DYNAMIC SEISMIC ANALYSIS OF ANCHORED SHEET PILES

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ABSTRACT

In this paper, the use of steel sheet pile systems in seismic zones is discussed. First, an introduction to the topic and the actual calculation methods are explained and also a new approach to the seismic calculation is outlined. After that, the methodology followed in the study is explained, including the use of MATLAB for the time history signal treatment and the nonlinear FEM program PLAXIS for the dynamic seismic analysis. Finally, a discussion on the results and a new proposal for the reduction factor in sheet pile walls calculation are presented. The results show that a reduction factor of 2.8 could be considered with the used system configuration and design spectrum, instead of the factors allowed in the European Standards which range from 1 to 1.6 for soil retaining structures. This factor between 2 and 3 is in line with international standards and recent researches.

INTRODUCTION

Sheet pile systems are an interesting solution to be implemented in quays and harbors where seismic resistance is required. There is a vast array of studies proposing different procedures for their design [1, 2, 3, 4]. However, the conditions regarding their design are not specifically addressed.

Pseudo-static analysis is the preferred method utilized by engineers as it is simple and a system which is readily-available. It allows assessing the geotechnical stability of the sheet pile system. This requirement has a huge relevance when dealing with retaining structure designs. Nevertheless, pseudo-static analyses need an estimation of the seismic coefficient value [5]. Reference [1] and [2] have highlighted the relevance and the influence of this parameter on the design of sheet piles. Furthermore, the estimation depends highly on the own engineer's experience and criteria, which may, result in a conservative or non-conservative approach. To overcome this problem, more advanced analyses, such as dynamic methods, are increasingly being used and are available nowadays [1].

On the other hand, Dynamic analysis could improve how the seismic motion is introduced in the analysis by using acceleration-time histories. Thus, the behaviour of the whole system is better simulated under dynamic methods and the design becomes more precise. Despite this advantage, the geotechnical stability cannot be ensured with the dynamic method [6] and furthermore, it is highly demanding regarding time and required computational resources. Therefore, a methodology seeking for a complete design of sheet piles has to be proposed.

Hence, the present study aims to outline best practice for performing the seismic design of anchored sheet piles regarding the seismic reduction coefficient. Integrating the assessment of structural and geotechnical requirements in the same design procedure to obtain the seismic coefficient is the main focus of this study. Overall, this investigation attempts to provide guidance and make recommendations regarding the improvement of sheet pile design under the studied conditions. Further investigation will be needed to extend the validity of the method to different system configurations.

METHODOLOGY

The following study suggests a basic methodology for the seismic design of sheet piles to highlight an efficient design practice for these structures. Therefore, the study is performed under a simple case which aims to focus on the design methodology. It is important to note that Eurocode standards [7, 5, 8] and PIANC recommendations [9] have been adopted throughout the study. Hence, the following assumptions have been made:

- Liquefaction and scouring are neglected.
- The stratigraphy of the soil consists of one cohesionless sand layer (φ=30º) along the whole soil column. For modelling purposes, a rock layer is also considered at the bottom.
- The Hardening Soil Small Strains is used as the constitutive soil model.
- The water level is considered 4 meters below the surface. In addition, the difference between water levels at both sides of the front sheet pile is not considered.
- The seabed level is situated 15.5 meters from the surface.
- As a simplification, pressure due to movement of water within soil pores is not considered.
- The dynamic pressure of the seawater against the front sheet pile is introduced by means of the Westergaard hydrodynamic pressure.
- The sheet pile system consists in a front sheet pile anchored to a passive sheet pile.
- On top of surface, a distributed load of 20 kN/m^2 is assumed.
- The toe level of sheet piles, sheet piles sections and steel grades are defined as a conclusion of the design.

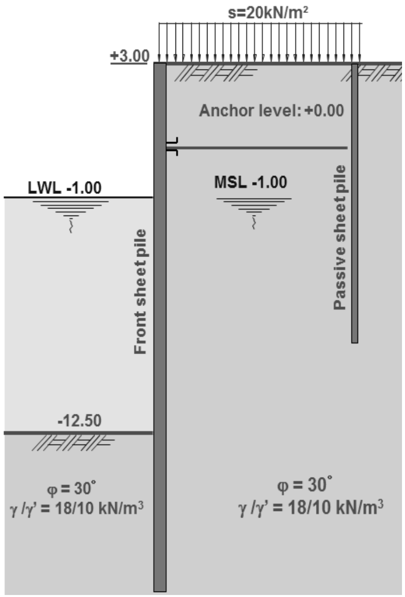

Figure 1. Conditions of the study

The sheet pile design needs to involve the assessment of geotechnical and structural requirements. Consequently, two analyses are proposed according to EN 1998-5 [8], pseudo-static and dynamic analyses, in order to fulfil a complete design of a sheet pile system. Both of them are performed using 2D Plaxis software [6]. The way in which the seismic action is considered in the model is the main difference between them. The pseudo-static analysis simulates the earthquake as an additional inertial force by means of the seismic coefficient whereas the dynamic analysis is able to take into account the accelerogram of the seismic action.

