Church “Igreja Nossa Senhora dos Navegantes”, Parque das Nações: Soil Structure Interaction

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ABSTRACT

This paper presents a the case study of the church of Nossa Senhora dos Navegantes, structure with a reinforced concrete founded over TRM micropiles and located at the Expo /Oriente, in Lisbon.

This study aims to reflect on the soil-structure interaction (SSI), whose consequences have sometimes been neglected in the field of civil engineering, because it is considered a beneficial effect regardless of the geotechnical conditions where the structure will be founded.

The essence of this work is based on the analysis of the structural behavior taking into account the SSI effects. Thus, the structure in question is simulated by a finite element model, applying different foundations solutions foundations. The parameters used in the simulation of the foundations, were calibrated by a full scale load test performed at the construction site.

1. INTRODUCTION

This paper aims to show the difference between a common structural design, in which the stresses are obtained without allowance for soil settlements, in opposition to a design approach considering an analysis with the soil-structure interaction, where the stresses acting on the structure are obtained considering the soil deformability.

The analysis will consist on a practical case modeled using SAP2000 software. By taking into account the SSI effect, the foundation differential settlements will influence the load transmitted from one column to another, and hence the redistribution of forces in the superstructure members. The magnitude of the load redistribution is dependent on the stiffness of the elements of the superstructure, as well as on the magnitude of the differential settlement. Foundation settlements may introduce new conditions of load distribution at the structured elements leading to that cause distress and cracking of those elements, and may even lead to the ground plastic rupture. It is a function of the flexural rigidity of the superstructure. The structural stiffness can have a significant influence on the distribution of the column loads and moments transmitted to the foundation, and the load redistribution may modify the pattern of or mitigate settlements.

2. SSI EFFECT

Considering the SSI effect on structures implies that its modeling will not use fixed support bases, simulating foundations, but springs in order to introduce the equivalent stiffness of the soil.

The consequences of the introduction of springs in the model, is a uniformization of the settlements which cause a similar
uniformization on stresses. With that uniformization of stresses the most stressed elements will be required to redistribute its load to the least loaded ones ([1] Frank, 2014).

Keep in mind that adding springs to the foundation of the structure will decrease of its overall stiffness, the frequency will decrease, which will influence the determination of seismic acceleration [2] (Mylonakis G., Gazetas G, 2001), [3] (Mylonakis G., Gazetas G, 1998) in accordance with European Standards [4] (EN1998-1-1, 2005), as evidenced by Figure 1 and the following equations (eq.1) and (eq.2).

\[ f = \frac{1}{2\pi} \sqrt{\frac{K}{m}} \quad \text{eq.1} \]
\[ T = \frac{1}{f} \quad \text{eq.2} \]

Other important aspects while considering the SSI effect. That could influenced the rigidity of the structure and the construction process and the height of the building.

3. CASE STUDY

The case study corresponds to the central core of church Nossa Senhora dos Navegantes.

The structure has four reinforced concrete arches (Figure 3), divided by two orthogonal directions, which provide support for flat slabs and facades of the upper floors of the building. The central body also contains a bell-tower (Figure 5), with a considerable height of 40 meters, by two braced beams, connected to the arcs. Regarding the resistant walls of the structure, the geometry is semicircular (Figure 4).
The structure is founded over TRM micropiles.

3.1 GEOLOGICAL SCENARIO

The site of the INSN, located at the Tagus River bank (known for its soft soils), intersects three different geological-geotechnical formations. At the site heterogeneous landfills can be found at the surface to the depth of 5 to 7.5m with an N\textsubscript{SPT} raging from 1 to 12 blows. Underneath this layer, alluvial deposits can be found with thicknesses, varying, from 1.5 to 4.5m with a N\textsubscript{SPT} raging from 1 to 10 blows.

The Miocene layer, formed by silty-clay materials and a N\textsubscript{SPT} raging from 20 to 50 blows, has a thickness between 0.45 and 1.65m. The standard penetration test identified an increase of resistance with the depth, reaching above 60 blows on N\textsubscript{SPT}, which corresponds to very stiff clays. Finally, rocky nature formation were intersected constituted by calcarenites, sandstones and shellstones intertwined in the previous layers. These formations are characterized by fractures with F4 to F5 and quality index RQD between 10% and 55%. Its thickness can vary in depth between 0.2 m and 5 m.

The groundwater table level was detected near the surface (between 0.7 and 2.3 m) without any dependence from the river tides, due to the high content of clay in the ground. An analysis was performed to determine the aggressiveness of the water, where it was found that the environment was not aggressive, because all parameters are well below the exposure class XA1, according to the Portuguese standard NP-ENV206-1 2005.
3.2 ADOPTED FOUNDATIONS SOLUTIONS

Given the nature of the subsoil and the expressiveness of the load distribution, a solution of deep foundations by driven micropiles TRM was used to support the vertical loads, and foundation beams between cap was used in order to resist to horizontal loads and bending moments (Figure 11).

