Influence of stiffness contrast in non-horizontally layered ground on site effects

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15 WCEE
LISBOA 2012

SUMMARY:
The aim of this study is to analyse the influence of the interface slope and stiffness contrast between layers on the seismic response of the soil. To perform this analysis, the finite element code SAP2000 was used to extract the vibration modes in the linear elastic range, while the FLUSH code was used to evaluate the influence of the non-linear response of the soil. Two types of bi-dimensional models were studied: horizontal stratification and dipping interface between layers, considering different combinations of soil properties and dip of the interface. The soil response was analysed in terms of amplification factors and transfer functions. The results demonstrate that soils with the non-horizontal stratification present higher amplification factors. It was also verified the decrease of resonance frequencies and amplification factors with increasing input motion amplitude.

Keywords: Stiffness contrast; non-horizontal interface; site effects; numerical modelling.

1. INTRODUCTION

The earthquake-induced ground motion depends on the intensity, distance and fault of the earthquake. It is well known that for a given earthquake event, the shaking at sites located at the same distance to the fault, can present large variability as result of different local conditions, known as site effects.

The site effect, induced by topography geological structure and/or ground properties, can change significantly the frequency content, the amplitude and the duration of the ground motion.

Usually, the seismic site response admits the soil is horizontally stratified, for example when seismic response is evaluated considering the vertical propagating shear waves.

The hypothesis of horizontally layered ground is mainly adequate for recent sedimentary soil deposits, however, there are many cases in which the interface between layers may have small slope or there is a paleotopography that controls the geologic structure, as for instance a river valley.

This work studies the influence of stiffness contrast between layers, relative thickness of the layers and of the slope of the interface between different geological materials on the seismic response of the ground. The analysis compares the response of two bi-dimensional models: one with horizontal and the other non-horizontal stratification. Two finite element programs were used: SAP2000 (Computers and Structures, 1998) and FLUSH (Lysmer *et al*., 1975). The vibration modes were extracted and transfer functions and amplification ratio were computed.

The results suggest that soils with non-horizontal interface are associated to higher amplification factors.

2. NUMERICAL MODELLING

2.1. Method of analysis

The dynamic properties of the soil are strongly dependent on the level of deformation induced by the seismic motion. For small levels of deformation, such as in seismic methods, soils exhibit linear elastic behaviour, however for higher levels of distortion the response is nonlinear and dependent of the number of loading cycles.

In this study two finite element codes were used: SAP2000 (Computers and Structures, 2009) and FLUSH (Lysmer *et al*., 1975). The modal analysis was used to study the mode shapes of the layered ground in the linear range with SAP2000 code. The linear equivalent method was used in FLUSH code to take into account the nonlinear behaviour of the soil in the ground response. This method applies an iterative process to obtain compatible dynamic soil properties (shear modulus and damping ratio) with the induced level of distortion. However, the equivalent linear method is used to simulate the seismic response of the soil for small to medium levels of deformation, because is not able take into account the effect of the number of cycles of loading. This method uses the stiffness and damping strain-dependent curves. In this work, the unified equations proposed by Ishibashi and Zhang (1993) were adopted for plasticity index PI=50, to minimize the influence of the effective confining pressure on the shear modulus reduction and material damping ratio curves.

The seismic loading was introduced using a pulse, which correspond to constant Fourier amplitude in frequency-domain, to equally excite all the frequencies. The seismic loading was introduced for three levels of peak acceleration, 0.1g, 0.5g and 1.0g, to evaluate their effect on the seismic response.

2.2. Models

Two model types were defined (Figure 2.1) to study the influence of the thickness of the layers (h), the stiffness contrast (Vs_1/Vs_2) and inclination of the interface between strata (i) on the seismic response of the soil. Model type 1 has horizontal interface, while model type 2 has non-horizontal interface. The models have 60m in length by 40m in height.

Each model has two layers, soil 1 is the top layer and the soil 2 is the bottom layer. The initial damping ratio of both soils corresponds to 2%. The characteristics of the analysed models are presented in Table 2.1 and Table 2.2.

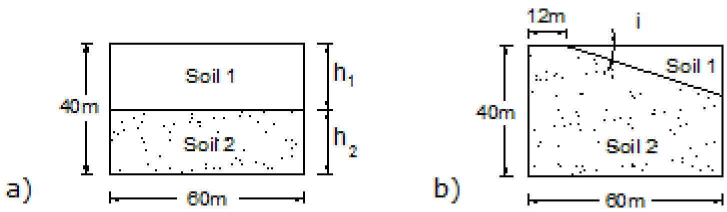


Figure 2.1. Models: a) Model type 1 – horizontal interface, b) Model type 2 – non-horizontal interface**.**

Table 2.1. Characteristics of Models Type 1.