On one hand, pseudo-static analysis evaluates the geotechnical stability of the system. For that purpose, the phi/c-reduction method is used for determining the safety factor associated to the overall stability. According to EN 1997-1 [7], using the Design Approach 1 with combination 2 and considering the characteristic properties of the soil, the safety factor has to be 1.25. This calculation cannot be performed under a dynamic analysis and hence, this demonstrates the need for a pseudo-static analysis. On the contrary, the dynamic analysis assesses structural requirements in terms of design forces and displacements that can be verified following EN 1993-5 [10] which is the Eurocode 3 Part 5 dedicated to steel sheet piles. This standard takes into account, through the soil model used, the energy dissipation by means of the soil material damping depending on the soil strains. This calculation cannot be performed under a pseudo-static analysis [6] and hence, it demonstrates the advantage of dynamic analyses.

Looking into the different approach and outcome of each analysis type a proposal can be done. Not only are both analyses conceived independently, but also the proposed methodology relates their results in order to develop a more thorough design approach. Consequently, the sheet pile design becomes an iterative process aiming to converge to the same result either in pseudo-static or dynamic analyses. The design procedure is schematized in Figure 2. Furthermore, the main steps of the proposed design are detailed below.

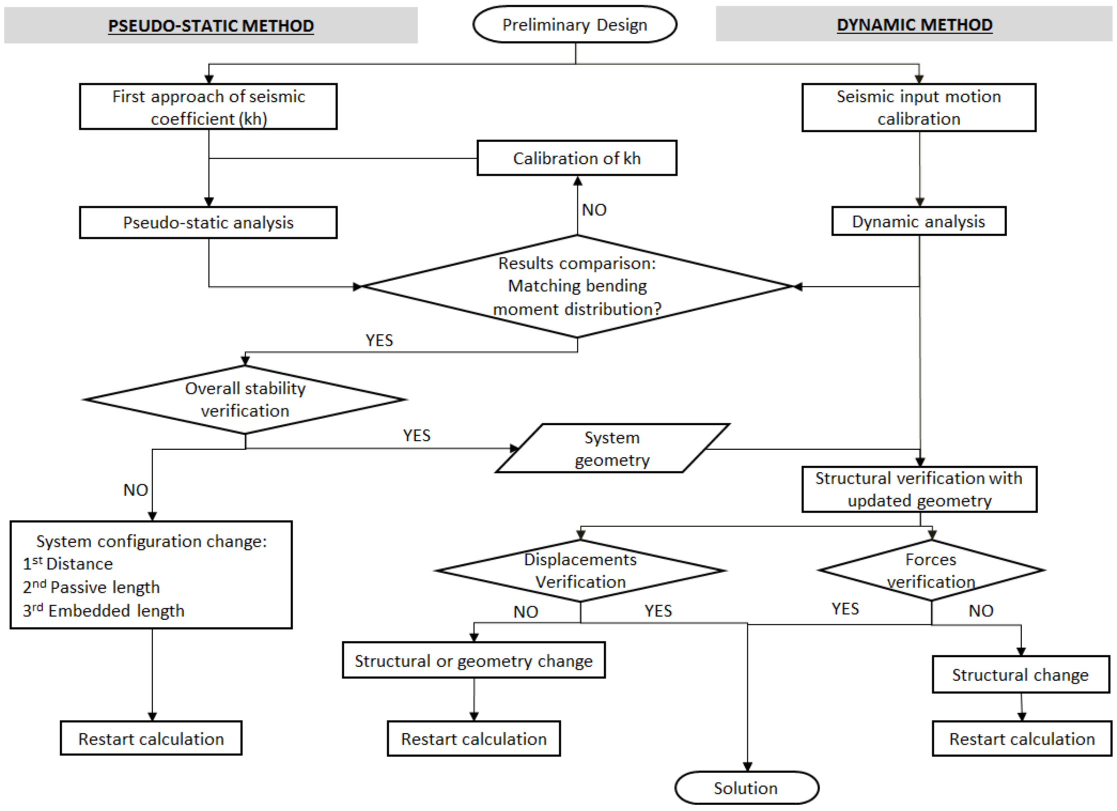

Figure 2. Proposed design methodology for sheet piles under seismic design.

