depth according to Equations 1 and 2:

$$E_S(z) = E_{0S}\left[\frac{p(z)}{p_a}\right]^A \qquad (1)$$

where :

$$P(Z) = \left[\frac{(1+2)K_0}{3}\right]\rho_S.Z \qquad (2)$$

P(Z) = Pa if Z < Z0,
Z: denotes the depth; E_{0S} : reference Young modulus for P (Z)=Pa (E_{0S} = 20 MPa)
K_0: is the coefficient of lateral earth pressure at rest (K_0=0.5); Z0 designates the thickness of the soil layer close to the surface with a constant Young modulus (Z0=1 m)
Pa: is a reference pressure (Pa =100 kPa),
A: parameter dependent on the soil porosity (A=0.5).
ρ_s: soil mass density (ρ_s =1700 kg/m^3)

The total mass of the slab is assumed m_{st} = 80 Tons. The lateral stiffness of the superstructure and it's fixed base natural frequency are respectively: K_{st} = 12149 kN/m et f_{st} =1.9 Hz.
Numerical modeling is carried out using the finite difference software FLAC3D based on a continuum finite difference discretization using the Lagrangian approach (FLAC3D).It uses an explicit scheme to solve the equation of motion using lumped grid point masses derived from the real density surrounding zone.

The finite difference mesh used in the numerical simulations is depicted in Figure 2. It includes 13776 nodes. The wave reflection at the boundaries is prevented using viscous absorbing boundaries.
The procedure of Free-Field Boundaries aims at absorbing outward waves originating from the structure. It involves the execution of free-field calculations in parallel with the main-grid analysis. The lateral boundaries of the main grid are coupled to the free-field grid by viscous dashpots to simulate a quiet boundary (Parish et al 2009).

The seismic motion is applied at the rigid base in term of a velocity time history. It corresponds to the Chi-Chi earthquake that occurred in Taiwan (Figure 3). The amplitude of the ground motion has been scaled to fit a maximum velocity of 40 cm/s. The corresponding frequency content is concentrated between 0.4 and 4 Hz.