Model	Soil 1						Soil 2						Vs_1/Vs_2
	h_1 [m]	γ_1 [KN/m^3]	ν	Vs_1 [m/s]	$E_{0,1}$ [KPa]	$G_{0,1}$ [KPa]	h_2 [m]	γ_2 [KN/m^3]	ν	Vs_2 [m/s]	$E_{0,2}$ [KPa]	$G_{0,2}$ [KPa]	
1.1.1	10	18	0.4	100	51429	18367	30	19	0.4	50	13571	4847	2
1.1.2	10	18	0.4	100	51429	18367	30	19	0.4	1000	5428571	1938776	0.1
1.2.1	30	18	0.4	100	51429	18367	10	19	0.4	50	13571	4847	2
1.2.2	30	18	0.4	100	51429	18367	10	19	0.4	1000	5428571	1938776	0.1

Table 2.2. Characteristics of Models Type 2.

Model	Soil 1						Soil 2					Vs_1/Vs_2
	i [°]	γ_1 [KN/m^3]	ν	Vs_1 [m/s]	$E_{0,1}$ [KPa]	$G_{0,1}$ [KPa]	γ_2 [KN/m^3]	ν	Vs_2 [m/s]	$E_{0,2}$ [KPa]	$G_{0,2}$ [KPa]	
2.1.1	5	18	0.4	100	51429	18367	19	0.4	50	13571	4847	2
2.1.2	5	18	0.4	100	51429	18367	19	0.4	1000	5428571	1938776	0.1
2.2.1	15	18	0.4	100	51429	18367	19	0.4	50	13571	4847	2
2.2.2	15	18	0.4	100	51429	18367	19	0.4	1000	5428571	1938776	0.1

2.3. Finite element mesh

The two-dimensional finite element models are in plain-strain conditions. The vertical displacement of the nodes is restrained, and the bottom nodes have all degrees of freedom restrained.

The accuracy of the results obtained by the finite element method depends on the dimensions of the elements in the direction of wave propagation. To avoid the artificial loss of the high frequencies, Kuhlmeyer and Lysmer (1973) recommended a minimum size for the elements, which corresponds to about 1/8 of the minimum wavelength. The elements in the direction of wave propagation are 1.5m high, ensuring the accurate representation of at least 4 vibration modes in models with $V_{s,min}$ = 50m/s and 2 vibrations modes in models with $V_{s,min}$ = 100m/s.

2.4. Model calibration

The validation of a uniform layer of soil laid on rigid bedrock (the soil properties are γ_1=18 KN/m^3, ν = 0.4 and V_s= 100m/s) was done in the linear elastic range.

The model response was compared with the vertically propagating shear waves in elastic damped layer, in terms of transfer function.

As expected, both transfer functions match perfectly (Figure 2.2).

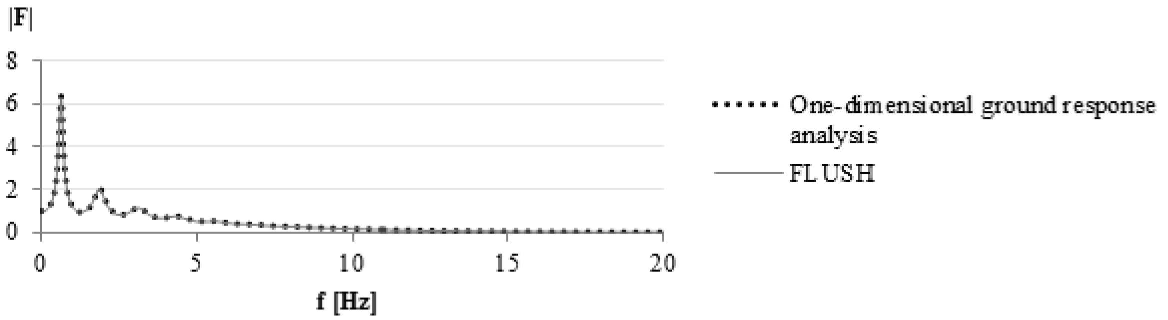


Figure 2.2. Transfer functions: model response (FLUSH) vs. vertically propagating shear waves in elastic damped layer.