Dynamic analysis: seismic input motion calibration

The dynamic analysis considers the accelerogram of the desired earthquake to be studied. Regarding the general methodology, the study proposes an elastic response spectrum as the parameter defining the earthquake, which is the adopted practice in all the seismic standards. As a common practice, this spectrum is assumed to be obtained at the model top surface. Hence, the input artificial accelerogram to be applied at the base of the model shall simulate the design or target spectrum at the surface of the model. To achieve that matching, the dynamic analysis requires a calibration of the input seismic motion.

Primarily, the target elastic spectrum is defined in terms of Eurocode standard. The study proposes to evaluate a spectrum associated to a soil Type C with a Peak Ground Acceleration (PGA) equal to 0.4g according to EN 1998-1 §3.2.2.2 [5]. Therefore, the basic acceleration, a_b, is equal to 0.27g.

The seismic calibration is carried out using a 1D model of the soil column in 2D Plaxis software. The input acceleration time-history is obtained for a rock outcrop (Type A in EN 1998 [5]) and introduced at the bottom of the model through a prescribed displacement. Afterwards, by means of a dynamic calculation, the seismic motion is propagated along the soil column. At the end of the analysis, an elastic response spectrum is obtained at top of the surface and compared to the target spectrum, Type C in this case. Due to the properties of the soil, damping and its natural vibration periods, the spectrum obtained differs from the target spectrum. Therefore, the input accelerogram needs to be modified such that the simulated spectrum at surface fits the target spectrum at the end of the calibration process.

Commonly, the seismic calibration performed in 2D Plaxis uses the Rayleigh α and β damping factors [6]. These parameters modify the damping of soil at the frequencies where peaks at the spectrum are found. In spite of this, sometimes it can become difficult to calibrate the seismic motion by means of this parameter. Thus, the present study carries out a modification of the input accelerogram in terms of energy.

The proposed method directly modifies the input accelerogram instead of adjusting the soil constitutive model, normally carried out with the Rayleigh damping [6]. Alternatively, the calibration fine tunes the energy of the frequencies which does not fit the target spectrum. For instance, a great peak of the simulated spectrum above the target spectrum means that the corresponding frequency has a too high energy input which has to be reduced to match the target. Consequently, this method needs to determine the energy for each frequency of the accelerogram. This can be obtained using the Power Spectral Density (PSD) from the Fast Fourier Transformation (FFT) of the signal, which is a mathematical operation that determines the amount, or the energy, of each frequency needed for producing the associated accelerogram.

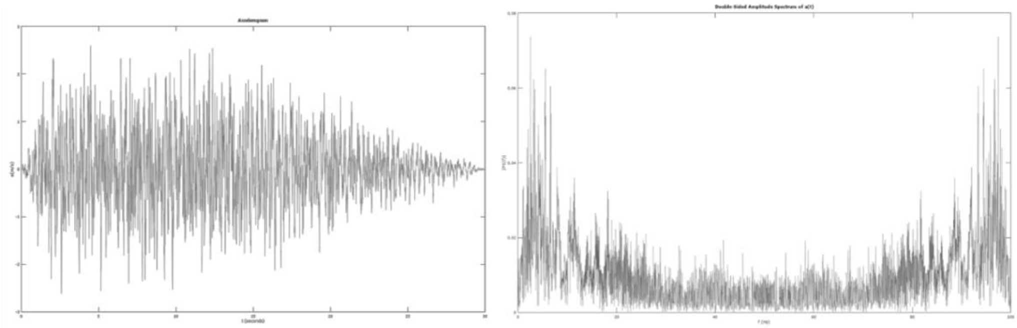

Figure 3: Accelerogram (left) and its associated symmetric PSD spectrum (right).

When the associated PSD spectrum is obtained, the energy of the desired frequencies is adjusted. Afterwards, an inverted FFT is carried out to recover the now modified accelerogram. Finally, it is introduced again on the base of the model to perform a dynamic analysis. This procedure is iteratively carried out until the target spectrum is achieved, which typically takes five to ten iterations. Note that the matching with the target spectrum is much better than the common Rayleigh adjustment as it can be seen in the following sections.

