1. INTRODUCTION

This paper is based on a dissertation in the field of seismic analysis (Teixeira, 2010), namely of the seismic analysis of bridges. It was intended to evaluate the response of the structure taking into account the interaction with the soil and compare it with simplified analysis. These simplified analysis can be preformed through the analysis of the structure and foundation, without the consideration of the soil column, or through analysing the structure with a rigid base, ie not taking into acount any effects of the soil. It was also intended to evaluate the differences between carrying out a seismic analysis where the specific properties of the foundation soil are taken into account and a analysis based on the spectra defined in the Eurocode 8 (EC8) for the different types of soil.

To achieve the objectives it was necessary to evaluate the different ways to take into account the damping, to assess the importance of certain factors on the seismic analysis of structures, to compare the spectra of the EC8 with the spectra obtained for specific soil columns and finally to compare the seismic analysis results obtained based on different models.

2. THEORETICAL ELEMENTS

2.1. CALIBRATING THE DAMPING MATRIX

There are different ways to take into account the damping. In the following the Rayleigh damping, the Extendend Rayleigh damping or the Non-Proportional damping will be briefly presented.

- **Rayleigh Damping**

The damping matrix can be obtained through a linear combination of the mass matrix with the stiffness matrix, which leads to a modal damping matrix. The damping coefficient, ξ, of mode i is given by the equation 1 b) (Clough & Penzien, 2003), where α and β are parameters that should be defined as a function of the intended damping.

$$C = \alpha\, M + \beta\, K; \qquad \xi_i = \frac{1}{2}\left(\frac{\alpha}{p_i} + \beta\, p_i\right). \qquad \textbf{(1) a) b)}$$

This method only enables to exactly calibrate the damping of two frequencies. Using the method of least squares, and accepting that the calibration is only approximate, is possible to increase the number of frequencies for which the damping is being controlled.

- **Extended Rayleigh Damping**

For the extended Rayleigh damping the damping matrix is obtained according to equation 2 a) and the damping of the mode is given by the equation 2 b) (Clough & Penzien, 2003)

$$\boldsymbol{C} = M \sum_b a_b\, [\, M^{-1}\, K\,]^b\,; \qquad \xi_n = \frac{1}{2p_n} \sum_b a_b\, p_n^{2b}. \qquad \textbf{(2) a) b)}$$

These damping matrix also presents the orthogonality conditions and enables to control the damping coefficient for the number of frequencies desired. The coefficients a_b are determined by solving a system of equations involving the damping and frequency for the modes which the damping is intended to be calibrated.

- **Non-Proporcional Damping**

When a system is composed by various materials the damping matrix can be found by assigning different damping values to each part of the structure. When the non-proportional damping is adopted the the orthogonality conditions are not fulfilled and a modal analysis can not be adopted. In the case of a system composed by the soil and by the structure, the damping matrices are given by the equations 3 a) and 3 b), where the coefficients α and β are defined in order to calibrate the damping of each part to the desired frequencies. Finally, the damping matrix of the whole soil-structure is obtained by adding the two previous referred matrices (Clough & Penzien, 2003)

$$C_{soil} = \alpha_{soil}\, M_{soil} + \beta_{soil}\, K_{soil}; \qquad C_{str} = \alpha_{str}\, M_{str} + \beta_{str}\, K_{str}; \qquad C = C_{soil} + C_{str} \qquad \textbf{(3) a) b) c)}$$

2.2. MODEL FOR THE SOIL BEHAVIOR

A soil exposed to a seismic action can be modeled, in an approximate way, through a column with only shear deformability. The soil column is modeled through a stack of soil elements only with shear deformation. The shear deformation due to the seismic action leads to a degradation of soil properties that should be taken into account, presenting the soil a nonlinear behavior. However it is possible to use a linear elastic soil model where the properties are such that this model presents a behavior equal to the obtained for the nonlinear analysis for a specific level of deformation. This model is named as equivalent linear model. For a soil with constant properties along the depth and presenting a linear behavior the vibration modes and frequencies are given by (Virtuoso & Mendes, 1994)

$$\phi_k(y) = C\, cos\left[(2k-1)\frac{\pi\, y}{2H}\right]; \qquad f_k = (2k-1)\frac{v_s}{4H}; \qquad \textbf{(4) a) b)}$$

where: G - shear modulus of the soil, ρ - density of the soil; ϕ_k - vibration mode k; f_k - vibration frequency of mode k, y - depth measured from the top of the soil column; the latter equations have to be used with the reduceded properties of the soil related to the level of strain imposed by the seismic action.

2.3. COMPUTER PROGRAM FOR STRUCTURAL ANALYSIS

To obtain the seismic response of structures, considering or not the joint behavior of the soil, it was developed a computer program for structural analysis. This program enables the user to choose the way to consider the damping and the different types of seismic analysis: modal analysis along time, modal response spectrum analysis or step by step along time.