3. DISCUSSIONS OF THE RESULTS

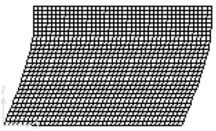
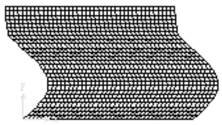
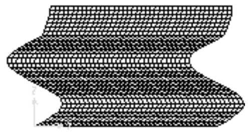
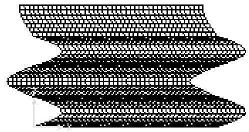
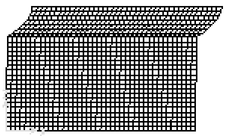
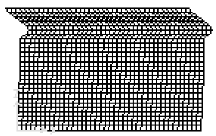
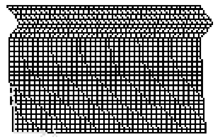
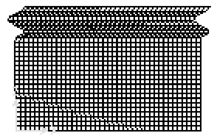
3.1. Modal analysis

The modes shapes extracted using SAP2000 modal analysis and with physical meaning are presented and discussed.

3.1.1. Model 1

The modes shapes extracted are presented in Table 3.1. Because the soft layer has lower fundamental frequencies than the stiff layer, it exhibits mode shapes of higher order. For example, the 4th mode shown in Table 3.1, is the 4th mode for the soft layer, but just the 1st or 2nd for the stiff layer.

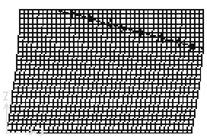
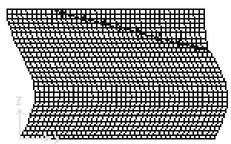
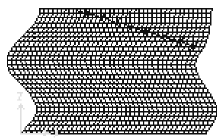
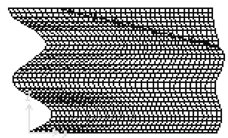
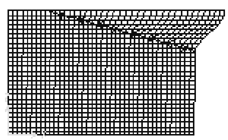
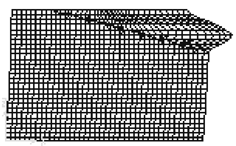
Table 3.1. Vibration modes of model 1.1.1 and 1.1.2 (h_1=10m).

Vs_1/Vs_2	1st mode	2nd mode	3rd mode	4th mode
2 (Model 1.1.1)	 f_1 = 0.32 Hz	 f_2 = 1.00 Hz	 f_3 = 1.73 Hz	 f_4 = 2.47 Hz
0.1 (Model 1.1.2)	 f_1 = 2.42 Hz	 f_2 = 6.89 Hz	 f_3 = 8.70 Hz	 f_4 = 11.99 Hz

3.1.2. Model 2

Model 2 has two layers with the interface inclined 5º or 15º. Table 3.2 present the vibration modes associated to both studied stiffness contrast combinations. In the case Vs_1/Vs_2= 0.1, only two vibration modes were determined, as a consequence of the used size of the elements. The soft layer controls the response of the model, as it mainly controls the deformed shape.

Table 3.2. Vibration modes of models 2.2.1 and 2.2.2 (i=15°).

Vs_1/Vs_2	1st mode	2nd mode	3rd mode	4th mode
2 (Model 2.2.1)	 f_1 = 0.32 Hz	 f_2 = 0.97 Hz	 f_3 = 1.64 Hz	 f_4 = 2.28 Hz
0.1 (Model 2.2.2)	 f_1 = 3.14 Hz	 f_2 = 6.76 Hz	-	-

3.2. Equivalent Linear Method

The results obtained with the linear equivalent method are analysed in terms of frequencies, amplification factors, defined as ratio between peak acceleration at the surface and at the base, and transfer functions between the bottom and the top of the model.

3.2.1. Model 1

Model 1 corresponds to the horizontally stratified soil. In this case, the highest amplification factors were, in general, associated to the models with thicker stiff layer (Figure 3.1). This tendency is more clear in models with increasing stiffness with depth (Vs_1/Vs_2= 0.1), which have also higher stiffness contrast than Vs_1/Vs_2= 2.