This solution of deep foundations is constituted by two types of driven and grouted tubular micropiles, allocated as seen on Figure 9, installed in accordance with the respective internal resistances and lengths of about 12.5 m:

- TRM Ø170,0 x 10,6 mm, is installed to resist to vertical loads with a maximum value of 855 kN, and its equipped with a grouting shoe of Ø250 mm at the toe;
- TRM Ø118,0 x 9,0 mm, is installed in areas where vertical loads are inferior or equal to 500 KN, and its equipped with a grouting shoe of Ø200 mm at the toe;

The micro-concrete XAS C25 / 30; XA2 (P); D_{max} 10 mm; S4; Cl0.4, was adopted inside and outside the micropile tubes in order to promote the lateral resistance and protect the micropile from corrosion [6] (Pinto, 2014).

3.3 FULL SCALE LOAD TEST

The static full scale load test consisted on applying a vertical compression load on the head of a micropile TRM Ø118,0 x 9.0, using three load-unload cycles which are defined on Table 1.

<table>
<thead>
<tr>
<th>Cycle load</th>
<th>Cycle unload</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 = 15 tf</td>
<td>P1 = 25 tf</td>
</tr>
<tr>
<td>P2 = 25 tf</td>
<td>P2 = 50 tf</td>
</tr>
<tr>
<td>P3 = 50 tf</td>
<td>P3 = 75 tf</td>
</tr>
</tbody>
</table>

Table 1 - Loads applied on each cycle

The reaction structure was composed by HEB steel profiles and concrete slabs, supported by prefabricated concrete shackles. The reaction force is produced by the weight of the reinforced concrete, which is controlled by a calibrated hydraulic jack, installed between the cap of the
micropile and the reaction structure. The entire reaction structure can be seen on Figure 7.

In order to read the test loads and the settlement at the micropile cap (total axial strain), some instrumentation was installed consisting on 4 gages, 1 load cell and 4 topographic targets.

The micropile tested was characterized by the parameters shown below as seen in Table 2.

Table 2- Main characteristics of the micropile

<table>
<thead>
<tr>
<th>Type of micropile</th>
<th>Length (m)</th>
<th>D (mm)</th>
<th>Yield tensile strength (MPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRM 118.0 x 9.0</td>
<td>12</td>
<td>110</td>
<td>320</td>
<td>420</td>
<td>C25/30</td>
</tr>
</tbody>
</table>

The geotechnical scenario was accessed through the results of a site geological and geotechnical investigation, as shown in Figure 8.

The commercial software Structural Analysis Program 2000 is not much suited to soil analysis elements but with the right parameters it can result in an acceptable line of results for the requirements of this study as seen by the complete model on Figure 10. Shell elements were used to simulate thin slabs and concrete walls, as in these cases the thickness did not justify the use of thick elements, because the deformation by shear force was not a priority due to the thickness of the structural elements. It was also necessary to use shell elements to simulate the walls, as well as the slabs, by having irregular geometric shapes, such as arcs and openings, as seen on Figure 13, Figure 14, Figure 15 and Figure 16, which had to be analyzed with the use of these elements. Beams and columns were modeled with frame elements, with dimensions easily represented, as seen on Figure 11 and Figure 12. The foundations were simulated through fixed supports in this first analysis.
5. ALTERNATIVE DESIGN WITH SSI

As already stated a static load test was executed on the construction site and, continuing that the foundation of the structure will work majority by tip over a high stiffness layer of shellstones. The best approach was to follow the hypothesis of small deformations, which is based on the principle that the stressed material undergoes small deformations, returning to its initial position when unloaded, it
was acceptable to consider that it has a linear elastic behavior [5] (Terzaghi, 1996).

In order to consider the SSI effect, as mentioned above, a fictitious stiffness was used instead of fixed rigid support structure in the vertical direction [4]. To calibrate this stiffness, the static load test performed on site was used. Using the equation (eq. 3) \( F = K \cdot \delta \); in which \( F \) is the applied force in kN, \( K \) is the stiffness in kN/m and \( \delta \) corresponds to the settlement in meters, thus, it was possible to determine the overall stiffness of the foundation. Three distinct stiffness calculations were calculated, as can be seen by (eq. 4), (eq.5) and (eq.6), each associated with one of the charging cycles, so it was necessary calculate an average of the values to obtain a more reliable value (eq. 7).

\[
F = K \times \delta \Rightarrow K = \frac{F}{\delta} \quad \text{eq.3}
\]

\[
K_1 = \frac{1100}{12.5 \times 10^{-3}} = 88000 kN/m \quad \text{eq.4}
\]

\[
K_2 = \frac{840}{7.6 \times 10^{-3}} = 110000 kN/m \quad \text{eq.5}
\]

\[
K_3 = \frac{550}{3.5 \times 10^{-3}} = 160000 kN/m \quad \text{eq.6}
\]

\[
K_{med} = \frac{K_1 + K_2 + K_3}{3} = 120000 kN/m \quad \text{eq.7}
\]

6. RESULTS

The data that is considered pertinent to the access the structural behavior, such as the stresses acting on the beams, the columns, the resistant gantries and natural frequencies of the structure are analyzed.