3. ANALYSIS OF RESULTS

In this chapter the results obtained from a seismic analysis of bridges with indirect foundations using the program that was developed are presented. To begin different techniques to calibrate the damping matrix were tested. Then a parametric analysis was done to determine which parameters affect the response of structures and the relative influence of each one. The EC8 response spectra were compared with the spectra obtained for specific columns of soil to understand the differences between using the spectrum of the EC8 and performing a site soil study. Finally the seismic responses obtained for different models were compared.

All the presented analysis were based on artificial accelerograms for the type 1 earthquake and soil A of the Portuguese National Annexe do the EC8 (Guerreiro, 1998). Five signals were generated along time, with a duration of 40 seconds. Although the accelerograms had been generated for the zone 1.3 of the EC8, the conclusions can be generalized to other zones with different seismic intensity. This generalization can be done because the results correspond to the maximum acceleration obtained at the level of the structure in different soil columns based on the reduceded properties, and so the difference for the accelerations that would be obtained in other seismic zones depend only on a scale factor, function of the reference accelerations for each zone.

In all the analysis presented in this chapter, the structure was modeled as an one degree of freedom oscillator because this approximation is valid for the longitudinal analyse of bridges. The rotation at the top of the pile was blocked to simulate the effect of the piles cap. It was considered a range for the soil damping within normal values however for the damping of the structure it was assumed a constant value of 0.05. In the analysis several model types with different complexity levels were considered:

- **Partial model**

The partial model of analysis consists in considering only the structure at the surface and the foundation through the pile and springs, ie the soil column is not modeled. These springs are deemed to simulate the deformation of the surrounding soil, connecting the pile to a fixed base.

- **Global model**

In this model the structure, the pile and the soil column are considered together. As in the partial model, springs are used to simulate the deformability of the soil surrounding the pile but now the springs establish the connection between the pile and the soil column. A global model enable to perform a more rigorous seismic analysis because it has into account the interaction behavior of the structure and the soil.

- **Model of the structure**

The structure model consists in considering a fully fixed support at the base. In the case of this type of model it was carried out a modal analysis with the spectrum of the soil type D of the EC8.

In Figures 1, 2 and 3 a scheme of the previous models is presented.

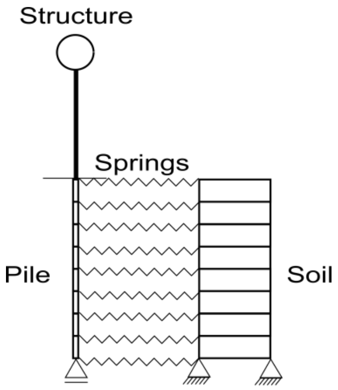


Figure 1 - Partial model

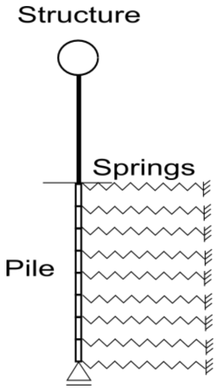


Figure 2 - Global model

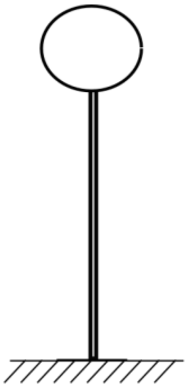


Figure 3 - Model of the structure

- **Relation between the period of the different models**

When considering the structure attached to the pile and the soil, a larger fundamental period is obtained compared to the one in which a rigid connection at the base is assumed, since the connection to the rigid base has now an equivalent deformability due to the foundation and soil. The period of the structure is the one that is obtained when considering a rigid connection at the base and the period of the global model is the one that takes into account the equivalent deformability of the foundation and soil. The relationship between the period of the structure, $T_{structure}$, and the period of the global model, $T_{global\ model}$, is represented by α and is given by

$$\alpha = \frac{T_{structure}}{T_{global\ model}}. \qquad \textbf{(5)}$$

The period of the structure in the partial model (period of the partial model) is almost coincident with the period of the structure in the global model because the deformability of the foundation is dominant over the deformation of the soil. This means that the deformation of the soil column is negligible compared to the deformation of the foundation. Thus if the two models have the same deformability of the foundation, the period of the structure will be almost the same too. This implies that the relationship between the period of the structure and the period of the partial model is approximately expressed by

$$\alpha \cong \frac{T_{\text{structure}}}{T_{partial\ model}}. \quad \textbf{(6)}$$

All the figures presented in following represent the maximum acceleration obtained for the structure according to the period of the structure. When is referred only the word "period" it means the period of the structure.