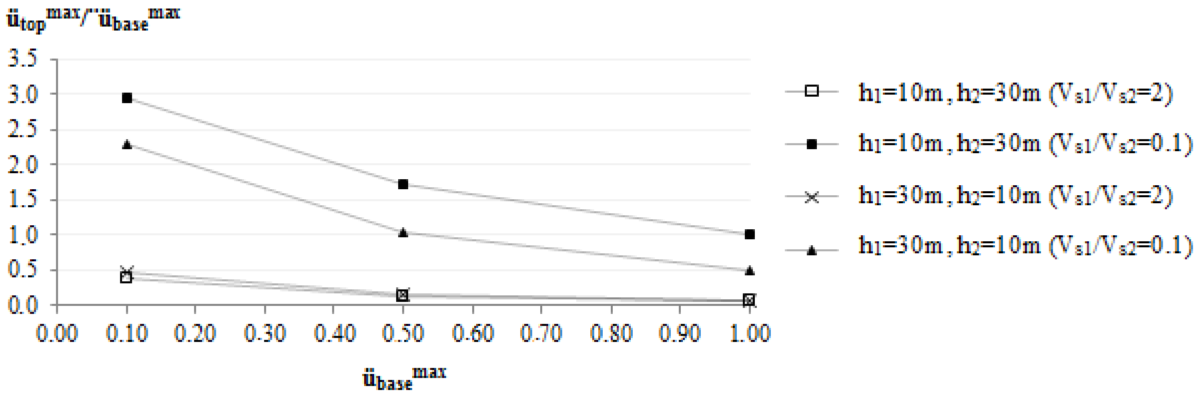


Figure 3.1. Amplification factors of model 1.

The results obtained with the models for Vs_1/Vs_2= 2 were relatively insensitive to the variation of the thickness of the layers, as result of the filtering effect of the softer (lower) layer. In this case, the amplitude of the surface motion was always lower than the input motion (attenuation).

The results obtained for the cases with Vs_1/Vs_2= 0.1 indicate that soils with increasing stiffness with depth and higher stiffness contrasts are associated to higher amplification factors.

Figure 3.2 presents the transfer functions of the models with the same relation h_1/h_2 for different stiffness contrast. The effects of the non-linear behaviour of the soil are visible in Figure 3.2. The amplitude and the resonant frequencies decrease with the intensity of input motion, due to the increase in damping and reduction of the shear modulus of the soil. According to one-dimensional wave propagation models (Kramer, 1996), the fundamental frequency of the soil, in the linear elastic regime, is given by $V_s/4H$, where H is the thickness of the layer and V_s the shear wave velocity of the soil. Applying this expression, it's possible to verify that for the case with Vs_1/Vs_2=0.1, the first and the third resonant frequencies are associated to the fundamental frequencies of the soft (2.5 Hz) and stiff soil layers (8.4Hz), thus the decrease of the peak amplitude with increasing order of the frequency does not occur. This is also verified for the model with Vs_1/Vs_2=2, with frequencies of 0.4 Hz (soft soil layer) and 2.5Hz (stiff soil layer), however in this case the higher peak amplitude was obtained for the fundamental frequency.

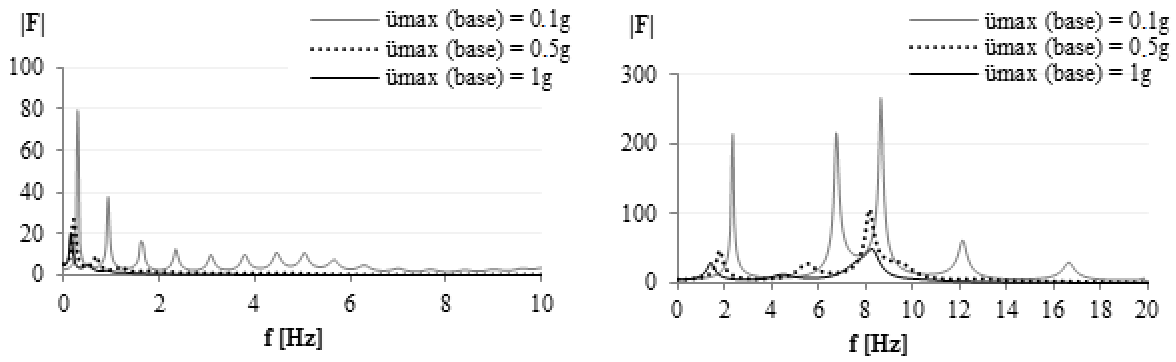


Figure 3.2. Transfer functions obtained with models with h_1= 10m and h_2=30m, for Vs_1/Vs_2=2 (left) and Vs_1/Vs_2=0.1 (right).

3.2.2. Model 2

The amplification factors obtained in models with inclined interface between layers, for $Vs_1/Vs_2=2$ and $Vs_1/Vs_2=0.1$, are presented in Figure 3.3 and Figure 3.4, respectively.

As in the previous case, when the bottom layer is softer ($Vs_1/Vs_2=2$), it acts as a filter of the seismic waves, because the results are relatively insensitive to the variation of the thickness and to the inclination of the interface between layers.

The amplification factors obtained when stiffness grows with depth ($Vs_1/Vs_2=0.1$ - Figure 3.4) are considerably higher than for the case $Vs_1/Vs_2=2$, especially for the input motion with the lowest amplitude (0.1g). This is because the response occurs mainly in linear elastic range and with very low damping coefficient.

