Underpinning and Foundation Refurbishment Techniques

Procedures, Design and Safety Requirements

EXTENDED ABSTRACT

Manuel João Niza das Neves

Júri

Presidente: Prof. Doutor José Manuel Matos Noronha da Camara
Orientador: Prof. Alexandre da Luz Pinto
Vogal: Prof. Doutor Victor Manuel Pissarra Cavaleiro

October 2010
Underpinning and Foundation Refurbishment Techniques

Procedures, Design and Safety Requirements

EXTENDED ABSTRACT

1. Introduction

The safeguard of the built heritage has been gaining an increased importance among the various entities related to construction. Nevertheless, the shift of paradigm that needs to take place in order to achieve an overlap of new construction by rehabilitation/reuse of buildings is still far from being established in contemporary society.

However, there are a few construction techniques, which have been successfully implemented for several years, that enable the execution of temporary and definitive works, namely excavations in urban areas and underpinning, in an economical, practical and, above all, safe manner. The growing number of projects of this nature was not accompanied by the development of standards and codes of practice specifically dedicated to this subject. As a result, it is often required from engineers to thoughtfully adapt the existing regulations, applied to new construction, to the project at hand.

This paper, whose main objective is to review/overview some of the construction techniques associated with underpinning operations and the systematization of the needed steps applicable to two procedures in particular (micropiles and jet grouting), aims to incorporate, in a single document, the most important features and the safety requirements involved in these projects.

Finally, three case studies of underpinning are presented, concerning the application of the stated techniques, design by the company JetSJ Geotecnia, Lda, between March and September of 2010.

2. Underpinning project and construction techniques

The rehabilitation of an existing building, mostly 40 to 50 years old, motivated by a change of use or structural damage, which may be a consequence of insufficient soil bearing capacity, may require an underpinning project.

This type of work requires skilled labour, not only constructors, but also in the planning stage, since there is not an universal solution applicable to all cases. In fact, the underpinning solution depends on many factors, among which are the mechanical properties of the support stratum of soil, the conservation conditions of the foundation elements and, above all, the restrictions imposed during this operation.

The need for reinforcement of foundations is generally associated with works under an existing construction or in their immediate proximity (changes in boundary conditions of the ground foundation), or induced by the degradation with time of the foundation stratum. The first case is becoming increasingly common in urban areas, due to the need of mobility, resulting in the execution of tunnels or underpasses, but also the creation of underground car parks, associated with the construction of several levels of basements.
It is possible to intervene in various manners in order to reinforce/underpin foundations. One possibility is to improve the soil mechanical properties, increasing its bearing capacity and its stiffness. On the other hand, it is also possible to act on the foundation itself, improving its resistance or reducing the foundation-soil contact stresses.

2.1. Micropiles

Micropiles are presented as a variant of deep foundations, and consist of piles of small diameter between 75mm and 350mm, cast in situ, vertical or executed with an angle. These elements, when compressed, transmit their forces to the ground primarily by lateral friction (floating piles), although there is a small contribution from the bearing resistance. In general, the execution of micropiles is divided into the following stages [1], as illustrated in Figure 1:

- Drilling to the specified depth;
- Placement of the reinforcement;
- Gravity fill injection of grout;
- Pressure postgrouting injection, when applicable.

2.2. Pre-stressed connection

The use of this GEWI type systems results, firstly in the installation of a certain normal stress at the interface between the beam and the underpinned element. Moreover, the load transfer to the micropiles produces, according to the strut and tie method, tensions that can be absorbed at the expense of the resistance of these steel bars (Figure 2).
2.3. Jet grouting

The physical process of jet grouting technique can be summarized in the following steps [20]:

- **Soil fracture**: the initial structure of the soil is broken and the soil particles or fragments are dispersed by the action of one or more horizontal jets;
- **Mixing and partial replacement**: a part of the particles or fragments of soil is replaced and the other part is mixed with the injected grout;
- **Cementation**: the remaining soil particles are bonded together as the grout sets and hardens, forming a single body.

This technique can be applied to both incoherent and cohesive soils, as a result of the conversion of the potential energy, obtained from pumping the grout, into kinetic energy (Figure 3), allowing the creation of jet elements with various forms.

![Figure 3. Schematic sequence of the jet grouting method, adapted from [3].](image)

3. Design and limit states

3.1. Micropiles

When considering a solution with micropiles, as like as in any other engineering design, it is necessary to conduct a cost benefit analysis of the technique. Typically, the scenarios in which a micropile solution stands out from the remaining underpinning/reinforcement techniques are:

- Adverse conditions of the soil stratum below the current foundation, such as the existence of layers of debris, or boulders, or even high groundwater;
- Restricted accesses and/or limited overhead clearance;
- Existence of subsurface voids (like karstic soils);
- Restrictions on noise emission and vibration;
- Superstructure sensitive to settlements.

