INFLUENCE OF SLENDERNESS ON THE BEHAVIOUR OF MICROPILES

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ABSTRACT

The aim of this study is to develop a critical analysis for the buckling of micropiles with high slenderness, taking into account the action of axial loading. In order to clarify the definition, classification, application and methods of design of micropiles was added like additional information, pointing out the buckling compression. To better understand the sensitivity of various parameters in micropile-soil interaction, taking into account the lateral instability, the author proceeded to a numerical approach. The modelling of the structure is performed using a calculation model by 2D finite elements. It’s also described the main design and execution criteria considered in the solution for the underpinning of pavements and structures of industrial warehouses located at the site of the “Antiga Trefilaria”, as well as the monitoring the of the superstructure behaviour in response to the developed work. It’s also presented the results of loading tests performed in micropiles, considering the heterogeneity of geological formations, which confirmed the perfect adaptation of this indirect foundation solution to the conditions of local geotechnical and geological scenario. Finally, it presents some general considerations about this work.

1. INTRODUCTION

The use of micropiles has changed significantly in recent years since its first use in the 50’s, when Dr. Fernando Lizzi developed the concept of micropiles groups in historic buildings. The first application consisted on lightly loaded groups of piles that were designed to reinforce unstable soil mass. Currently the micropiles have a wide application in geotechnical structures, rehabilitation projects, and strengthening of new structures in urban areas and such solutions have evolved to high load capacity systems [5]. This document contains a review of relevant historical research, as well as reports of recent experiences obtained directly from applications on micropiles with high load capacity solutions.

In order to understand the technique of micropiles, Chapter 2 of this document intends primarily to describe the existent solutions (features, definition, types and benefits) and construction procedures associated with micropiles. The preparation of this text has resulted from a literature research, therefore much of the information that is contained there, can be found in the texts mentioned in the bibliography.

In Chapter 3 is discussed the main methods of geotechnical design used for this type of foundations. This chapter also deals with the considerations about the structural design of the micropiles, and focuses on practical aspects of construction and connection details to the superstructure.

The Chapter 4 aims to provide a description of procedures to study the issue of buckling of micropiles as well as recommendations for conducting its analysis in a systematic way. The analysis of this phenomenon is completed by a parametric study using a calculation model through finite elements method.

In Chapter 5 the intention was to follow a practical example of the increasing occupation of alluvial soils with inherent problems of resistance and deformability. This chapter presents the adopted solutions for the treatment of the soil foundation, the ground floors foundations and the underpinning of the foundations existing in the industrial warehouses, in steal structures, at the place of the “Antiga Trefilaria”, in Sacavém, near the “Trancão” River (Figure 1). With the intention of drawing conclusions about the assumptions and adopted criteria, it was performed a characterization of the area, under analyzes, to have a known geotechnical scenario and were also preformed two static load tests in the same area in order to optimize the final design solution and to predict the settlement of the very compressible areas, like soft areas.
2. MICROPILES

Originally designed in Italy in the early 50’s, the solution of micropiles came up with the need to improve the foundations of historic buildings, or act as a method of rehabilitation, taking into account the damages during the 2nd World War. It was necessary a solution compatible with different types of soils, which could be applied in reduced areas and minimizing the effects on adjacent structures [8]. The original concept of micropiles was due to Dr. Fernando Lizzi that in Fondedile Construction Company had developed a solution called "Pali Radice" (root cuttings) whose aim would be to create a foundation system similar to the roots of trees. The success of this application was so huge that drew the attention of all professionals in geotechnical engineering and led to a quick expansion of this building process, not only the great ability to withstand axial forces but also by the versatile application in different geological sceneries [5]. The micropiles can be defined as high slenderness element composed of cement grout sealing and / or injection, and having a steel profile as reinforcement that resists to the majority of the total design loads. This load is mainly resisted by the steel and conveys to the surrounding soil primarily by lateral friction. The main characteristic of this type of indirect foundation is a high load capacity that is based primarily on the lateral friction (in the presence of solid rock, the tip resistance could also become significant), which can be provided even for a weak soil features [2].

The micropiles, like the conventional piles, can be drilled or driven, although the typical construction involves four key stages (Figure 2):

- Drilling;
- Placement of reinforcement;
- Sealing;
- Injection of cement grout at high pressure.