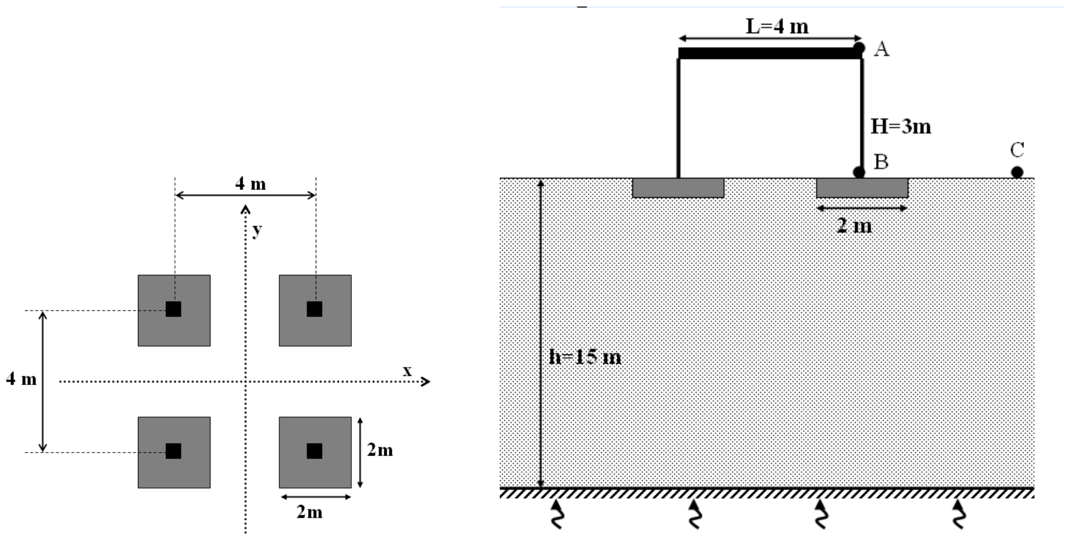

Figure 1: Problem under consideration

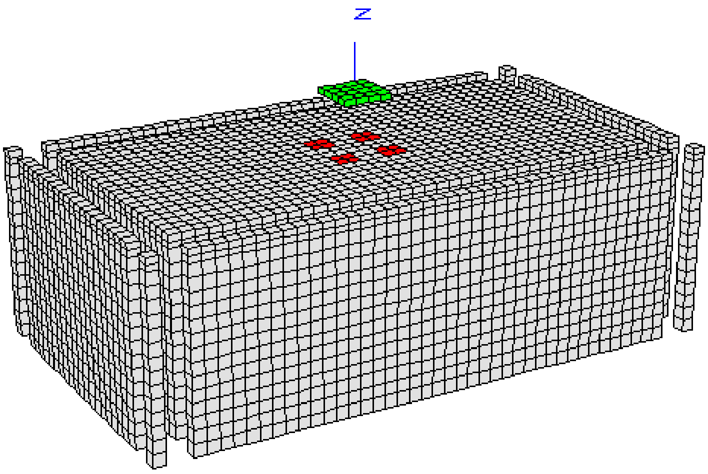

Figure 2: 3D finite difference mesh used in the analysis of the soil-structure system

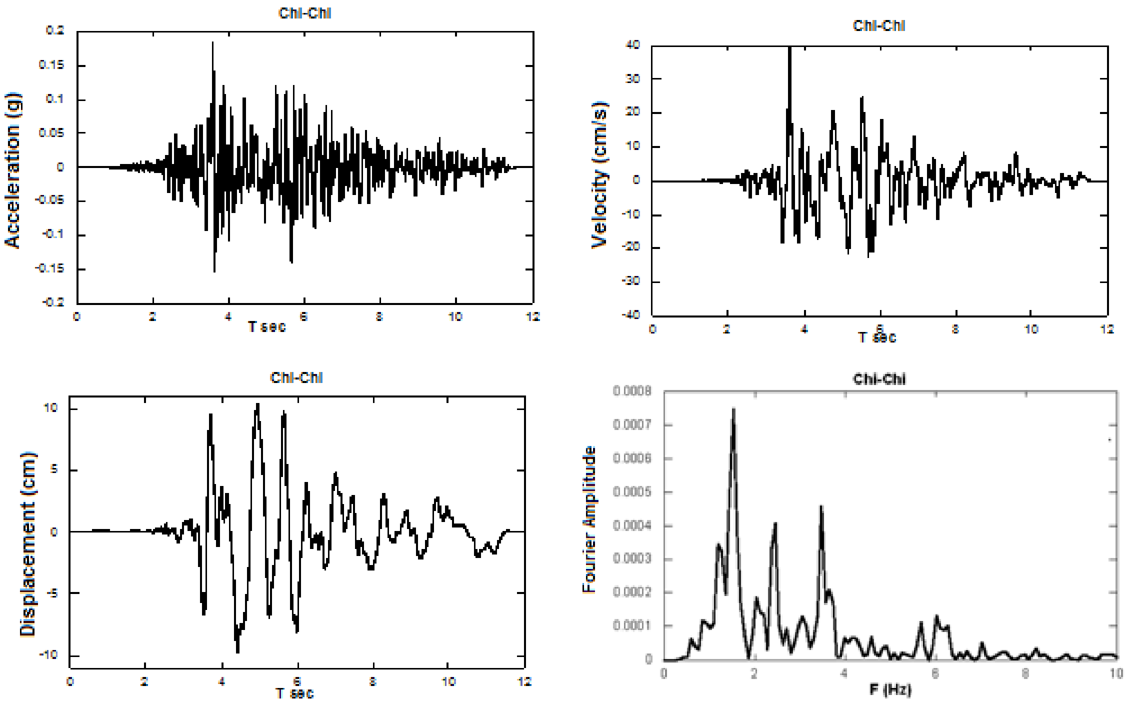

Figure 3: Characteristics of the ground motion – Chi-Chi Earthquake (1999).