Comparing the results of the models with i=5º and i=15º, it is possible to verify that, in general, the higher inclination of the interface between layers is associated to lower amplification factors. In this case, the soil is subjected to higher levels of distortion and consequently, to a more pronounced variation in dynamic soil properties (decrease of stiffness and increase of damping ratio).

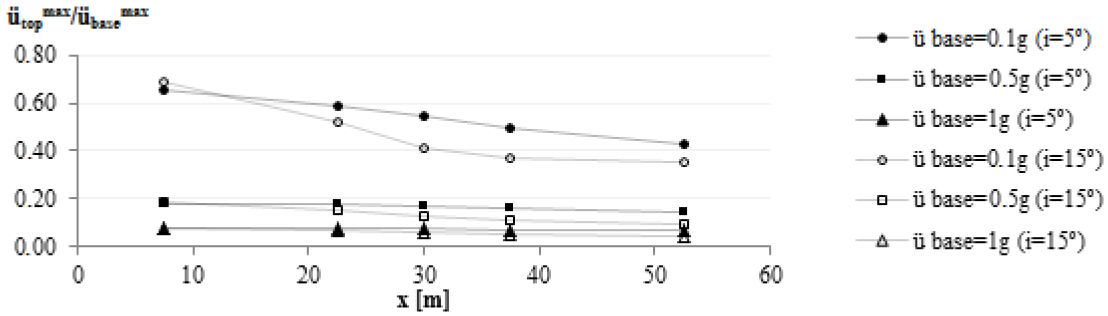


Figure 3.3. Amplification factors of model 2 - $Vs_1/Vs_2=2$.

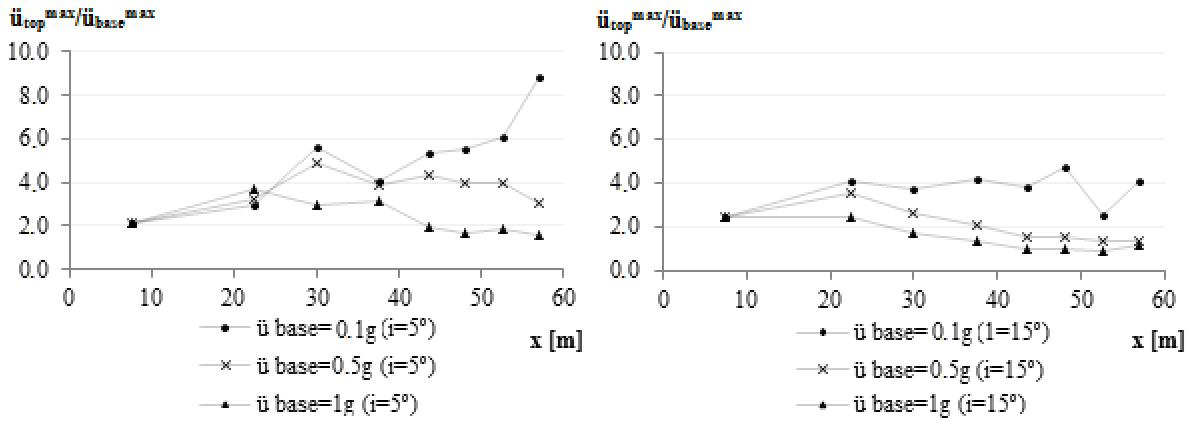


Figure 3.4. Amplification factors of model 2 - $Vs_1/Vs_2=0.1$.

Figure 3.5 shows the transfer functions obtained with the model 2.1.1 (i=5º and $Vs_1/Vs_2=2$), at points located on the surface of the soft soil (1^{st} point - x = 7.5m of Figure 3.3) and stiff soil (5^{th} point - x = 52.5m of Figure 3.3). Both cases have the same first resonant frequency, however the amplification associated to the higher frequencies, at the 5^{th} point, is attenuated.

The results obtained with models type 2, with inclined interface between layers, indicate that, in general, soils with non-horizontal stratification are associated to higher amplification factors. It was also verified the reduction of the amplification factors with increasing input motion, as a result of the variation of the dynamic properties of the soil.