Pseudo-static analysis: Estimation of the seismic coefficient

As previously mentioned, pseudo-static analysis considers the earthquake as an additional inertial force considered by means of the seismic coefficient. According to EN 1998-5 §7.3.2.2 [8], the horizontal seismic coefficient is defined as:

$$k_h = \alpha \frac{S}{r} \tag{1}$$

Where:

α is the ratio of the design ground acceleration on type A ground, a_g, to the acceleration of gravity g

S is the soil factor

r is a reduction factor depending on the type of the retaining structure

However, the determination of the values for above parameters has some uncertainties, especially for sheet piles. For instance, EN 1998-5 [8] has no clear clause for the value of reduction factor for sheet piles. According to Table 5.1 of EN 1998-5 [8] the value to be used is equal to 1. Nonetheless, PIANC recommendations [9] already propose a reduction factor equal to 1.67 whereas [11] outlines possible reductions between 50%-70% (factors of 2 to 3) when dealing with retaining structures. Given that the estimation of the seismic coefficient is the key factor for assessing the geotechnical requirements, the ambiguity associated with calculating this value has a huge influence on the results. Either an underestimation or an overestimation could occur, leading to unsatisfactory designs.

Under this situation, the study proposes the estimation of the seismic coefficient using the results of a more advanced analysis, in this case, the dynamic analysis. Other studies have used similar procedures in order to estimate the seismic factor. For example [4] carries out a calibration of the seismic coefficient using the results from an analysis with shaking tables. At this step of the design is where the two analyses become interdependent. The proposed methodology calibrates the seismic coefficient based on the bending moment distribution and values of the front sheet pile. Hence, the calibration is carried out comparing the results from pseudo-static analysis to the results of dynamic analysis. The estimated value for the seismic coefficient is the one with the best associated fitting to the dynamic bending moment distribution. As a result, the design methodology becomes an iterative process as shown in Figure 2.

DISCUSSION OF RESULTS

Seismic input motion calibration

The seismic input motion calibration has been carried out in a 1D model of the soil column using 2D Plaxis software. The soil column is 40 m deep where the first 37 meters are a sand soil. At the bottom of the column there is a layer of 3 meters of rock. The calibration is performed under free field conditions.

As a first iteration, the accelerogram associated to the elastic response spectrum at the rock has been used. The accelerogram has been simulated through SIMQKE [12] software. This software is able to transform an elastic response spectrum into a set of artificial accelerograms. For that purpose, the spectrum at rock has been defined according to EN 1998-1 §3.2.2.2 [5] considering a soil Type A with basic acceleration equal to 0.27g.

The elastic response spectrum at surface after performing the first iteration of the process is shown in Figure 4. As shown below, the simulated spectrum has a significant difference with the target spectrum. An outstanding result to also note is that a great peak is generated at a period of around 1 second which is the soil first natural period. Additionally, the spectral acceleration at the plateau is significantly higher than the standardized spectrum. Hence, a calibration is needed.

The modification of the input accelerogram has been made based on the energy modification process. In addition to this, Rayleigh damping has also been used to adjust the spectral acceleration at small periods and on the plateau. Resultantly, a Rayleigh damping of 0.5% is imposed at the lowest frequencies (2.5 Hz and 16 Hz).

Considering the results of the first iteration, the calibration of the accelerogram has been adjusted according to the main peaks of the simulated spectrum. Consequently, the energy of periods around 1 second (alternatively, frequencies around 1 Hz) and the periods of the plateau have been changed.

The modification has been performed iteratively such that a sufficient fit to the standardized spectrum is fulfilled (Figure 4). Note that according to EN 1998-1 §3.2.3.1.2 [5], using artificial accelerograms any point of the simulated spectrum has to be above the 90% of the normative spectrum.

Upon completion of the calibration, the input accelerogram is used to conduct the dynamic analysis of the sheet pile system. According to the proposed methodology, dynamic results are used to evaluate structural requirements according to Eurocode standards [10, 5, 8, 7] and PIANC recommendations [9]. However, the structural verification is not the focus of this study. For this reason, it is left aside as there is a wide range of documentation and standards detailing this verification process. Furthermore, dynamic results are used to estimate the seismic coefficient for the pseudo-static analysis. The following section discusses how this estimation is achieved.

Finally, as a part of the control of the seismic signal, a verification has to be made in the 2D model. It has to be checked that the elastic response spectrum at surface remains unaltered from the 1D calibration. This verification is performed at the boundaries of model, where the free field conditions, are imposed. Figure 4 also compares the spectrum of 1D and 2D models. It demonstrates that the obtained 2D spectrum complies well with the standard spectrum in Figure 4.