The micropiles are a specialized tool from a range of geotechnical solutions to solve very specific problems, on which the mechanical characteristics of the soil do not provide bearing capacity in surface areas, being necessary to achieve great depths to obtain appropriate values of resistance and limit settlements to acceptable values. These elements are also included in the type of foundation of structures subjected to anti-gravity action. However, applications of micropiles can be divided into two groups, structural support (foundation of new structures, improving the ability of foundations, reinforcement for seismic actions ...) and overall reinforcement of the soil “in-situ” (reduction settlements, stabilization of slopes ...).

This method has a wide range of benefits (regardless the type of micropiles and construction process), which, in fact, explains its increasingly use:

- Little disruption of the surrounding soil in terms of vibration and noise;
- High load capacity in terms of the diameter of the micropiles, even in poor soil characteristics;
- Allow an excellent control of settlements;
- Possibility of working in limited areas;
- Good income in its implementation.

The disadvantages of this solution:

- It’s a specialized intervention with the need of very specialized firms, with appropriate equipment and manpower;
- It doesn’t support instability phenomena in soft/incompetent soils where there is the danger of buckling;

Figure 1 View of the intervened warehouses [1]
• Limitation of load capacity due to the small diameters used in this technique.

3. STRUCTURAL DESIGN OF THE BEHAVIOUR OF THE MICROPILES

This chapter aims to “unify” the design approach for micropile (Figure 3). It follows a multi-step approach shown in the next text [4]:

- **Feasibility**
- **Review All Available Project Information and Geotechnical Data**
- **Develop Applicable Loading Combinations**
- **Initial Design Considerations**
  - Section of Spacing;
  - Selection of Length;
  - Selection of Micropile Cross Section;
  - Selection of Micropile Type;
  - Selection of equipment taking into account the site main conditions.
- **Final Design**
  - Design for Geotechnical Limit States;
  - Design for Structural Limit States;
  - Connection to the micropiles caps
  - Service Limit States
  - Corrosion Protection
  - Seismic Considerations

![Figure 2 Typical micropile construction sequence [3]](Image)

![Figure 3 Detail of a typical high capacity micropile [4]](Image)
4. BUCKLING OF MICROPILES

The structural capacity of a micropile is often determined by the geotechnical capability dictated by lateral friction between the grout used in the micropile and the surrounding soil, rather to strength of the elements that constitute it. However it’s reasonable to believe that when intersecting soft soil, monogranular saturated sandy soil with potential for liquefaction, micropile could be heavy loaded, and the buckling may be a phenomenon that will affect the load capacity of micropile [6].

This chapter intends to present some fundamental concepts that characterize the behaviour of the structures about the buckling phenomena and present a brief parametric analysis on the influence of certain factors on the question of buckling. This analysis consisted of applying the finite element analysis of linear stability of a micropile confined by the soil environment to determine the critical loads and buckling modes based on the consideration of geometrically nonlinear effects.

The program used was ADINA (Automatic Dynamic Incremental Nonlinear Analyses, Version 8.5) which aims, among other things, to do a linear and nonlinear finite element analysis. For the study in question was used a tool for linear analysis of buckling, in order to obtain the lowest critical buckling load for different scenarios (Figure 4 and Figure 5), then the analyzes proceeds to a variation of parameters as the modulus of soil reaction, section, moment of inertia and length of micropiles, determining, in each case, the lowest critical load of buckling of the structure.

In those several scenarios it was considered three types of micropiles, as illustrated in Table 1. Adopted the yield stress value of 500 MPa and modulus of elasticity of steel was considered equal to 200 GPa.

<table>
<thead>
<tr>
<th>Name</th>
<th>Micropile tube</th>
<th>Outside Diameter [mm]</th>
<th>Thickness [mm]</th>
<th>Area [m²]</th>
<th>$f_y$ [MPa]</th>
<th>Yield load [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Section 1 (CT1)</td>
<td>118 x 7,5</td>
<td>118</td>
<td>7,5</td>
<td>26,04</td>
<td>500</td>
<td>1301,8</td>
</tr>
<tr>
<td>Cross Section 2 (CT2)</td>
<td>118 x 10,6</td>
<td>118</td>
<td>10,6</td>
<td>35,77</td>
<td>500</td>
<td>1788,3</td>
</tr>
<tr>
<td>Cross Section 3 (CT3)</td>
<td>170 x 10,6</td>
<td>170</td>
<td>10,6</td>
<td>53,08</td>
<td>500</td>
<td>2654,1</td>
</tr>
</tbody>
</table>

Table 1 Characteristics of micropile

In order to use the finite element method to analyze the buckling problem it is necessary to admit that the material (micropile and soil) has linear elastic behaviour (linearity) and that the displacements and deformations, as it comes to stability analysis, require a nonlinear behaviour.