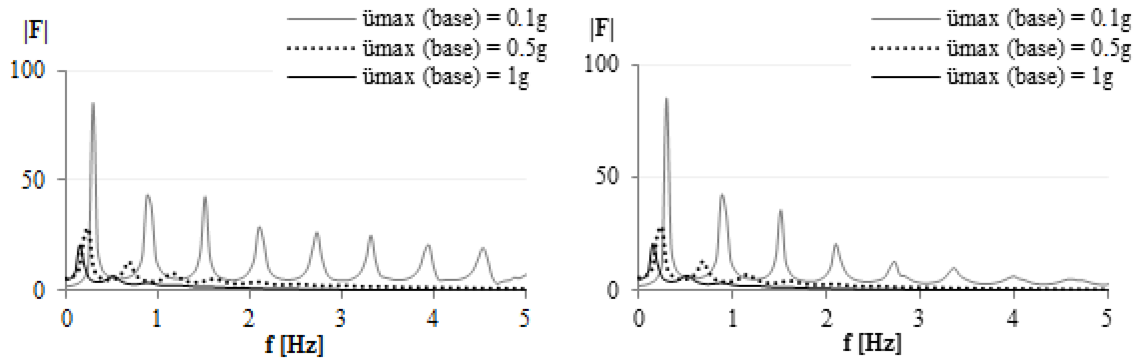


Figure 3.5. Amplification factors of model 2.1.1(i=5º and Vs_1/Vs_2=0.1), located at 7.5 m distance (1st point; left) and at 52.5 m (5th point; right). See Fig. 3.7 for location of the points.

3.3. Comparison between models

To evaluate the influence of the inclination of the interface between layers, three models with the same stiffness contrast were compared: i) horizontal stratification (h_1=3m; h_2=37m), (ii) i=5º and (iii) i=15º. The control point was chosen to compare the response, because it is over the same thickness of the layers in all models: h_1=3m; h_2=37m (Figure 3.6).

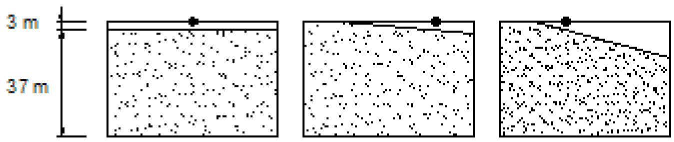


Figure 3.6. Position of the control point.

Figure 3.7 presents the amplification factors obtained with the horizontal (i=0º) and non-horizontal stratification (i>0º) models. In both cases, the amplification is higher for soils with inclined interface. The case V_{s1}/V_{s2}=0.1 amplifies more for i=5º than for i=15º, while the opposite occurs for V_{s1}/V_{s2}=2, thus the filtering effect of the softer layer plays an important role. The amplification factors decrease with increasing input motion, as a result of the non-linear behaviour of the soil.

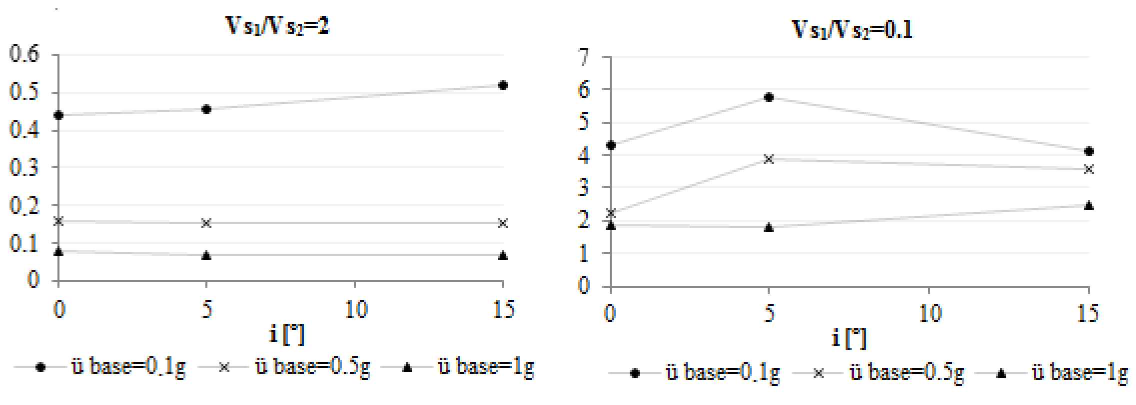


Figure 3.7. Amplification factors dependence on the inclination of the interface, i.

Analysing the fundamental modes of vibration of models 2.1.2 (i=5º, V_{s1}/V_{s2}=0.1) and 2.2.2 (i=15º, V_{s1}/V_{s2}=0.1) (Figure 3.8), it can be noticed that the relative position of the control point changes from one model to the other. The vicinity of the lateral boundaries may justify the decrease in the amplification observed.