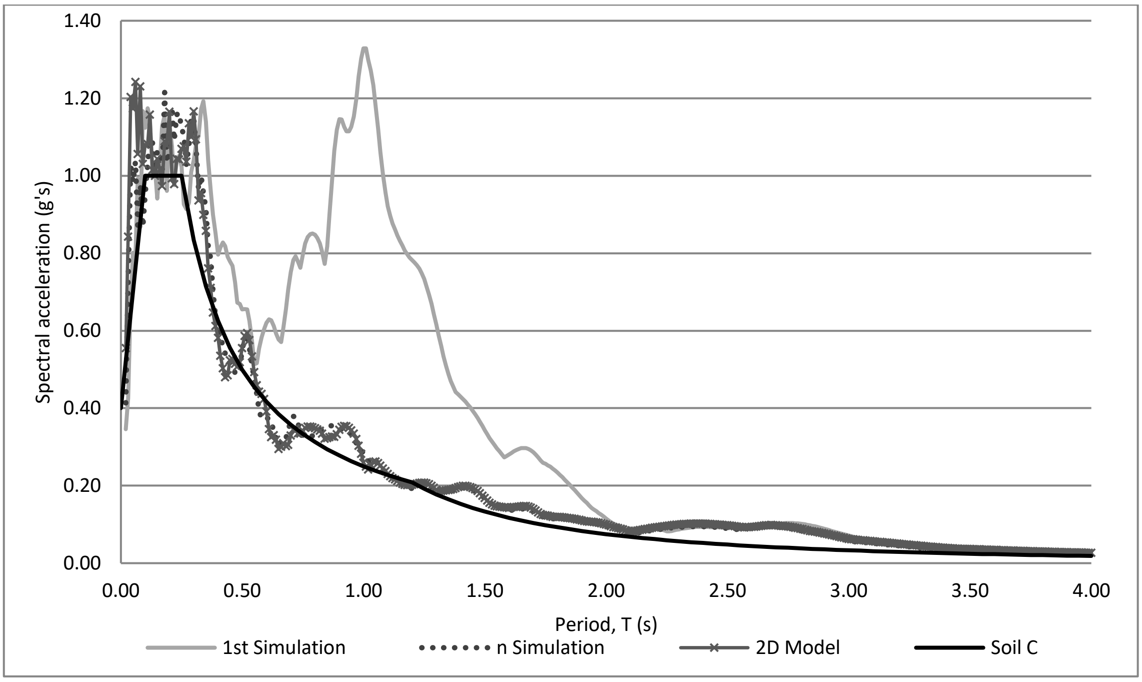

Figure 4. Final simulated response spectrum after seismic input motion calibration.

Estimation of seismic coefficient

The pseudo-static analysis needs to simulate the same conditions of the dynamic analysis for assessing the overall stability of the system. The case conditions of the pseudo-static analysis rely on the value of the seismic coefficient. Henceforth, the estimation of this parameter is of vital importance

First of all, the study analyzed the convenience of the utilization of the factor already proposed in PIANC recommendation and standards [9]. Therefore, as a first approach, the selected value for the reduction factor is 1.67. It has to be pointed out that along the whole study the PGA at surface, equal to 0.4g, is used as the design acceleration (αS).

Under these conditions, a great active wedge is developed which involves a huge soil body mass. The passive wall is required to be situated outside that active wedge in order to develop its anchoring function. Consequently, the overall stability is achieved when the passive wall is located approximately at 130 meters from the front sheet pile. These results may prove the sheet pile system to be unfeasible under seismic conditions. In order to verify this, the pseudo-static results are contrasted with dynamic results to determine the most suitable design approach.

The comparison of the results reveals that the pseudo-static conditions are not in line with dynamic conditions. Specifically, the bending moments of the front sheet pile take on a different distribution in the pseudo-static analysis when contrasted against the dynamic analysis. Under the pseudo-static analysis, it acts as simple supported beam whereas in dynamic analysis it behaves as a continuous beam (Figure 5). Moreover, the maximum bending moment also varies quite largely, as in pseudo-static it takes a values of 6723 kNm compared to 2835 kNm in the dynamic analysis. In light of these results, it can be concluded that the approximation for the seismic coefficient leads to an overestimation of the seismic internal forces in the sheet piles. Consequently, an alternative estimation needs to be proposed.