Despite a more realistic study should consider a behaviour between an analysis in plane stress and plane strain state, it was assumed, due to the very close results provided by the program in both analyses, that the final results would focus in the analyses in plane stress (plane laminar structure subject to existing efforts only on its plan where it’s acceptable as valid the following assumptions: $\sigma_{xz} = \sigma_{yz} = \sigma_z = 0$).

The results for the cases 1 to 6 can be analyse in tables below (Table 2, 3 and 4), which show the values of critical load and the deflection in each case.

For cases 3 and 4 it is possible to observe the results of the variation of critical load with the reaction module of the soil in Figure 6.

From the analysis of previous data it shows that in most situations the critical load is higher than the design load and in the areas where the phenomenon of buckling is a constraint, the reaction modules of soil are reduced to very low values. With the same result it is possible to observe that the modulus of reaction influences the critical load, this is to say, the critical load of instability increases as the surrounding soil improves its mechanical properties, so the buckling phenomenon is most likely to occur in soils with very low resistance properties.

Looking at the deflection graphics it is possible to watch that with the increase of the transversal dimensions, the control is more efficient over the horizontal displacements suffered by micropiles, while with the variation of slenderness is observed an excessive increase in the amplitude of the horizontal displacements.
Figure 4 Case 1 to 4

Figure 5 Case 5 and 6
### Table 2 Achievements case 1 (left) and case 2 (right)

<table>
<thead>
<tr>
<th>Micropile</th>
<th>Critical Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CT1) 118 x 7.5 [mm]</td>
<td>4.93</td>
</tr>
<tr>
<td>(CT2) 118 x 10.6 [mm]</td>
<td>6.42</td>
</tr>
<tr>
<td>(CT3) 170 x 10.6 [mm]</td>
<td>20.89</td>
</tr>
</tbody>
</table>

### Case 1 - Critical Load – $P_{cr}$ (kN)

<table>
<thead>
<tr>
<th>Micropile</th>
<th>Critical Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CT1) 118 x 7.5 [mm]</td>
<td>0.79</td>
</tr>
<tr>
<td>(CT2) 118 x 10.6 [mm]</td>
<td>1.03</td>
</tr>
<tr>
<td>(CT3) 170 x 10.6 [mm]</td>
<td>3.34</td>
</tr>
</tbody>
</table>

### Case 2 - Critical Load - $P_{cr}$ (kN)

<table>
<thead>
<tr>
<th>Micropile</th>
<th>Critical Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CT1) 118 x 7.5 [mm]</td>
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</tr>
<tr>
<td>(CT3) 170 x 10.6 [mm]</td>
<td>3.34</td>
</tr>
</tbody>
</table>

### Table 3 Achievements - case 5

<table>
<thead>
<tr>
<th>$K_s$ (kN/m²)</th>
<th>Micropiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>118 x 7.5 [mm]</td>
</tr>
<tr>
<td>1051.0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6 Variation of critical load with the module reaction – case 3 (left) and case 4 (right)

Figure 7 Deflections for pre-selected cases

Figure 8 Representation of displacements – case 1 (left) and case 2 (right)
With the consulting of the previous data it is possible to state that the condition of considering an elastic support (spring) increases the value of critical load condition by changing the deflection form, which proves to be an important phenomenon when analyzing the critical load of the system micropile-soil.

From the analysis of the results in case 6, it is also possible to state that the phenomenon of buckling compression is not determinant relatively to the yield resistance of the micropiles ($P_{cr}=4910$ kN > $N_{rd}=3315.3$ kN).

**5. MONITORING OF A WORK WITH THE USE OF MICROPILES TECHNOLOGY**

The aim of this chapter is to present the observation of a work, where the technology adopted were drilled and driven micropiles. Another goal was to study the main design and execution criteria for the adopted solutions for the underpinning of pavements (that concerns the treatment of the soil solution of the foundation and ground floors) and structures of industrial buildings located on the site of the old Trefilaria, next to the Trancão River.