3.1. CALIBRATION OF THE DAMPING MATRIX

In this section it is presented a comparison between the different ways used to test the calibration of the damping matrix. The global model, already presented, was used to illustrate those differences. The values considered for the period of the structure cover the range of the first two periods of the soil, equal to 1,0 s and 0,33 s. In this example it was assumed a value of 0,5 for the parameter α.

The results obtained with the two types of Rayleigh damping, the modal analysis and the non--proportional damping, are presented in the Figure 4.

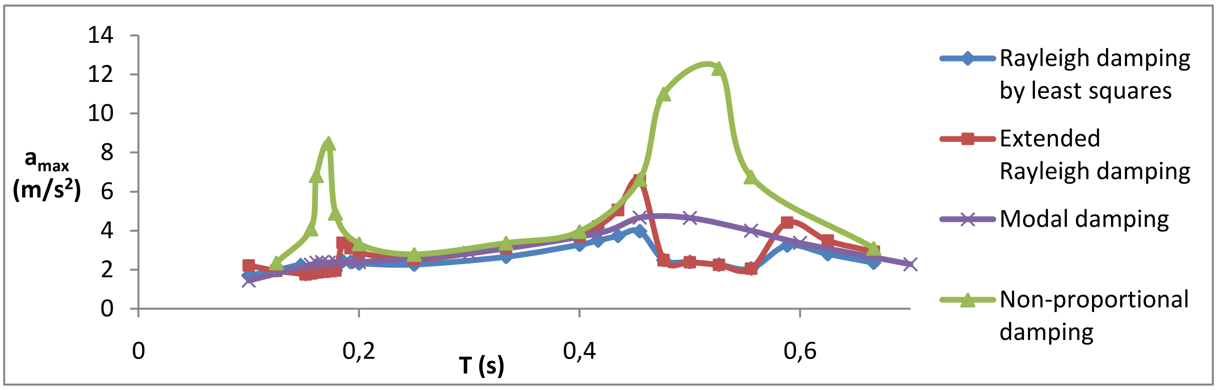


Figure 4 - Comparison between different dampings

From the figure 4 it can be observed that the Rayleigh damping calibrated by least squares leads to approximate values by default; none of the Rayleigh damping or modal analysis allows to solve the problem of resonance. Only the non-proportional damping, which seperates the contribution of the soil and the structure, allows to attribute different damping coefficients for the different parts of the system.

3.2. PARAMETRIC ANALYSIS

The parametric analysis consisted in evaluating the influence of different parameters on the variation of the response of structures with different periods. The global model was again used to perform this parametric analysis. Several examples of soil columns were tested but only one is going to be presented, the one that corresponds to the column with a period of 1,0 s and 0,33 s for the first and second modes of vibration, respectively. The different parameters analyzed and the conclusions achieved are presented in the next paragraphs.

- **Relation betwwen the structure period and the period of the global model**

It is presented in the figures 5 and 6 the relationship between the period of the structure and the period of the global model with the maximum acceleration at the level of the structure.

When the x-axis represents the period of the global model, as it was adopted in figure 6, the response of the oscillators is independent of the parameter α. Thus, it is possible to conclude that the response depends only on the period of the global model. The value of the period of the structure doesn't allow to determine the maximal acceleration if the characteristics of the foundation are not known. From a curve for a particular value of α it is possible to determine any curve for another value of this parameter, relating the periods of the structure with the periods of the global model. In the following of this section it is adopted a value of α equal to 0,5.

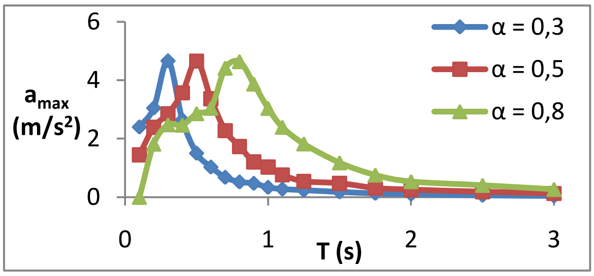


Figure 5 - a_{max} according to the $T_{structure}$

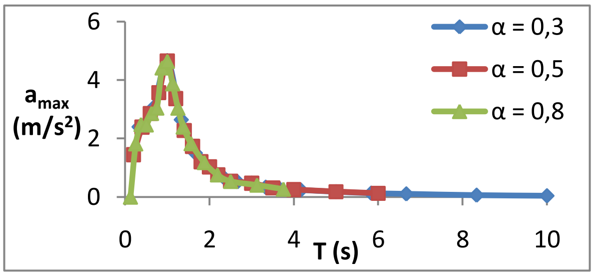


Figure 6 - a_{max} according to the $T_{global\ model}$

- **Damping of the soil**

The damping coefficient of the soil was considered with values between 0,05 and 0,20. It was verified that the lower values of the response in terms of the peak acceleration corresponds to the higher damping. It was also verified that the peak response on the second frequency of the soil column tends to be more attenuated or even disappear with the increase of the damping. Out of the frequencies of the soil column, the response to the different dampings are nearly coincident.

