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Design and execution of retaining-walls using the reinforced jet-grouting technique

Conception et réalisation de murs de soutènement par la technique du jet-grouting renforcé

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ABSTRACT: This article presents a solution for the design and construction of reinforced jet-grouting structures. In particular, it discusses the application of reinforced jet-grouting for retaining walls in excavations for basement construction. The use of jet-grouting as a structural element with flexural work is not common, as this product is typically used almost exclusively under pure compression. Flexural forces require the reinforcement of this material with steel bars, and the use of a finite element model is presented as a possible design tool for this purpose. The work described was successfully completed using the concept of reinforced jet-grouting with corrugated steel bars. Additionally, the article outlines the specific procedure for performing jet-grouting in a complex colluvial geology with large, embedded rock blocks in a heterogeneous granular matrix, making it challenging to create ideal intersecting cylindrical jet-grouting columns.

RÉSUMÉ: Cet article présente une solution pour la conception et la réalisation de structures renforcées de jet-grouting. En particulier, l'étude de la solution de jet-grouting renforcé appliquée aux murs de soutènement des excavations pour la construction des sous-sols est commentée. La technique du jet-grouting en tant qu'élément de structure avec travail de flexion n'est pas courante puisque ce produit est généralement utilisé presque exclusivement en compression pure. Les efforts de flexion rendent nécessaire de renforcer ce matériau avec une armature en acier et l'utilisation d'un modèle d'éléments finis est présentée comme un outil de conception possible à cet effet. Les travaux commentés, menés à bien, ont été calculés et exécutés avec ce concept de jet-grouting renforcé de barres d'acier ondulées. De même, l'article présente la procédure particulière pour effectuer le jet-grouting dans une géologie colluviale complexe avec de grands blocs de roche encastrés dans une matrice granulaire hétérogène qui rendent difficile la réalisation de colonnes cylindriques idéales de jet-grouting se croisant.

Keywords: Jet-grouting; retaining walls.

1 GUIDELINES

This article introduces a specific procedure for the design and construction of retaining walls using the reinforced jet-grouting technique in areas with complex colluvial geology. To provide a practical example, the application of this method is illustrated through a project carried out in Andorra la Vella (Andorra). The project was designed by the architect Jordi Batlle Jordana, and the original calculations were performed by Beal AEC, S.L. using their own methods.

Jet-grouting technology enables the creation of cement-treated soil volumes with significantly improved strength and deformation properties compared to the original soil, while also achieving a substantial reduction in permeability. However, it is uncommon to use this technique for creating structural inclusions in the ground capable of withstanding flexural forces, such as retaining walls.

In the specific case we present, the choice of the structural type of retaining wall is influenced by two main factors:

- The ground consists of colluvial soil with large rock boulders (>1m) within a heterogeneous granular matrix.
- The water table is high, located above the excavation floor.

1.1 Containment geometry

The case that serves as our example involves an excavation for constructing multiple basement levels on a site with a sloping topographic surface, featuring an elevation difference of about 10 meters, ranging from 1028 to 1018. The site covers an area of approximately 8000 square meters, and the required excavation depth entails the construction of retaining walls, spanning heights from 7.50 to 16.50 meters. (See Figure 1 and Figure 2).