2.2 Modeling of soil Behaviour

Every constitutive model available in the literature has its own advantages but also its limitations. It is well known that the soil exhibits nonlinear behavior, even at low strain levels. The strain thresholds for which non linearities may appear are usually very small (10-6 to 10-4). That's why it's interesting to investigate the domain of validity of the linear model and how this simplification could impact the soil and structure response. For more details about soil behavior modeling, the reader can refer to Hardin (1978), Prevost (1987) or Jardine et al (1991). As an alternative to fully non linear method, the equivalent linear method could be used to model the wave propagation in the soil. This method integrated in Flac3D will be used in the present study. It consists on updating the value of soil modulus and damping factor at each step of the calculation. Note that for explicit scheme the time step is significantly reduced which ensure a good convergence of the method. The non linear behavior of the soil is represented by a modulus degradation curve characterized by the modulus reduction factor Ms (Equation 3):

$$M_s = \frac{a}{1 + \exp(-(\log(\gamma) - x_0)/b)} \tag{3}$$

For clayey soil: a = 1.017, b = -0.587 and x_0 = -0.633 (Seed & Sun, 1989). These parameters are adopted in the present study. Figure 4 illustrate the variation of the normalized shear modulus and the hysteretic damping with the shear strain.

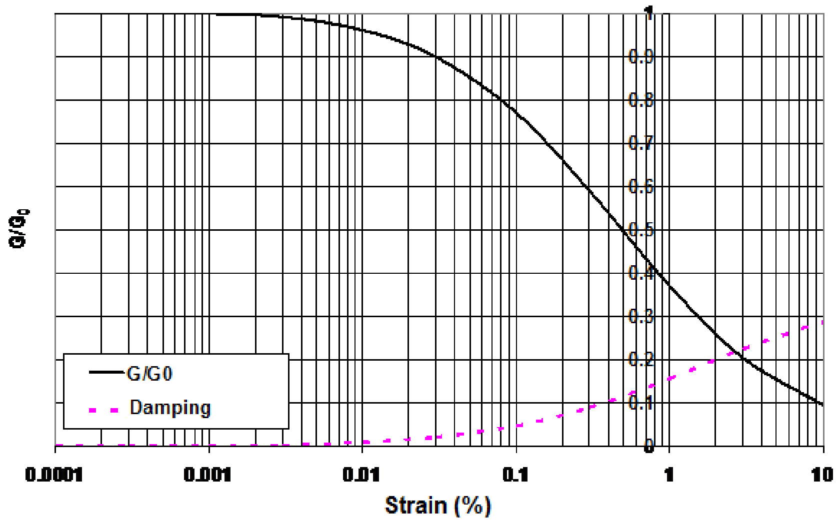

Figure 4: Modulus reduction factor and hysteretic damping curves

3. ANALYSIS OF THE RESULTS

3.1 Free Field

Figure 5 presents a comparison of the amplification of the lateral velocity corresponding to the Chi-Chi earthquake and obtained respectively with linear and non linear soil model. For non linear behavior, It can be noted a significant decrease in the dynamic amplification. For example, at the soil surface, the lateral amplification is about 0.85 for non linear model while it reaches 2.24 for linear behavior. This result is in agreement with the observations of Yu et al (1993).

Figure 6 depicts the response spectrum relative to the free field ground velocity (normalized amplitude). It shows several peaks in the case of non linear behavior which means that the soil motion could be amplified at a large frequency range. The first peaks are induced at frequencies far away from the input load frequencies. For non linear behavior, special attention should be given for the low frequency range where the seismic motion could be significantly amplified. This result could be explained by the stiffness reduction at high strain level. For linear behavior, the resulting motion is filtered at the fundamental frequency of the soil close to 1 Hz.

The resulting shear strain corresponding to the free field seismic motion is given in Figure 7. A 1% shear strain maximum amplitude is obtained close to the soil surface which corresponds to a reduction factor of the shear modulus G/G0 of 40% and a damping factor of 15% (Figure 4). These results confirm the significant reduction of the shear modulus and the appearance of the low resonance frequencies.