- **Stiffness of the connection soil-pile**

It was compared the response when considering a reaction modulus for the connection between the soil and the pile (k_{spring}) equal to the deformation modulus of the soil and a value four times greater. The consideration of two distinct values for the reaction modulus is related to the fact that the degradation of the soil properties affect the value of the modulus of deformation of the soil, or the shear modulus, but not the value of the modulus of reaction of the soil-pile connection. From the analysis of figures 7 and 8 it is possile to conclude that the response does not depend on the value adopted for the reaction modulus.

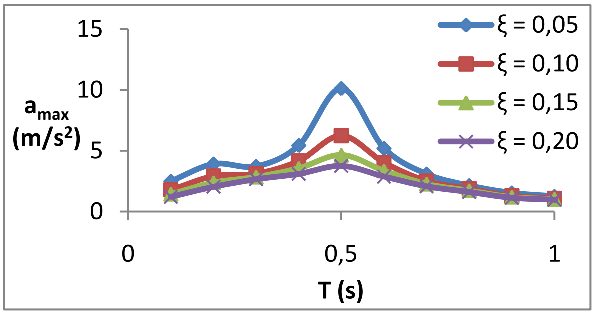


Figure 7 - Effect of the soil damping

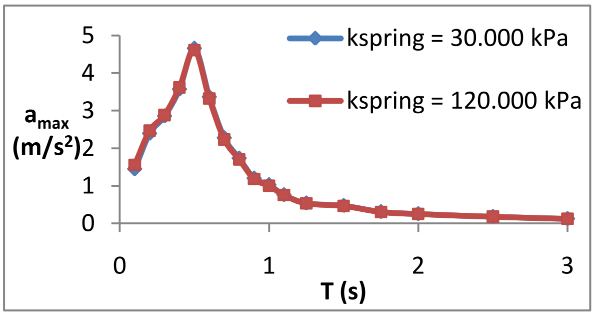


Figure 8 - Effect of the connection stiffness

- **Period of the soil column**

To evaluate the effect of the period of the soil, various examples of soil columns, with different heights and deformability (constant), but with the same period were considered and it was concluded that the responses are almost coincident, ie the effect of the soil depends only of the value of the first period. The conclusion reached was the same when adopting a variable deformation modulus in height. It is presented in the Figure 9 the results of an example of three soil columns. The first column has a constant modulus of deformability and the last two have a variable modulus of deformability in depth, one with a stiffness for the connection soil-pile constant and equal to the average deformation modulus in height and the other with a stiffness variable in height and proportional to the deformation modulus. From the presented results it is possible to conclude that the responses of the various columns are almost coincident, ie the response depends mainly on the period of the soil column, being almost independent of the other mechanical characteristics of the soil. It should be noticed that the soil damping was considered equal for all the examples.

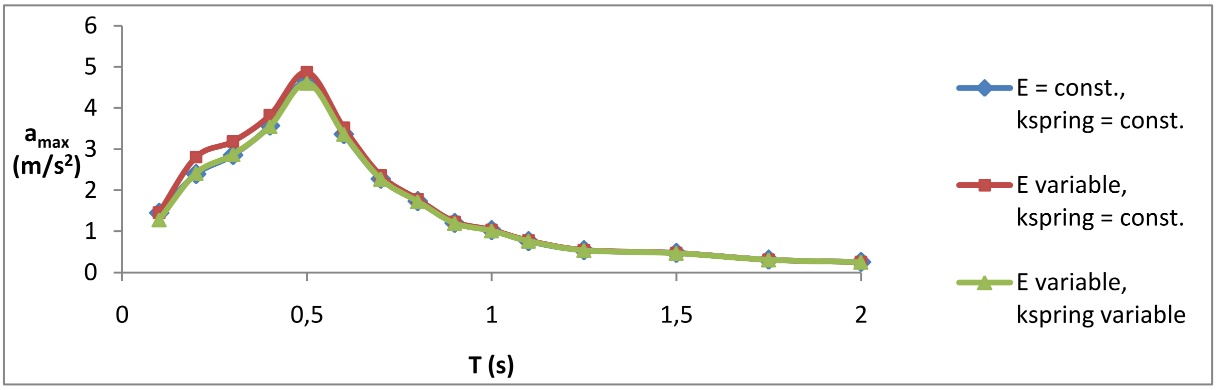


Figure 9 - Effect of the soil frequency

3.3. COMPARISON BETWEEN RESPONSE SPECTRA

According to the EC8 the soil types are classified based on the value of the average mean shear wave velocity, $v_{s,30}$, determined by the equation 7 a) where v_i and h_i represent the velocity of the shear waves (to a distortion equal to or less than 10-5) and the thickness in meters for a total of N layers existing in the first 30 meters. The parameter $v_{s,30}$ takes into account changes of the shear wave velocity along the depth, beeing a weight value in order to represent an average value. This weighting is based on the thickness of the layers and therefore the $v_{s,30}$ takes into account the frequency of the soil ($\boldsymbol{f_s}$). If v_s is constant in depth the $v_{s,30}$ is given by 7 b)