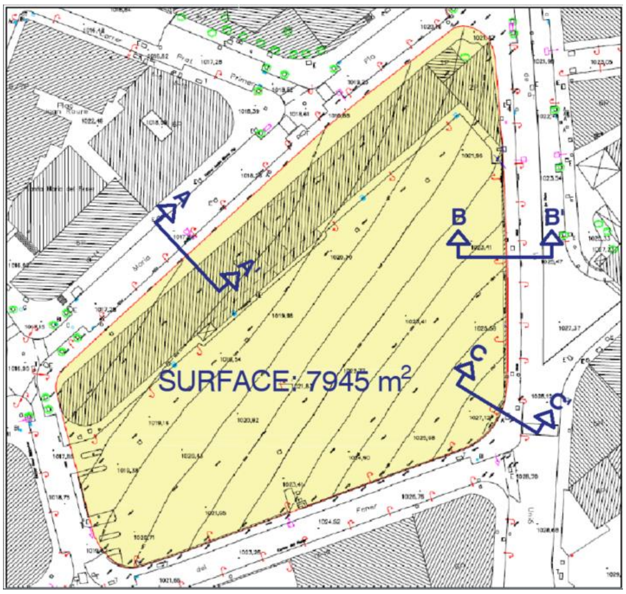

Figure 1. Perimeter of the excavation and location of the typical cross-sections.

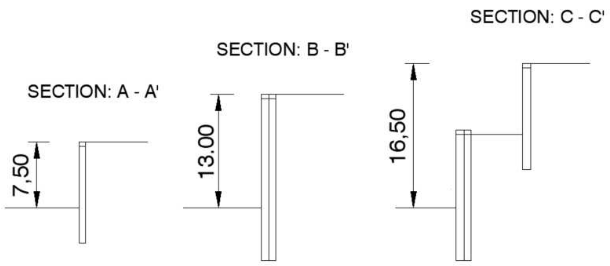

Figure 2. Typical cross-section, showing the highs of the contention in meters.

1.2 Ground characteristics

The ground to be excavated and retained consists of a thin anthropic layer followed by a thick, coarse fluvio-torrential alluvial layer with granite boulders of up to 1 meter in size, within a heterogeneous granular matrix of sand and gravel.

Distinct layers can be identified:

Geotechnical Layer 1: Surface Granular Material

- Density: 18 kN/m3
- Cohesion: 0,0 kN/m^2
- Friction Angle: 28º
- Deformation Modulus: 11 MPa

Geotechnical Layer 2: Fluvial-Torrential Granular Material (Figure 3)

- Density: 19,8 kN/m^3
- Cohesion: 5,0 kN/m^2
- Friction Angle: 30º
- Deformation Modulus: 44 MPa

Figure 3. Soil samples taken from Geotechnical Layer 2. Granite boulders wrapped in sandy clay matrix.

2 EXECUTION OF STRUCTURAL WALLS USING REINFORCED JET-GROUTING

The walls were constructed using secant soil columns treated with jet-grouting. Jet-grouting columns are created by mixing the soil with a slurry through drilling to the maximum depth of the column and blending it with cement slurry during the ascent, with rotation of the drilling rods. (See Figure 4).

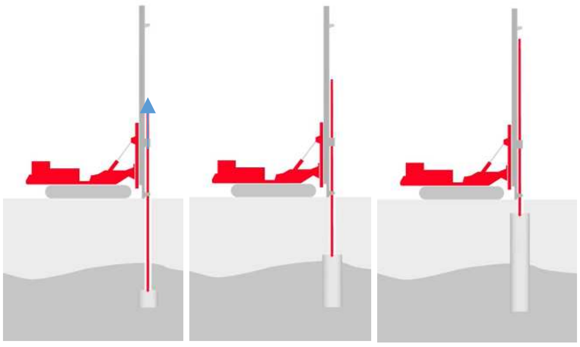

Figure 4. Execution of a jet-grouting column. From bottom to top, withdrawal with rotation while de cement slurry is injected.

Among the different variants of jet-grouting, the one commonly known as Type 1 jet-grouting was used, which employs a cement slurry as the cutting and mixing fluid (For further information on jet-grouting, you can refer to P. Croce 2014 book.).