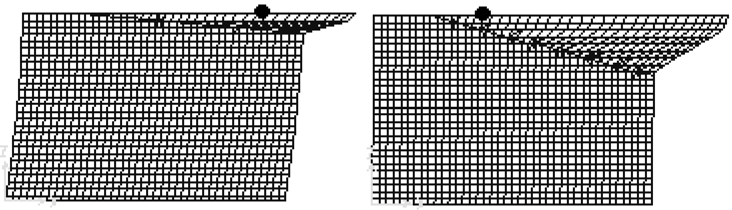


Figure 3.8. Fundamental modes of vibration of models 2.1.2 (i=5º) and 2.2.2 (i=15º) and position of the control point.

Figure 3.9 and Table 3.3 present the transfer functions and dynamic soil properties associated to the control point, at the surface of soil 2 (h_1=3m and h_2=37m). It was verified the reduction of the fundamental frequency of the soil with increasing input motion, due to the reduction of the shear modulus and increase in damping.

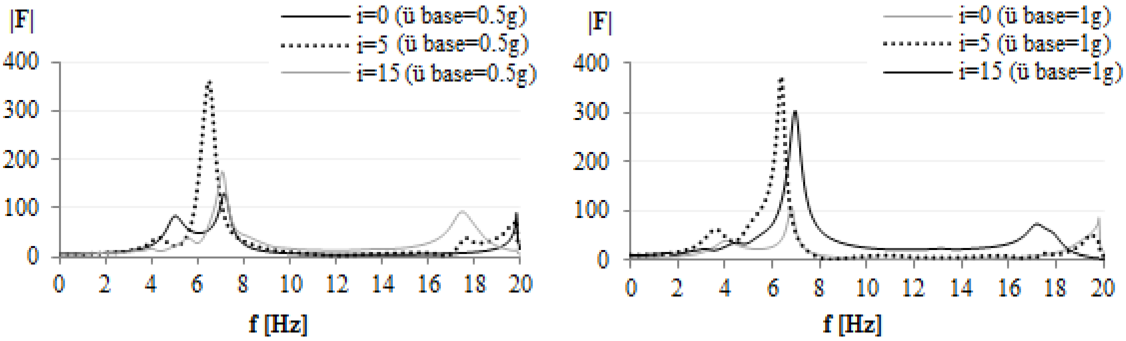


Figure 3.9. Transfer functions associated to the control point (h_1=3m and h_2=37m) for Vs_1/Vs_2=0.1.

In general, the higher amplification of the input motion is associated to the fundamental frequency. However, in this case, the higher amplification was obtained in the second resonant frequency.

It should be noticed that, if both layers were independent, the fundamental frequency of layers 1 and 2 would correspond to 8.3Hz and 6.7Hz, respectively, according to the expression presented in 3.2.1 (one-dimensional wave propagation models). In Figure 3.9 these two frequencies are the 1st and 2nd resonant frequencies of the system, which are slightly smaller than the frequencies computed in the linear elastic range, due to the variation of the dynamic properties of the soil.

Table 3.3. Dynamic soil properties obtained from the equivalent linear method.

	Vs_1/Vs_2 = 0.1						Vs_1/Vs_2 = 2					
$ü_b^{max}$ [g]	0,1						0,1					
Soil	1			2			1			2		
i [º]	0	5	15	0	5	15	0	5	15	0	5	15
G/G_0 [%]	90.2	90.3	92.9	100.0	100.0	100.0	100.0	100.0	100.0	90.8	90.6	92.3
ξ [%]	1.7	1.6	1.4	0.7	0.7	0.7	0.7	0.7	0.7	1.6	1.7	1.4
$ü_b^{max}$ [g]	0,5						0,5					
Soil	1			2			1			2		
i [º]	0	5	15	0	5	15	0	5	15	0	5	15
G/G_0 [%]	58.3	44.9	50.7	100.0	100.0	100.0	100.0	100.0	100.0	54.3	54.9	55.5
ξ [%]	6.5	8.6	7.5	0.7	0.7	0.7	0.7	0.7	0.7	6.8	6.8	6.7
$ü_b^{max}$ [g]	1,0						1,0					
Soil	1			2			1			2		
i [º]	0	5	15	0	5	15	0	5	15	0	5	15
G/G_0 [%]	44.7	34.0	29.3	97.9	97.9	98.0	100.0	100.0	100.0	34.3	35.5	37.2
ξ [%]	9.0	11.2	11.8	0.9	0.9	0.8	0.7	0.7	0.7	10.8	10.6	10.5

Figure 3.10 shows maximum shear strain profiles of the models, for both stiffness contrast combinations. The profiles associated to $Vs_1/Vs_2=2$ are relatively insensitive to the variation of the inclination of the layers, due to the filtration effect of the waves in the softer soil. The maximum shear strain of the models with $Vs_1/Vs_2=0.1$ was obtained for the lowest inclination of the interface between layers (i=5º).