Regarding the main existing constraints, the solutions have been developed in order to allow the excavation of fill materials and execution of hollow section micropiles, to support a new reinforced concrete slab. The main constraints were the following:

- **Geological and geotechnical** – the buildings were already built over a layer of fill, resting over a geological scenario, dominated by the alluvial basin of the Trancão River. With the geologic / geotechnical information collected from site investigation as well from the monitoring and instrumentation devices (Erro! A origem da referência não foi encontrada.) it was considered that the land is submitted mainly to vertical movements due to the consolidation of the very soft soil. That was caused by the increase of the stress due to the weight of landfills (with thicknesses of around 4m), transmitted to the alluvial mud and very soft clay ($0.4 \text{ MPa} < q_c < 1 \text{ MPa}$). This process resulted in settlement rates over time of about 5mm per week which, according to the preformed studies, spreaded over several years until reaching values of around 1.0 m [9].

It was identified the following soil groups classified from the surface:
- Landfill Deposits (consisting of mainly sandy-clay with rocky areas, with thicknesses between 4.50 m and 5.50 m);
- Alluvial Deposits (underlying the previous line, with thicknesses between 12.0 m and 23.0 m, and sometimes with interbedded sandy lenticules, which conditioned the phenomena of consolidation in terms of modeling and consolidation. These formations are primarily composed of silty-clay mud with small sandy-silt lenticules); Miocene Substrate (underlying formations mentioned above), this material that can be described like: fine sand silt, more or less muddy, with some stiff mud, medium to fine sandy silt, slightly muddy, sand grains-carbonated; clays silt, micaceous, fossiliferous calcareous, fractured and with friable passages; clay marl.

### Table 4 Achievements - case 6

<table>
<thead>
<tr>
<th>Buckling Mode</th>
<th>Critical Load - $P_{cr}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1º Instability Mode</td>
<td>4910</td>
</tr>
<tr>
<td>2º Instability Mode</td>
<td>4918</td>
</tr>
<tr>
<td>3º Instability Mode</td>
<td>5173</td>
</tr>
</tbody>
</table>

![Deflections for case 6](image_url)
- **Structural** - The new structural solution included a system of loads distribution different from the one that was used in the initial structure. In areas where there was the existence of small rates of settlement, it was adopted the solution of compression fills, replacing existing landfills by lightweight aggregates (Figure 11). Thereby increasing the degree of consolidation of the alluvial materials and therefore reducing the rate of the allowed settlements.

Another task was to underpin the foundations of the industrial warehouses, which consisted essentially in the underpinning of the founding of the steel structures through micropiles solidarised with prestressed bars, to the massive caps and beams of underpinning system (Figure 12). In this operation drilled micropiles were used, consisting of steel pipes, steel type N80 (API 5A), with a minimum diameter Ø177, 8 mm and 10.0 mm wall thickness, with yield stress fy > 562MPa and ultimate stress fu > 703MPa, accommodating an axial service load with maximum value of 1400kN [9].

For the foundation of the new ground-floor slabs driven micropiles were used, made of metal ductile iron pipes (Figure 13), type TRM, with Ø170mm minimum outside diameter and 10.6 mm thick wall, with yield stress fy > 300MPa and ultimate stress fu > 420MPa, accommodating an axial load of service with the maximum value of 1300kN [9].

All micropiles were reinforced at its overall length by Ø50mm type “GEWI” bar, steel A500/550;

- **Conditions of neighbourhood** – The adopted solutions had to consider the coexistence of the treatment soil operations with the occupation of the stores already delivered to the owners;
• **Duration of the work** – Structural and geotechnical solutions were chosen in order to meet the owner deadlines;

![Figure 12 Detail of underpinning of the superficial foundations inside the existing metal structure](image)

![Figure 13 View of driven equipment of micropiles and placement the reinforcement bar](image)

This chapter also presents a micropile full scale compression load test, which scheme could be seen in Figure 14. This test was made to evaluate the performance of an early solution of strengthen foundations as well as of soil improvement, when submitted to downdrag phenomena caused by the consolidation of surrounding soil. The data represented below is related to previous trials in a drilled micropile, at the site where the works took place, and was performed with the aim of characterizing the soil behaviour, assessing the adequacy of construction method and test the solution behaviour.