However, executing a jet-grouting column in soil with large rock boulders, as is the case here, presents a series of challenges that, until recently, seemed insurmountable:

2.1 Challenges in executing Jet-grouting columns in alluvial boulder deposits

- The initial drilling is generally performed with rotary drilling equipment, which is incapable of penetrating the rocky boulders that require rotary-percussive drilling. Rotary drilling is traditionally used for jet-grouting as it allows the injection of slurry through the drilling rods.
- Large boulders hinder the formation of a jet-grouting column with a cylindrical geometry since the "shadow effect" caused by any intercepted rock boulder screens the ideal axial symmetry of the jet. (See Figure 5)

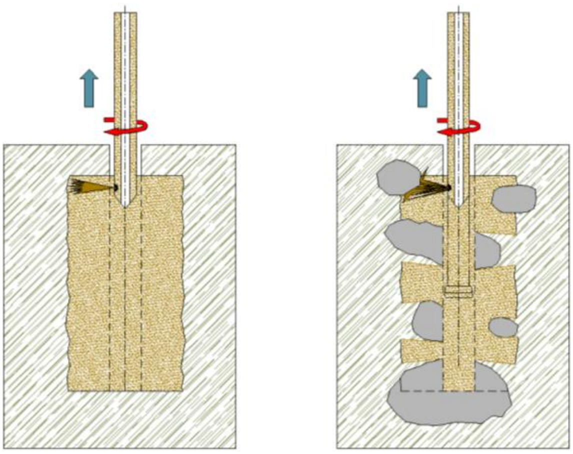

Figure 5. Comparison of Column Formation in Fine Granular Soil and Soil with Large Boulders.

2.2 Solution to the execution challenges of jet-grouting in rocky boulders

To address the previously mentioned problems, the following measures were taken:

a) A DHH pointed hammer was used at the bottom of the drilling to enable rotary-percussive drilling of the rocky boulders. In order to conduct the compressed air to the bottom hammer and, simultaneously, to conduct the cement slurry to the monitor at the bottom of the drilling rod, a Type 2 jet drilling rod with double concentric pipes was used. (See Figure 6).

Note: Commonly, the Type 2 jet drilling rod is a dual rod that allows the conduction of compressed air to a dual nozzle through which cement slurry is injected, enveloped in a concentric jet of air, reducing the dispersion of the jet and concentrating its energy in a smaller impact area.

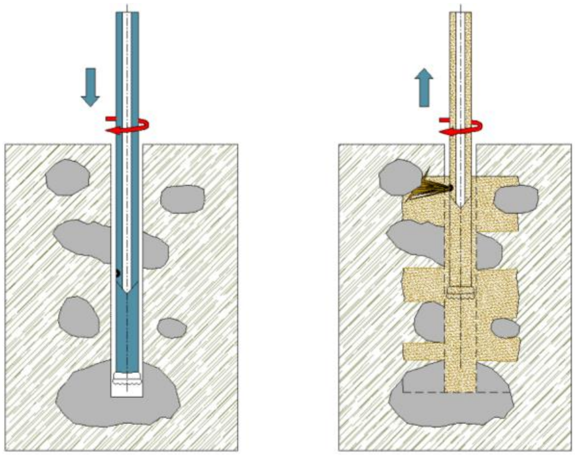

Figure 6. Drilling and injection phase. During drilling, the compressed air actions the hammer. During withdrwal, the cement grout jet erodes the soil and mixes with it.

b) The wall geometry is designed with two or three overlapping rows of jet-grouting columns, ensuring the continuity and impermeability of the wall despite the irregularities that may be caused by intercepted boulders. (See Figure 7).

Plan layout of jet-grouting columns: double or triple row of columns: (See Figure 7).

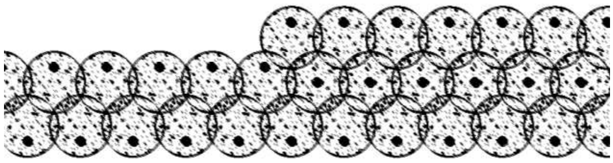

Figure 7. Layout of the jet-grouting columns in plan. The thickness of the wall is created by a double or triple row of intersecting columns.