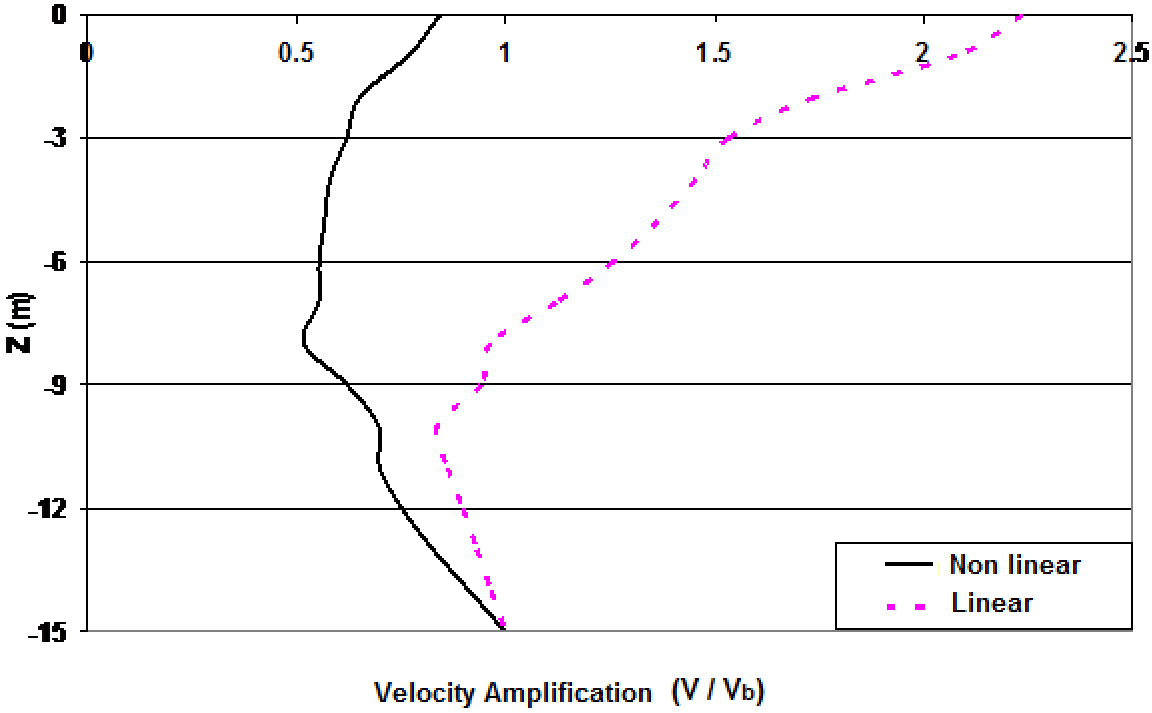

Figure 5: Influence of the constitutive modeling on the free field soil response (Amplification of the lateral velocity)