Bond length design results from the Bustamante’s method, in accordance with Equation (3.1):

\[
L_i > \frac{N \times FS}{\pi \times \alpha \times \phi \times \tau_{c-s}}
\]  

(3.1)

where \( N \) represents the axial load, \( FS \) the safety factor, \( \alpha \) the expansion coefficient of the bond length, \( \phi \) is the drilling diameter and \( \tau_{c-s} \) the grout-to-ground bond strength.
When designing these elements the end bearing resistance is usually neglected. This decision is justified by the reduced cross section of the tip of the micropile, but also due to the drilling techniques used, that can result in an accumulation of debris on the bottom of the hole, difficult to remove completely. The maximum axial compression that a micropile can be subjected to, according to article § 6.7.3.2 (a) of the EC 4 [4] is expressed in Equation (3.2),

\[ N_{pl,ad} = A_s f_{yd} + 0.85 A_c f_{cd} + A_{rd} f_{yd} \]  

where \( A_s \) represents the cross section of the steel hollow section and \( f_{yd} \) its yield stress, while \( A_c \) corresponds to the grout cross section and \( f_{cd} \) its design compressive strength. The last term is related to the reinforcement bars inserted in the micropile, being \( A_s \) and \( f_{yd} \) its cross section and yield stress. However, the previous expression is only valid when the shear load is inferior to half of the plastic shear resistance.

Just like any other slender element, in certain situations it is required to consider the buckling of micropiles, namely when the elements surpass a certain limit slenderness (\( \lambda_t \)). In these cases, the micropiles are supported by metal supports similar to the illustrated in Figure 4, considering the effective span the distance between these supports.

The design axial tension of a micropile can be obtained by removing the term related to the strength of the grout (since it is assumed that its tension strength is null) form Equation (3.2), thus obtaining the expression (3.3), according to § 6.2.3 of EC3 [5].

\[ N_{pl,ad} = A_s f_{yd} + A_{rd} f_{yd} \]  

The connection between the micropiles and the structure to underpin is usually assured by underpinning beams on each side of the wall to support, as illustrated in Figures 5 and 6.
The serviceability limit state of micropiles is verified by evaluating the elastic vertical deflection of the elements ($\Delta_v$), accordingly to Equations (3.4) and (3.5), and then comparing the obtained value to the limits prescribed in Annex H of the EC7 [7].

$$\Delta_v = \frac{NL}{EA} \quad (3.4)$$
$$EA = E_c \times A_c + E_{app} \times A_{app} \quad (3.5)$$

Where $N$ is the axial load while $L$ and $EA$ are the length and the axial stiffness of the micropile, considering both the stiffness of the steel section ($E_{ac} \times A_{ac}$) and the grout ($E_c \times A_c$).

### 3.2. Jet grouting

Unlike the previous technique, where the material properties were entirely known, jet grouting do not lead to accurate predictions of the final characteristics of the treated soil when in the design stage. This situation is due to the fundamental concept of this technique, which is not to replace completely the soil to be treated, but to improve its geomechanical characteristics by adding grout. Therefore, the final product is strongly conditioned by the initial characteristics of the soil, as well as its replacement percentage.

Typically, jet grouting solutions are profitable and stand out, in relation to other forms of injection, in the following situations:

- In heterogeneous soils, whose layers are well defined, resulting in an adjustment of the parameters of the jet for each type of soil, obtaining a uniform treatment in depth;
- When jet grouting columns have more than one purpose, such as excavations (common in underpinning operations), where these elements prevent the entry of water into the work site, as well as withstand the impulses of the soil and from other overloads;
- In underpinning operations executed from the outside of buildings, that after the cure of the material are perfectly bounded to the existing structure;
- When there are noise and vibration restrictions.

To calculate the length of jet column ($L_v$), the method of Bustamante is used, presented in Equation (3.6):

$$L_v > \frac{N \times FS}{\pi \times \phi \times \tau_{c-g}} \quad (3.6)$$

where $N$ represents the axial load, $FS$ safety factor, $\phi$ is the drilling diameter and $\tau_{c-g}$ the soil cement-to-ground bond strength.

Regarding axial compression resistance, some proposals from several authors are synthesized in Table 1.

<table>
<thead>
<tr>
<th>PROPOSALS</th>
<th>CLAY</th>
<th>SILT</th>
<th>SAND</th>
<th>GRAVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langbehn (1986)</td>
<td>8 a 12</td>
<td>8 a 12</td>
<td>14 a 17</td>
<td>17 a 21</td>
</tr>
</tbody>
</table>
Given the high dispersion of resistance values presented it is usual, when in a design stage, to specify a minimum compressive resistance, generally 2 MPa.