It is shown, in the following Table 3, Table 4, Figure 17, Figure 18, Figure 19 and Figure 20 the stresses and their greatest variation when comparing both analysis, (with and without SSI).

### Table 3- Stresses with and without SSI on columns

<table>
<thead>
<tr>
<th></th>
<th>P (kN)</th>
<th>M2(kNm)</th>
<th>M3(kNm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without SSI</td>
<td>390.6</td>
<td>-60.5</td>
<td>-34.6</td>
</tr>
<tr>
<td>With SSI</td>
<td>575.3</td>
<td>-9.2</td>
<td>-11.9</td>
</tr>
<tr>
<td>Δ MAX</td>
<td>184.7</td>
<td>51.3</td>
<td>22.6</td>
</tr>
</tbody>
</table>

### Table 4- Stresses with and without SSI on foundation beams

<table>
<thead>
<tr>
<th></th>
<th>V2 (kN)</th>
<th>V3 (kN)</th>
<th>T(kNm)</th>
<th>M2(kNm)</th>
<th>M3(kNm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without SSI</td>
<td>42.2</td>
<td>135.1</td>
<td>4.4</td>
<td>6.0</td>
<td>6.2</td>
</tr>
<tr>
<td>With SSI</td>
<td>576.7</td>
<td>3.8</td>
<td>113.8</td>
<td>63.9</td>
<td>242.3</td>
</tr>
<tr>
<td>Δ MAX</td>
<td>534.5</td>
<td>131.3</td>
<td>109.4</td>
<td>57.9</td>
<td>236.0</td>
</tr>
</tbody>
</table>

### Figure 17- Stresses without SSI

### Figure 18- Stresses with SSI
As it can be confirmed, in this work, the consideration of SSI makes significant differences on the structural behavior, mainly the stresses on the columns and foundation beams, as well as the natural frequency of the structure in relation to the modeled structure with rigid supports.

Thus, it is observed that the SSI can be particularly important in those cases where there is a large axial stress, concentrated in certain footings or founded over based on layered soils. It should be noted that even when passing the identified tolerable limits of differential displacement, the solution is simple. For shallow foundations, just increase the area of the footing and for deep foundations to increase the length and the shaft of the pile, until it reaches a soil with enough stiffness to prevent stiffness boundaries displacements.

In this scenario it is possible to confirm the good behavior of the TRM solution, as a foundation of great utility in the field of civil, structural and geotechnical engineering.

Regarding the foundations solution, it proved to be a solution to consider regarding future projects, specialized equipment is not necessary, nor hand labor, making the solution very versatile, with high productivity ratios that lead to considerable economic benefit in the work in general.

Static load tests plays a key role in optimizing the solution. In this case, in particular, the static test helped to reduce the length of the shaft of the pile, placing the toe in a single stiff layer of ground. Resulting in a large cost reduction and shortening of construction schedule. Despite its costs, a good knowledge of the ground foundation always bring great benefits.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz) without SSI</th>
<th>Frequency (Hz) with SSI</th>
<th>∆f (Hz)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>2.05</td>
<td>1.68</td>
<td>0.37</td>
<td>18%</td>
</tr>
<tr>
<td>2nd</td>
<td>2.88</td>
<td>2.54</td>
<td>0.34</td>
<td>12%</td>
</tr>
<tr>
<td>3rd</td>
<td>4.69</td>
<td>4.06</td>
<td>0.63</td>
<td>13%</td>
</tr>
</tbody>
</table>


7. MAIN CONCLUSIONS
associated, as demonstrated by this particular case.

This work presents a simple example about how to take account of the SSI. Clearly, the application will have to be done through the use of appropriate software to facilitate the introduction of elastic supports. The SAP2000 software was presented as a very versatile tool for the intended purpose. All theoretical results, granted by Plaxis and by SAP2000 software led to a result set in the same order of magnitude as those obtained by the use of full scale load test.

8. PHOTOGRAPHS TAKEN DURING AND AFTER THE COMPLETION OF CONSTRUCTION

This next chapter intends to present the monitoring of the construction process, in order to have a greater understanding of the superstructure, as well as the reasons as to why was a complex model created to simulate the superstructure Figure 21 to Figure 28.

Figure 21- Execution of a Micropile TRM

Figure 22- Foundation beams

Figure 23- Slab and columns

Figure 24- Slab and columns (aerial view)
9. REFERENCES

[1] Frank, R., *Some aspects of soil-structure interaction according to Eurocode 7 'Geotechnical design'* Roger Frank CERMES (Soil Mechanics Teaching and Research Centre, ENPC-LCPC) Cité Descartes, Champs-sur-Marne, 77455 Marne-la-Vallée cedex 2, France, 2006