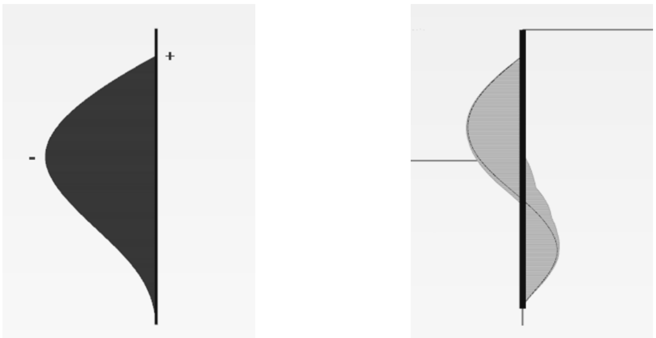

Figure 5. Bending moment distribution of the front sheet pile. Under pseudo-static analysis (left) and under dynamic analysis (right).

The present study proposes an estimation of the seismic coefficient using the results of the dynamic analysis. Different values of the mentioned parameter are considered. The estimation is based on fitting the pseudo-static bending moment distribution of the front sheet pile to the dynamic distribution.

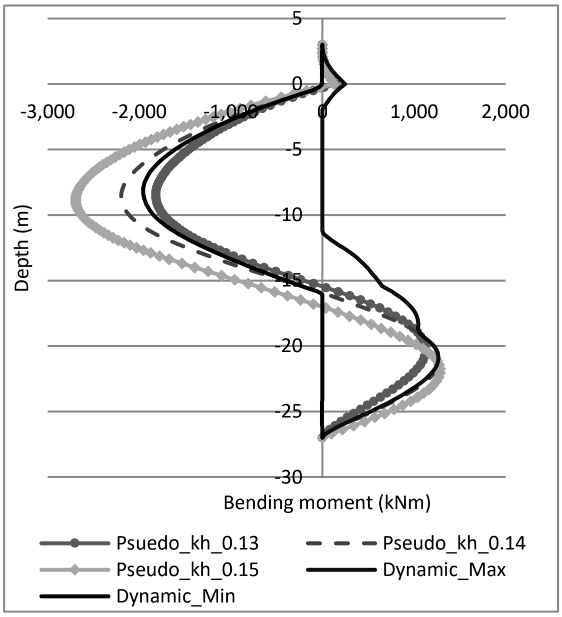

Figure 6. Calibration of the seismic coefficient.

Figure 6 shows different proposed values for the seismic coefficient. Also, it illustrates that the best fitting distribution is obtained using a k_h value equal to 0.14g. Considering the above finding, the associated reduction factor is equal to 2.8. Compared to the first approach, it has a significantly greater value. Nonetheless, it is in line with values already proposed by [11] for retaining structures. In addition, [4] proposes values for the reduction factor up to 2 however this particular study analyses a batter pile system, which is a more rigid structure, and as a result the values may become less comparable.

The results conclude that the values proposed in standards might need a revision considering the behaviour of sheet piles under seismic conditions. According to the results obtained, an increase of the reduction factor might be based on the dissipation of energy due to the soil-structure system, i.e. the consideration of the soil material damping which depends on the soil strains. Therefore, the reduction factor could depend on soil properties, interaction between soil and structure and the ductility of the system considering the structure and the soil as a whole. Consequently, it opens a line of investigation in order to seek new values for the reduction factor in the case of sheet pile systems.

CONCLUSIONS AND FURTHER STUDIES

The present study has outlined a design methodology for sheet pile systems under seismic conditions. The first focus of the study is placed on the manner in which the seismic motion is considered under the required analyses. For this reason, the seismic signal treatment for dynamic analysis has centered the first part of the study. It focuses on the calibration of the seismic input motion. The design methodology proposes a direct modification among the input accelerogram in order to achieve a good simulation of the design elastic response spectrum.

On the other hand, the study has evaluated the estimation of the seismic coefficient factor for pseudo-static analysis. It proposes the utilization of dynamic results in order to establish the value for this parameter. Consequently, the estimation process seeks the seismic factor which better merges the pseudo-static bending moment distribution of the front sheet pile with the dynamic distribution.

In summation, to conclude the study, a reduction factor for anchored sheet piles in cohesionless soils equal to 2.8 is proposed. It has a great difference compared to current values which range from 1 to 1.67 in the in force standards [8, 9]. Nevertheless, it opens the possibility to start counting on the dissipation of seismic energy due to the soil material damping and points towards further investigation on the ductility of the soil-structure system. Further studies might follow this line of investigation to try and find a consensual value in order to simplify the design of sheet piles.

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