In situations where tensions are applied to the jet columns, the usual solution is to insert in to them metallic elements, like micropiles, ignoring the tension resistance of the soil cement. In these cases, the ultimate limit state of tension of the reinforcement element and the geotechnical strength limit state between the reinforcement and the jet column should be verified.

Regarding the verification of the serviceability limit state, the columns are treated as micropiles, which means that the estimated vertical deflection of the elements ($\Delta_v$), calculated from Equation (3.7), should be compared to the limits prescribed in Annex H of the EC7 [7]. In that expression, $N$ is the axial load while $L$ and $EA$ are the length and the axial stiffness of the jet column.

$$\Delta_v = \frac{NL}{EA} \quad (3.7)$$

An estimate of the stiffness module of the soil-cement columns can be obtained graphically, which establishes a correspondence between the stiffness of the elements and their axial compressive resistance (Figure 7).

From within the gathered research papers it was possible to conclude that the stiffness of jet columns executed in incoherent soils is generally higher than when executed in cohesive soils. Nevertheless, it is also clear that the curing also plays an important role in the final stiffness of these elements.

<table>
<thead>
<tr>
<th>Source</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mosiici e Guatteri (1986)</td>
<td>2</td>
<td>6</td>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td>Xanthakos et alii (1994)</td>
<td>4 a 7</td>
<td>4 a 7</td>
<td>7 a 14</td>
<td>10 a 17</td>
</tr>
<tr>
<td>Baumann et alii (1984)</td>
<td>3 a 10</td>
<td>3 a 10</td>
<td>5 a 14</td>
<td>6 a 18</td>
</tr>
<tr>
<td>Fiorotto (no date)</td>
<td>2 a 4</td>
<td>6</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

**Figure 7. Wall connected to underpinning beams [2]**.
4. Case studies

4.1. Rosa Araújo Hotel

The design of the Hotel Rosa Araújo emerges in a context of rehabilitation of several buildings on the Rosa Araújo Street (Figure 8) in Lisbon, in order to build a hotel there. Given the need to preserve the integrity of the facades of edifices subjected to intervention, as well as the boundary conditions (Figure 9), it was necessary to design a solution that would limit both vibration and noise.

One aspect, apparently irrelevant in an early stage of development, was the geometry of the facades to preserve, more precisely the location of their balconies. Since the owner’s intention was to fully maintain these elements, the location of the micropiles was restricted. Another key feature was the use of a support structure to withstand the horizontal actions on the facades, leaving de underpinning micropiles subjected only to axial loads (Figure 10).

The adopted underpinning solution resorted to underpinning beams on each side of the walls, connected through pre-stressed GEWI type bars. The vertical loads were then supported by two rows of micropiles, the first executed within the existing building and the second on the outside.

On the main facade, the interior micropiles, for architectural reasons, could not be executed within the retaining wall, which implied that the buckling phenomenon had to be taken into account in their design. A similar situation took place with the micropiles that support the back facade, whose only difference was the type of intermediate support used. In the first case metallic supports were prescribed, while in the second concrete slabs were used, coincident with the future floors (Figure 11).
4.2. Portugália quarter in Arroios

Given the need to preserve the integrity of the facades of the Portugália brewery, built partially in masonry, it was necessary to design a solution that limited vibrations along the underpinning works. The remaining lot (Figure 12), dating from the 70s, occupied by more recent installations of the factory and the office buildings did not cause major restrictions, since its demolition was previously executed.

The major obstacle of this contract, and unlike the previous case study, was the execution of the underpinning operations of the facades/vertical elements of the marked zone in Figure 13, without performing any demolitions on the Portugália brewery building. The design plan allowed the excavation of the ground beneath the existing structure, between 1.70 m to 3.20 m deep, without much interference in the superstructure.

The underpinning solution (Figure 14) was somewhat similar to the one outlined in the previous example. However, the need to underpin so many nearby different elements, resulted in a complex solution. In most of the sections of the walls (P-Q, Q-R and R-S) the underpinning solution resorted to underpinning beams on each side of the walls, connected through pre-
stressed Gewi type bars, while the vertical loads were supported by two rows of micropiles, the first executed within the existing building and the second on the outside. For constructive reasons, the section of the wall (N1-N2) was only accessible from the interior of the wall. Therefore, only one underpinning beam was designed, connected with steel bars (subjected to dowel action) to the existing element. The adopted methodology to underpin the pillars consisted of an underpinning beam around them, pre-stressed against the vertical element through the use of GEWI type bars, with four micropiles, one in each corner.