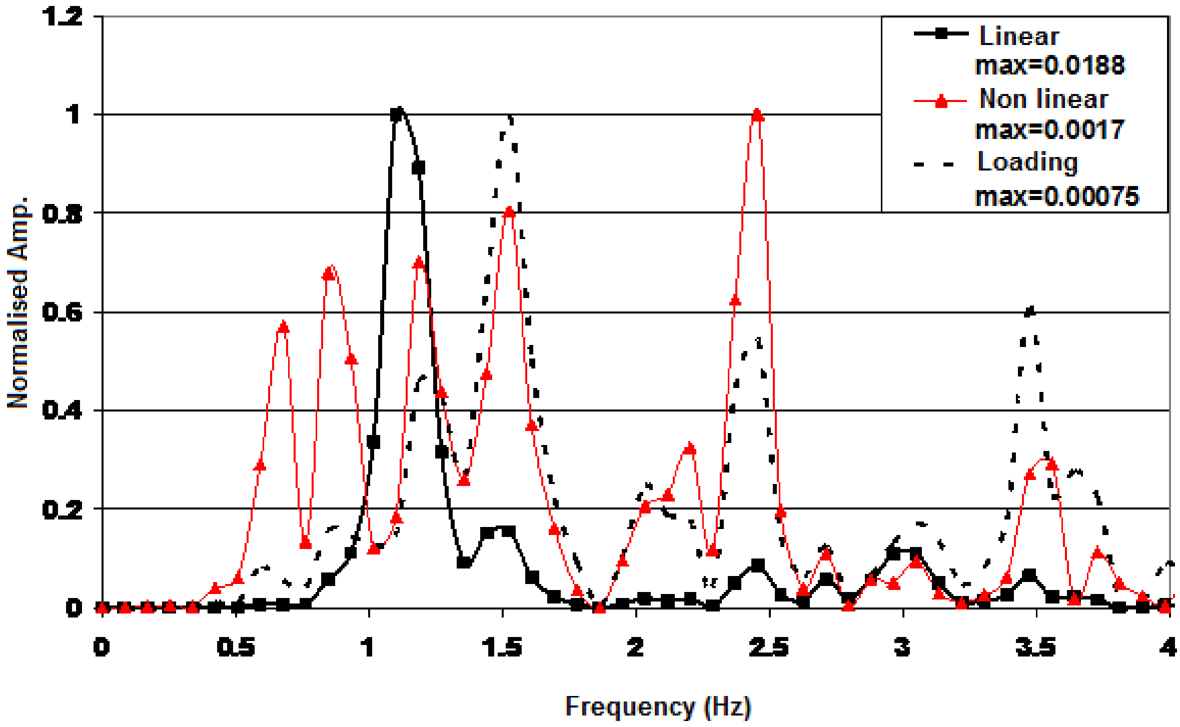

Figure 6: Free field response spectra – linear / non linear soil behavior

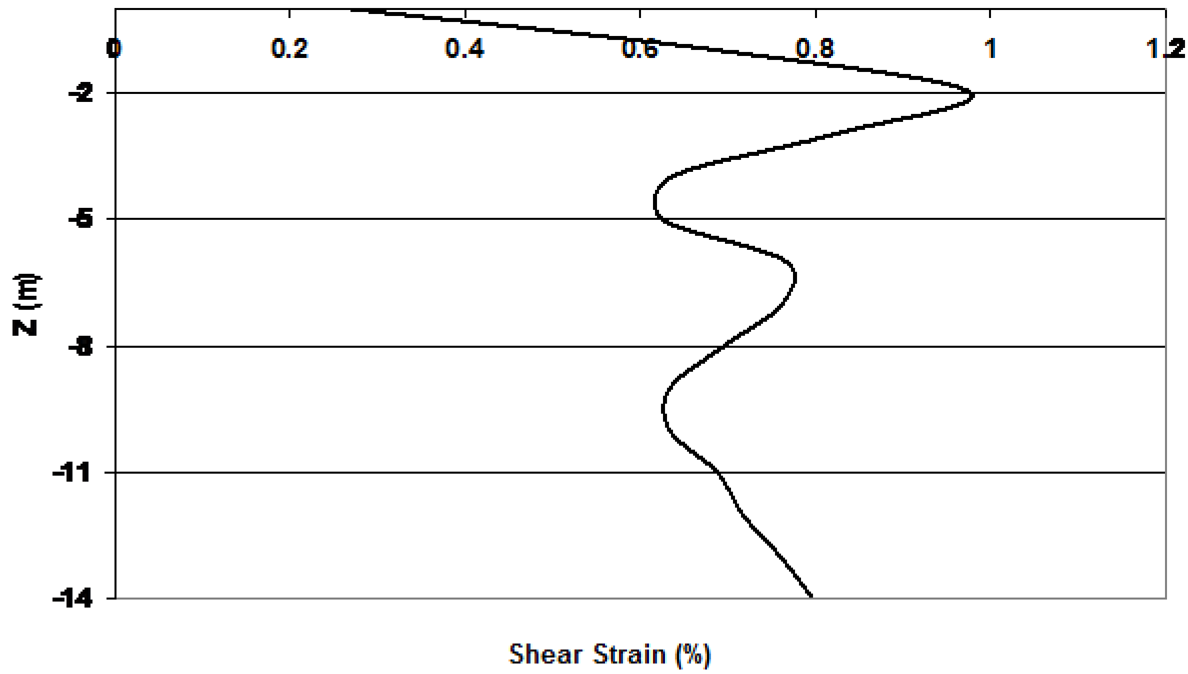

Figure 7: Maximum Shear Strain – free field motion

3.2 Soil Foundation Structure

The presence of the superstructure affects the dynamic amplification of the soil. Figure 8 presents this influence for non linear soil behavior. It can be observed an increase in the amplification that reaches a maximum value of 15% at the foundation vicinity. Figure 9 shows a comparison of the response spectra of the free field ground velocity and that obtained at the top of the structure. Oppositely to the free field response where several peaks appear at different frequency range, the structure response shows only a unique peak at 1.6 Hz which also appear in the loading spectrum. The structure is filtering the seismic response at its fundamental frequency.