$$v_{s,30} = \frac{30}{\sum_{i=1,N} \frac{h_i}{v_i}} \qquad\qquad v_{s,30} = \frac{30\, v_s}{H} \qquad \textbf{(7) a) b)}$$

The first mode frequency of a soil column with shear deformation is given by equation 8 a). Therefore the value of $v_{s,30}$ results directly proportional to the soil column frequency as presented in 8 b)

$$f_s = \frac{v_s}{4H} \qquad\qquad v_{s,30} = 120\, \boldsymbol{f_s} \qquad \textbf{(8) a) b)}$$

Considering the values of $v_{s,30}$ specified in the EC8 for each soil type and assuming a minimum and a maximum level of degradation of the soil properties for the zone 1.3, correspondent to a ratio G/G_0 = 0,16 and G/G_0 = 0,49 respectively, it is possible to determine the frequency range of the soil columns covered by each soil type. The ranges obtained are presented in Table 1.

Table 1 - Range of frequencies for each type of the EC8 soils

Soil	$v_{s,30}$ **(m/s)**		$\boldsymbol{f_s}$ **(Hz)**	
		$\boldsymbol{G/G_0}$ **= 1,0**	$\boldsymbol{G/G_0}$ **= 0,16**	$\boldsymbol{G/G_0}$ **= 0,49**
B	360	3	1,2	2,1
	800	6,67	2,67	4,67
C	180	1,5	0,6	1,05
	360	3	1,2	2,1
D	80	0,67	0,267	0,467
	180	1,5	0,67	1,05

Thus, there is a range between 1,2 Hz and 4,67 Hz, between 0,6 Hz and 2,1 Hz and between 0,267 Hz and 1,05 Hz for the soil type B, C and D, respectively. The spectra of the EC8 were compared with those obtained for soil columns with specific frequencies within the range for each soil type. Some of these comparisons are presented in figures 10 to 15. In the Figures 10 and 11 the spectrum of the soil B is compared with the spectra obtained for the soil columns with periods (T_s) of 1,0 s and 4,0 s respectively. In the Figures 12 and 13 it is presented the comparison of the spectrum of the soil C with the spectra of the columns with periods of 2,0 s (0,5 Hz) and 0,5 s (2 Hz) respectively. Finally in the Figures 14 and 15 the spectrum of the soil type D is compared with the spectra of the column with frequencies of 3,0 s (0,33 Hz) and 1,0 s (1,0 Hz).

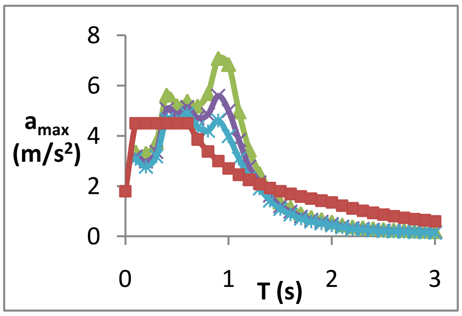


Figure 10 - T_s = 1,0 s - Soil B

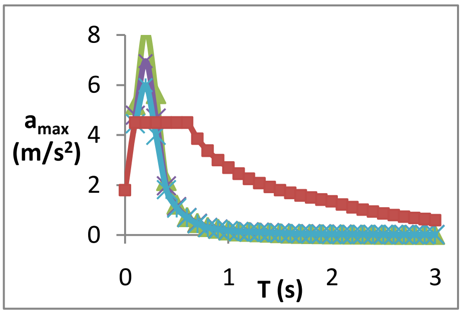
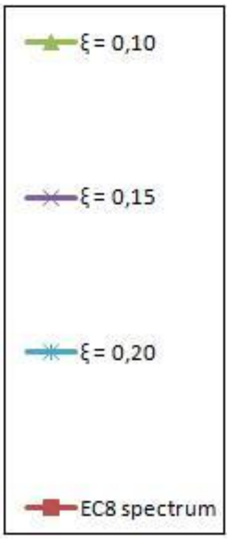