3 ALTERNATIVE DESIGN METHODS FOR REINFORCED JET-GROUTING WALLS

The common approach for calculating or designing a jet-grouting wall is to model it as a plate element (or the cross section as a 1D beam) that interacts with the ground in terms of stress and deformation. It's also common to model the interaction between the wall and the ground using an elasto-plastic spring model.

When the jet-grouting wall is thick and unanchored, it can be considered as a gravity wall where the self-weight of the jet-grouted volume plays a crucial role in supporting the excavation. In cases where the jet-grouting wall is heavily reinforced, for example, with HEB-type beams and anchors, the stiffness of the wall is typically only considered with the metallic beams, disregarding the structural collaboration of the jet-grouting.

However, when the jet-grouting wall is designed as a two-dimensional, flexible, and anchored element, and its reinforcement is light, for example, with corrugated steel bars (rebars or threaded bars), various considerations arise when modeling this "composite retaining wall", particularly in terms of modeling the behavior of the jet-grouting material.

Since the thickness of the wall consists of a treated and resistant soil volume and steel reinforcement, similar to reinforced concrete, one could model the section as a two-dimensional element with the characteristics of a reinforced concrete plate. However, the configuration of jet-grouting walls consists of overlapping columns in one, two, or even three rows (see Figure 7). This makes the wall thickness significant in relation to the other two dimensions, and a 2D plate model raises certain doubts regarding its suitability.

For these cases of thick, lightly reinforced, anchored jet-grouting walls, we propose the possibility of using a finite element model with a specific representation of the jet-grouting wall thickness.

In the case study, we have created a model for different sections of the retaining wall with the grids shown in Figure 8.

This model offers the advantage of evaluating the influence of the jet-grouting wall thickness and its interactions with anchors and parallel walls.

World experience on the problem of reinforced jet-grouting working as a wall is presented as case studies for many authors, but references do not mention design method or simply reference to conventional D-Wall calculation or Soldier-pile calculation. For Finite Element design of this type of jet-grouting walls the authors could find the Thesis of David Tran Yohanes Armediaz: *On the Modelling of Jet Grouting for Deep Excavation Analysis*, Chalmers University of Technology, Gothenburg, Sweden 2021.

Regarding the modeling of jet-grouting material, there are also references that discuss how to parameterize a low-strength mass concrete using the parameters of a Mohr-Coulomb model (for reference, see: Plaxis Bulletin, Spring issue 2009, www.plaxis.nl).

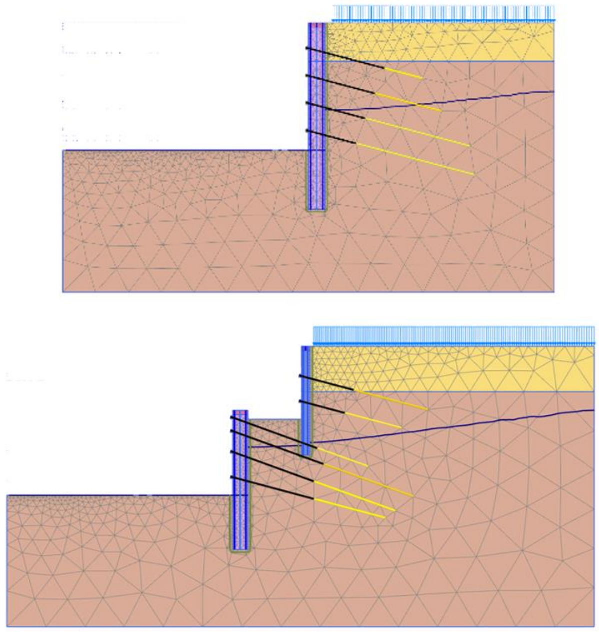

Figure 8. Finite element meshes used to model the jet-grouting walls in the case study.

Additionally, to account for the cracking of jet-grouting under tension, a conservative approach was taken by assuming zero tensile strength in the jet-grouting, instead of the usual approximate value of $f_{ctk}=10\%\cdot f_{ck}$, a value of $f_{ctk}=0$ was used. This consideration particularly affects the deformation of the wall since there is no tensile collaboration of the jet-grouting in the elastic phase before reaching plasticity.