Table 1 summarizes the influence of the constitutive soil model (linear/non linear) on the seismic response of the soil foundation structure. It reveals a significant reduction of the dynamic amplification in case of non linear soil model. This reduction reaches about 50 to 60 percent for the structure, the foundation and the free field ground movement (points A, B and C respectively in Figure 1). The decrease in the dynamic amplification induces a decrease of 50% in the seismic induced internal forces in the structure (bending moment and shear force).

Table 1: influence of the constitutive soil model on the seismic response of the soil-foundation-structure system

Model	**Velocity (m/s)**			**Internal forces**		
	Free Field (C)	**Foundation (B)**	**Structure (A)**	**M (kN.m)**	**N (kN)**	**T (kN)**
Non linear	0.337	0.395	0.716	238	222	160
Linear	0.892	1.012	1.45	430	216	291

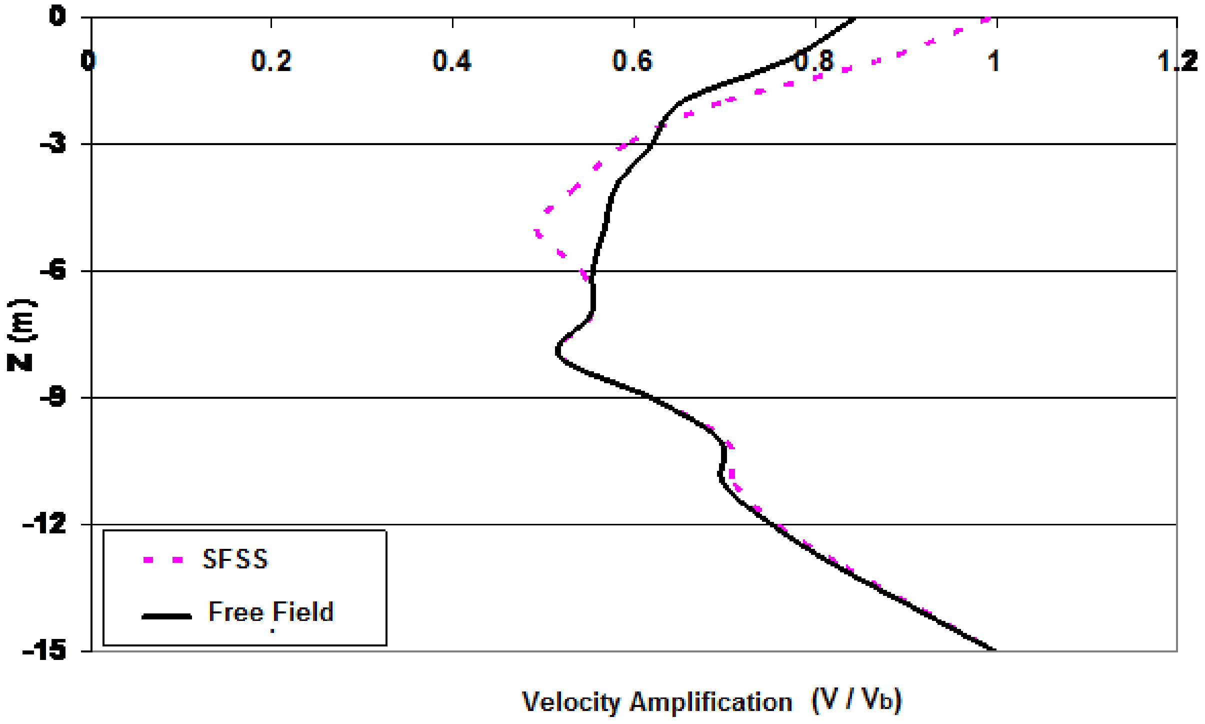

Figure 8: Influence of the presence of the structure on the dynamic amplification – non linear model