Figure 11 - T_s = 0,25 Hz - Soil B



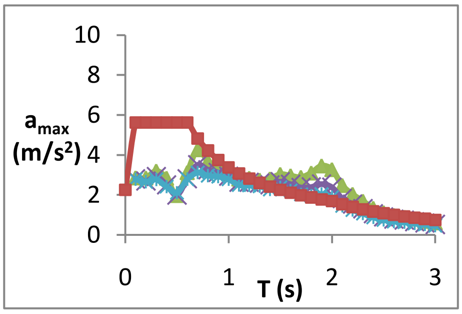


Figure 12 - T_s = 2,0 s - Soil C

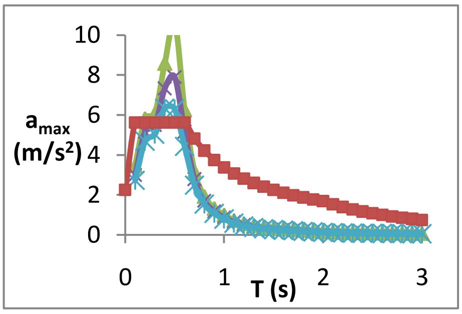


Figure 13 - T_s = 0,5 Hz - Soil C

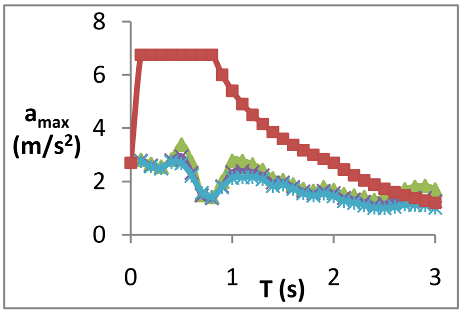


Figure 14 - T_s = 3,0 Hz - Soil D

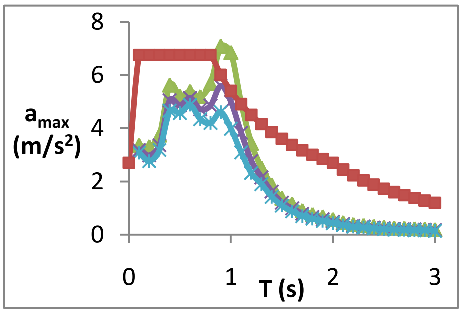


Figure 15 - T_s = 1,0 s - Soil D

When the system is in resonance the spectra of the specific soil columns with different periods shows, for most of the dampings values considered, higher values than the spectra of the EC8. However it must be taken into account that in a real soil the soil does not have a defined period and thus the resonance effects are more attenuated. The overlap between the ranges of period has the effect that the spectra of the EC8 have to be more conservative than it was strictly necessary. This ranges overlap is the result of not taking into account the level of degradation of the soil properties in the classification of the soil types. However, it shows that the classification of the soil can be done based on the inicial properties of soil, ie prior to the seismic action, which avoids complex studies of the degradation of the soil properties.

Based on the comparisons made it was concluded that in many situations an analysis using the local soil spectrum can lead to significantly lower values than those obtained with the spectra of EC8 for the period range common in bridges. For the type B soil a good fit is obtained when the soil columns have a low frequency within the respective range, ie for soils that present low values of $v_{s,30}$ and high levels of properties degradation. For all the other general situations the spectrum of the soil B is quite conservative. The soil type C spectrum is very conservative for soil columns with high frequencies within the respective range, ie for soils with high values of $v_{s,30}$ and low levels of properties degradation. For all other situations the values are well adjusted. Finally, for the soil type D the EC8 spectrum is quite conservative for the extreme cases, ie for the lower and the higher soil column frequencies within the respective range, corresponding to soils with low values of $v_{s,30}$ and high levels of degradation and to soils with high values of $v_{s,30}$ and low degradation levels.

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3.4. COMPARASION BETWEEN ANALYSES WITH DIFFERENT MODELS

The aim of this section is to make a comparison between different models used in the seismic analysis of structures, models that consider the interaction between the structure and the soil, and models in which the soil analysis is done separately from the structure analysis. This comparasion was made for soil columns classified as a EC8 soil type D.

- **Comparasion between partial and global models**

The results obtained with the global and partial model consedering a soil column with a period of 3,0 s (0,33 Hz) and 2,0 s (0,5 Hz) are presented in Figures 16 to 19.