Among the previous operations, only the underpinning of the wall sections P-Q and Q-R are to be performed from the street level (ground floor), while the remaining solution is to be executed from the basement of the existing building. Since all interior micropiles, for architectural reasons, could not be executed within the retaining walls, they were designed taking into account the buckling phenomenon. The support of the retaining walls was guaranteed by means of ground anchors, struts and ties. These walls were designed as Berlin concrete wall solutions, when coincided with the location of future walls, or as King post retaining walls in the remaining situations, thus facilitating their subsequent removal.

### 4.3. Montijo’s Motel

The building to intervene, which was under construction during the design of this project, is a medium size construction, with one floor above the ground and an area of approximately 2550 m² (Figures 15 and 16).

During the design stage of the building, the mechanical properties of the soil were estimated inaccurately, which was noticed during construction. Thus, and since the structure was already partially built, it was necessary to design an underpinning solution [52]. Taking into account the heterogeneity in strength and deformability of the foundation’s soil characteristics both in plant and in depth, a soil treatment solution, using jet grouting, was prescribed.
The jet grouting columns were designed to transfer the applied loads to the soil through lateral friction, to the deeper and more competent strata than the superficial ones. The geometry of the solution, presented in Figures 17 and 18, ensured that the ground/footing contact was larger than half of the footings.

Two jet columns were prescribed beneath each footing, one that extends until the competent stratum to ensure the required length in order to transfer the totality of loads through lateral friction. However, and to minimize the asymmetry caused by implementing a single column in the final solution, a second column, executed symmetrically to the first, was designed. For the above mentioned reasons, the second column should only be performed after the curing process of the first.

5. Conclusion

An underpinning project is strongly influenced by the sensitivity of the construction to underpin/reinforce as well as its boundary conditions. Therefore, solutions that resort to micropiles or jet grouting are very popular, since they limit noise and vibrations.

The use of micropiles is particularly advantageous, since it allows the execution of inclined holes that can even intersect the existing foundation, whether it is made of masonry or concrete. As a result, the application of micropiles is very widespread, especially since they can be executed in limited spaces. However, in most situations, these elements are not executed directly against the existing foundation, so they require an effective connection to the existing structure, generally achieved at the expense of underpinning beams. When the foundation is only accessible on one side, the beam is connected through steel dowels designed to support the shear in that interface. When both sides are at reach, the bond is guaranteed by pre-stressing the beams against the existing foundation.

Regarding the use of jet grouting solutions, its competitiveness, when compared to other techniques of soil improvement, results not only from the outcome of the technique (in terms of the final geomechanical characteristics of the soil), but also due to their low costs (execution and quality control). This technique, applicable to a very wide range of soils, can be incorporated in an extensive variety of situations such as foundation reinforcement, tunneling, as a water barrier or even as temporary or permanent support to excavation works. In fact, some of the decisive advantages of this technique are the effective bond between the treated
material and the existing structures, as well as the possibility of performing this procedure in low height spaces, inducing low noise and vibration.

Finally, it is of the most importance to draw attention to the fact that the current legislation focuses mainly on new construction. As a result, civil engineers often must adapt the existing methodologies to these situations.

6. Notation

<table>
<thead>
<tr>
<th>Roman capital</th>
<th>Roman lower case</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_d$</td>
<td>cross section of the steel hollow section</td>
</tr>
<tr>
<td>$A_{so}$</td>
<td>steel cross section</td>
</tr>
<tr>
<td>$A_c$</td>
<td>grout cross section</td>
</tr>
<tr>
<td>$A_b$</td>
<td>cross section of the reinforcement bars</td>
</tr>
<tr>
<td>$E_{so}$</td>
<td>Young’s modulus of the steel</td>
</tr>
<tr>
<td>$E_c$</td>
<td>Young’s modulus of the grout</td>
</tr>
<tr>
<td>$EA$</td>
<td>axial stiffness of the micropile</td>
</tr>
<tr>
<td>$EA$</td>
<td>axial stiffness of the jet column</td>
</tr>
<tr>
<td>$FS$</td>
<td>safety facto</td>
</tr>
<tr>
<td>$L$</td>
<td>micropile length</td>
</tr>
<tr>
<td>$L$</td>
<td>jet column length</td>
</tr>
<tr>
<td>$L_d$</td>
<td>design bond length</td>
</tr>
<tr>
<td>$N$</td>
<td>axial load</td>
</tr>
<tr>
<td>$N_{pl,ud}$</td>
<td>design axial force</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Greek symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
</tr>
<tr>
<td>$\phi$</td>
</tr>
<tr>
<td>$\tau_{c-a}$</td>
</tr>
<tr>
<td>$\tau_{c-s}$</td>
</tr>
<tr>
<td>$\Delta_{el}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acronyms</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
</tr>
</tbody>
</table>

7. References