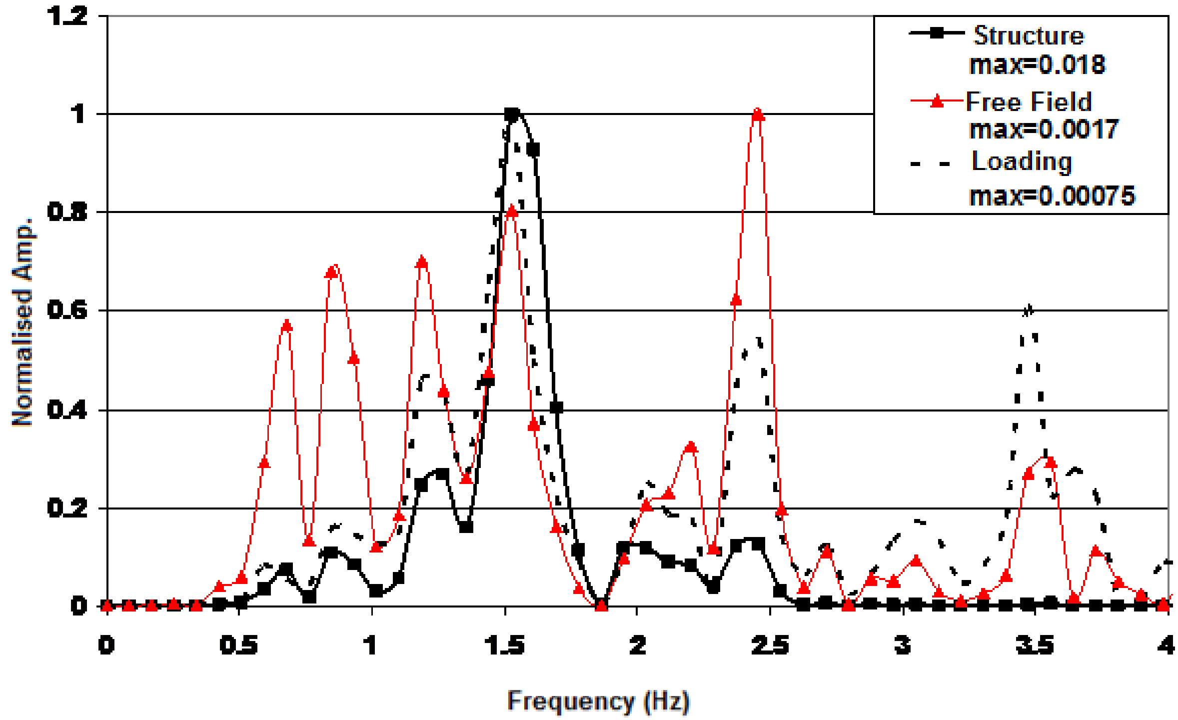

Figure 9: Response spectra (Loading/structure/Free field) – non linear model

4. CONCLUSION

This paper presented a numerical study about the influence of the constitutive soil model on the seismic response of the soil-foundation-structure system for building structures. The analysis was carried out using full 3D global dynamic analysis. Numerical simulations show that the soil-foundation structure interaction is a complex problem that involves several parameters particularly the frequency content of the seismic motion and resonant frequencies of the soil and the structure. The non linear soil behavior adds a level of complexity to the problem where the lateral ground movement could be amplified at different frequency levels. The influence of these frequencies is not important if they are far from the frequency content of the loading since the structure is filtering the seismic response at its fundamental frequency. The soil non linearity should be included in the assessment of the soil-foundation-structure response for moderate and large amplitude seismic motion since it leads to a significant reduction in the seismic induced response of the soil and the superstructure.

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