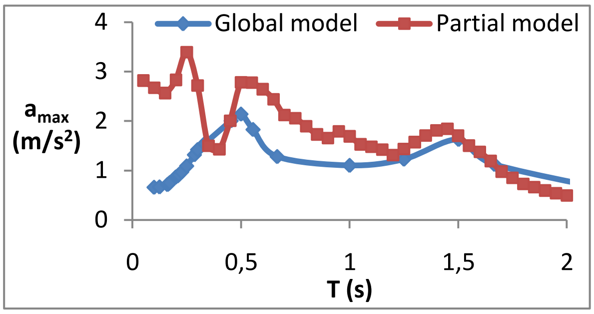


Figure 16 - T_s = 3,0 s e ξ = 0,10

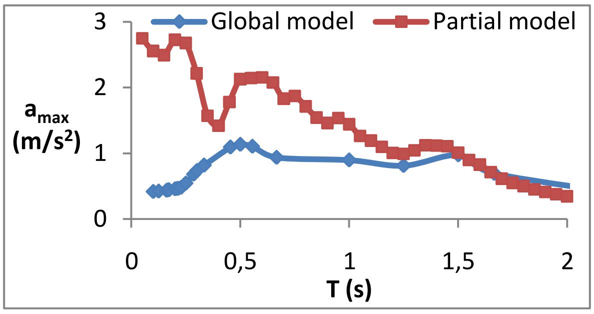


Figure 17 - T_s = 3,0 s e ξ = 0,20

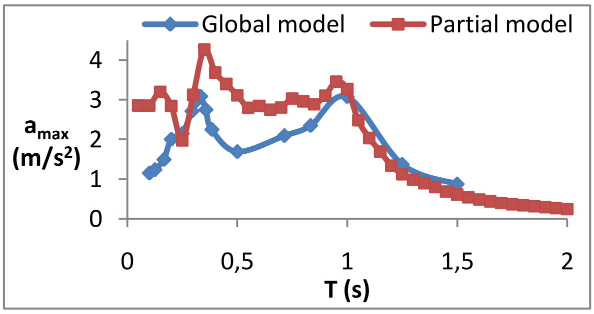


Figure 18 - T_s = 2,0 s e ξ = 0,10

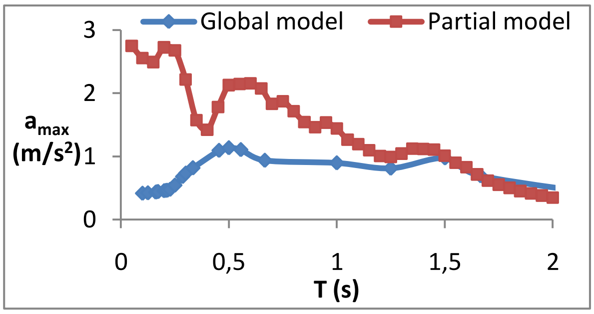


Figure 19 - T_s = 2,0 s e ξ = 0,20

From the results obtained it is possible to conclude that the partial model is generally conservative. The major differences between the values of the two models were found in the soil columns with higher periods. The differences are greater for periods shorter than the first period of the soil column, for higher periods the values obtained are very similar. Finally it appears that the major differences between the two models are verified for higher damping values. Generally for periods lower than the first period of the soil column the results obtained with a partial model are conservative, in contrast with the results obtained for structures with higher periods.

Despite the above conclusions, it is important to note that the partial model is not an exact analysis model because there are simplifying assumptions that deviate from reality. In the partial model it was used a spectrum obtained at the top of the soil column when in fact the seismic action is different for each point along the connection between the pile and the soil.

- **Comparison between the global model and the model of the structure for different values of the parameter α**

The effect of the foundation deformability can strongly influence the results therefore it is presented a comparison between results obtained with the global model for different values of the parameter α (see Figure 5), that takes into account the influence of the foundation deformability, and the results obtained from an analysis of the model of the structure with the EC8 spectrum for the soil type D. The comparison does not include the results obtained from the partial model analysis because, as mentioned before, the values do not differ significantly from those obtained with a global model. The results with the global model were obtained for values of α equal to 0,33, 0,5 and 1,0. It is presented in the Figures 20 to 23 the curves for soil columns with periods of 3,0 s (0,33 Hz) and 2,0 s (0,5 Hz).

Firstly it is possible to conclud that the results from the model of the structure become more conservative with the decrease of the frequency of the soil column. Moreover it was concluded that the curves obtained with the global model are shifted to the left and lead to significant differences between the two models when the parameter α takes lower values. Thus, it is possible to say that the analysis with the model of the structure, using the spectrum of the EC8, leads to a considerable number of situations where the acceleration values are significantly higher than the obtained with the global model. The differences are more pronounced for the higher periods of the soil column and when the effect of the foundation on the deformability of the structure is also higher, ie, for lower values of the parameter α.