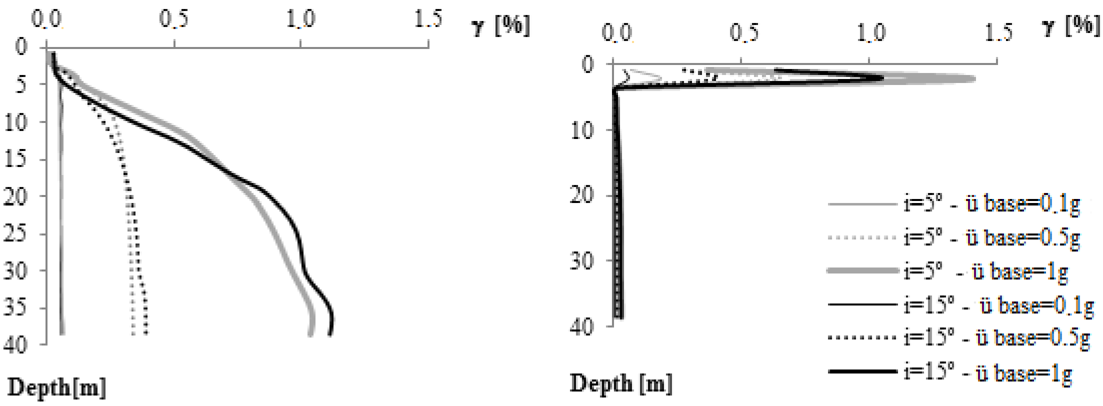


Figure 3.10. Strain profiles of the models with $Vs_1/Vs_2=2$ (left) and $Vs_1/Vs_2=0.1$ (right) ($h_1=3m$ and $h_2=37m$).

Table 3.3 and Figure 3.10 shows that the models subjected to higher levels of deformation are associated to higher losses of stiffness and higher damping. It's important to remember that, in this program, the compatibility between the deformation and soil properties is made for each element.

4. CONCLUSIONS

Generally, local site effects studies assume that the ground is horizontally layered. However, the response is sensitive to the slope of the interface between layers, indicating that this modelling hypothesis is not always valid.

It was shown that soils with non-horizontal stratification and higher stiffness contrasts are usually associated to higher amplification factors. It was also verified that the studied case with lower softer layers, are relatively insensitive to the variation of the studied parameters, essentially due to the filtering effect of the waves in the softer soil. As a result of the nonlinear behaviour of the soil, it was observed the reduction of the amplification factors and resonant frequencies with increasing input motion.

To consolidate the tendencies found in this study, other combinations of stiffness contrasts, thickness and inclination of the interface between strata should be tested, along with the influence of the boundary conditions.

REFERENCES

Beresnev, I.A. and Wen, I.A. (December 1996). Nonlinear Soil Response - A Reality?. *Bulletin of the Seismological Society of America*, **Vol. 86**, No.6, 1964-1978.

Computers and Structures, Inc. (2009). SAP2000 – Integrated Finite Element Analysis and Design of Structures. Version 14, Analysis Reference Manual. CSI, Berkeley, California.

Ishibashi, I. and Zhang, X. (1993). Unified dynamic shear moduli and damping ratios of sand and clay. *Soil and Foundations*, **Vol. 33**, nº 1, 182-191.

Ishihara, K. (1996). Soil Behavior in Earthquake Geotechnics. Oxford Engineering Science Series. Oxford Engineering Science Series: Oxford University Press.

Kramer, S. L. (1996). Geotechnical Earthquake Engineering. Upper Saddle River, New Jersey, USA: Prentice Hall, Inc.

Kuhlemeyer, R. L. and Lysmer, J. (1973). Finit Element Method Accuracy for Wave Propagation Problems. *Journal of the Soil Mechanics and Foundations Division*, ASCE, **Vol. 99**, No. SM5, pp. 41-427.

Lysmer, J., Udaka, J. and Tsai, C-F., Seed, H.B. (1975). FLUSH: a computer program for approximate 3-D analysis for soil-structure interaction problem. UCB/EERC - 75/330, Earthquake Engineering Research Center, University of California, Berkeley.

Seed, H.B., Murarka, R., Lysmer, J. and Idriss, I.M. (1976). Site-dependent spectra for earthquake-resistant design. *Bulletin of the Seismological Society of America*, **Vol. 66**, 221-243.