Working in this manner and modeling the embedded steel bars in the jet-grouting as equivalent stiffness steel plate elements, it is possible to obtain the stresses generated in the jet-grouting and perform the corresponding design check (see Figure 9). The stresses in the reinforcing steel bars can also be obtained from this model based on the efforts in the plate elements that represent them.

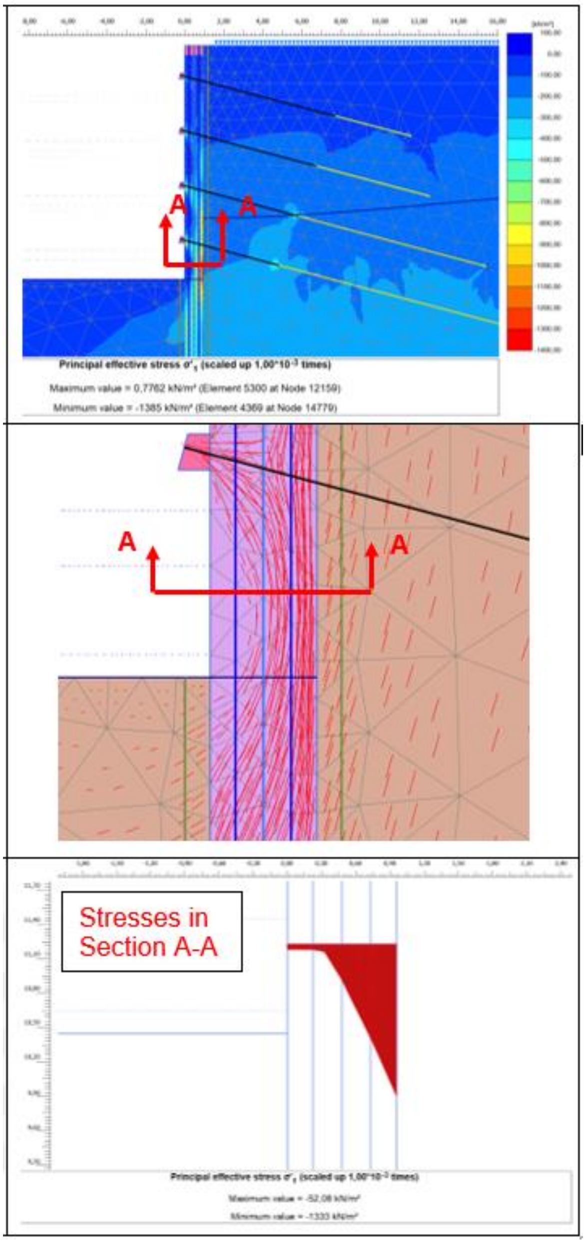

Figure 9. Estimation of the stresses generated in the body of the jet-grouting.

4 CONCLUSIONS

In the "El Fener" project in Andorra la Vella, a retaining wall has been successfully constructed using jet-grouting columns. The geotechnical complexity of the terrain required the development of jet-grouting execution systems that are compatible with the ability to drill throuh large granite boulders. To achieve this, the team has implemented rotary-percussive hammers at the tip of the drilling rods, under the jet-grouting nozzle holder.

The design of the wall, composed of 2 and 3 overlapping rows of overlapping jet-grouting columns, has ensured excellent structural performance as well as impermeability to the high-water table behind the wall.

Figure 10. Some photographs of the retaining wall after the excavation of the site.

The final result after excavation can be seen in the photographs in Figure 10.

The utilization of finite element models has made it easier to evaluate the stresses within the jet-grouting body and the embedded reinforcing steel. The finite element modeling has considered the behavior of the jet-grouting material according to an elasto-plastic Mohr-Coulomb type model, without tensile strength capacity.