![Figure 14 The micropile load test scheme](image)

In the following figures it’s represented the displacement vs. depth considering the cycles defined above, as well as the estimation of other quantities (Figure 15 until Figure 19).

![Figure 15 Cycles stage](image)
From the data interpretation it was possible to achieve the following observations:

- The ultimate load that the test shows is approximately 1800 kN, representing 55% of the micropile design load without lateral instability;
- Micropile execution method significantly weakened surrounding soil mechanical properties, especially in the very soft clays layer, where water was used during the drilling operations;
- High shaft resistance in the sandy deposits (expecting drag residual load);
- At ultimate test load, a lateral soil pressure was away from failure;
- The structural behavior of the micropile is very limited by lateral instability.
It was also performed a full scale compression load test in a driven micropile similar to the previous one. The data represented below is related to a comparison between the evolution of displacement vs depth in driven and drilled micropiles.

From the data interpretation it was possible to achieve that driven micropiles allow small settlements compared to those produced in drilled micropiles.

The instrumentation and observation of the consolidation process of the alluvial materials for about 4 years was also analysed. The Instrumentation and Monitoring plan was developed in order to enable a systematic control of the parameters considered relevant to the study of the evolution of settlements in the area, as well as to ensure a proactive monitoring of the behavior of the structure, particularly during operations of charging and excavation.
The observation was implemented before the beginning of the work (underpinning of the foundation) and has shown to be a key tool, to the confirmation of the solution efficiency. This can be shown in Figure 21 where it’s possible to confirm that the muds were submitted to a consolidation process, which could reach, in some places, rates of settlement of 1.0 mm / day [11].

Figure 21 Plant with the initial rate of settlement [11]

In this stage were installed, before and during construction, the following equipments: 100 topographic targets (to assess the overall and differential settlement between different points of the structure); 11 benchmarks (to assess the vertical settlements of the industrial buildings facades located in the most problematic places); 3 inclinometers within some of the boreholes of the geotechnical site investigation (to assess the potential susceptibility of alluvial formations to make horizontal movements in depth, once the Miocene substrate showed an elevated susceptibility towards the River Trancão); 4 inclinometers within some micropiles (to assess the possible micropiles horizontal displacements) and 5 piezometers (to assess changes in the piezometer level).

The devices installed were read, in the first instance, once a week to collect the maximum information in order to analyze the evolution of settlements and in the second stage (after complete most of the excavation and micropiles works) readings were taken monthly, since that the magnitude of the rate of evolution of the movements recorded were significantly lower.

The data produced by the devices installed indicated excessively different vertical settlements of steel frames in corresponding areas to the highest thickness of the alluvial material (Figure 22). It shows the need of strengthening the elements of the industrial buildings main facade in order to safely accommodate the efforts from the loads applied at the deformed structure.

Figure 22 Levels of settlements accumulated over 3 years in the different frames of the main frontage [7]
6. CONCLUSIONS

In general, the results indicate no need for checking the ultimate limit state of buckling in micropiles, which does not invalidate (knowing the high slenderness of micropiles) a tight control of some key factors such as elastic critical load, the axis midline deviation, geometric imperfections of the section and soil-micropile interaction.

In the adopted model, which had as main goal to measure the conditioning of the phenomenon of buckling by compression in the structural design of the micropiles, it was noticed that the buckling should not be a concern for the types of micropiles used in this study, but it can exist some cases in which buckling can be a major constraint in a project. Micropiles apart from being slender structural elements capable of carrying large loads, when penetrate soft soils are in danger of buckling even when in some design codes the require safety check against buckling is not needed.

Within the presented underpinning case study, the instrumentation and monitoring plan associated with an adequate characterization of the geological and a geotechnical scenario in a stage before the project started, proved to be a fundamental tool to support and justify the proposed rehabilitation and strengthening design. During the construction and exploitation, the instrumentation and monitoring, is also justified as a tool for analyzing and controlling the behaviour of the structure, confirming the suitability of the adopted solutions. The usefulness of load tests on piles presented themselves as important prediction tool, because it can assess the adequacy of the construction method, to determine the behavior of a pile and provide a representative consideration of the surrounding terrain. It also clarifies in terms of: ultimate limit states (load capacity) and serviceability limit states (deformation, creep behavior and elastic / plastic in the discharge).

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8. REFERENCES

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