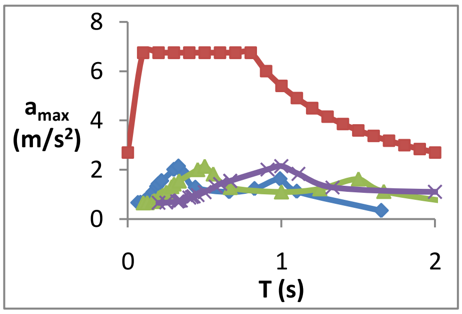


Figure 20 - T_s = 3,0 s e ξ = 0,10

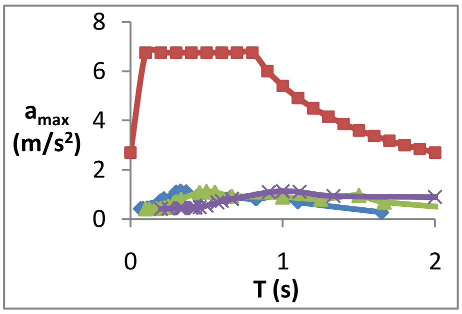
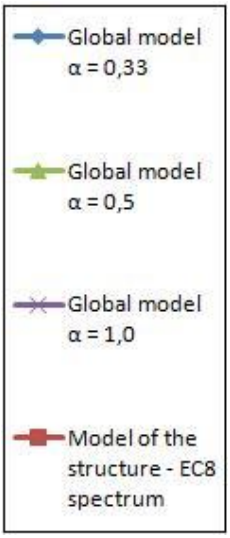


Figure 21 - T_s = 3,0 s e ξ = 0,20



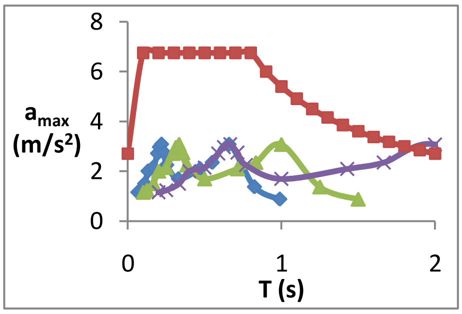


Figure 22 - T_s = 2,0 s e ξ = 0,10

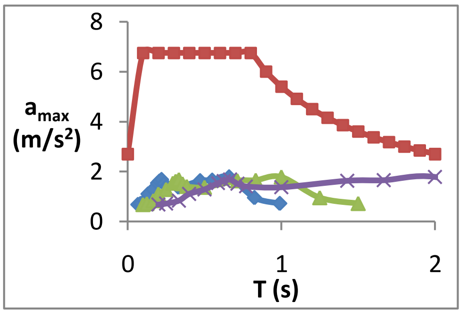


Figure 23 - T_s = 2,0 s e ξ = 0,20

4. CONCLUSIONS

Based on the methodologies tested to calibrate the damping matrix it was concluded that the Rayleigh damping leads to approximate values by default compared to the extended Rayleigh damping therefore the latter should be used whenever it is possible. The resonance problem, when different parts of the structure have different damping values but vibration modes with similiar periods, can only been solved through the non-proportional damping.

In reference to the parametric analysis, it is possible to conclude the following:

- As for to the structure characteristics it was concluded that the response depends mainly on the period of the structure taking into account the deformability of the foundation and not on the period of the structure, ie the period assuming a fully fixed support at the base.
- For the influence of the soil it was concluded that it can be taken into account just through the frequency of the soil column. This conclusion is valid for soil columns with a deformation modulus constant or variable in depth. The damping coefficient of the soil also affects significantly the structure response, but only in situations where the system is in resonance, out of the resonance the structure response is practically the same, even for significantly different dampings.
- Finally it was concluded that the stiffness of the foundation is not relevant for the structure response in absolute terms, ie the important factor is the relative effect of the foundation on the structure deformability.

Regarding the spectra of the EC8, it was concluded that they are an envelop of the spectra obtained for the specific soil columns that represent each soil types of the EC8. As the spectrum for each type of soil has to cover a significant range of frequencies it was verified that in many situations the spectra have very conservative values compared to those obtained with the spectrum of a specific soil column. This wide range of frequencies is due to two factors: firstly the classification of the soil defines large ranges of $v_{s,30}$ and secondly the level of degradation of the soil properties is not a parameter for the soil classification. On one hand this leads to a more simplified classification of the soil, but on the other hand it leads to values very conservatives in certain situations.
Finally, from the comparison between the results obtained with the different models considered it was concluded that the results obtained with the partial and the global models are similar in the usual frequency range of bridges. The differences between the two models occur for periods lower than the first period of the soil column. The difference is larger for the lower frequencies of the soil column and for the higher values of the damping coefficient. The partial model generally leads to higher values and therefore it is a conservative model.

Regarding the comparison between the global model, for different effects of the foundation deformability on the period of the structure, and the model of the structure analysed with the EC8 spectra it was concluded that the latter can leads to very conservative results. Within the analysed frequency range the differences are larger when the frequency of the soil column is lower and the effect of the foundation deformability on the reduction of the structure period is higher.

Possible future developments are comparisons between models without assuming a rigid support on the top of the pile but adopting rotational springs for this connection. The damping coefficient of the structure was kept to 5% throughout this work, therefore it could also be extended to other values.

5. REFERENCES

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