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Analytical method to check the uplift of a jet-grouting plug

Méthode analytique pour vérifier le soulèvement d'un bouchon de jet-grouting

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ABSTRACT: The construction of jet-grouting plugs is a common practice to carry out underground works, such as underground lines, underpasses, shafts, etc. Many times, these constructions are developed in clayey soils with low resistance capacity, where the open excavations are carried out below the water table. This situation makes necessary to carry out very deep walls to avoid uplift of the bottom slab. To shorten the length of the walls and guarantee the stability of the bottom slab, it is possible to execute jet-grouting column plugs, improving the stiffness of the wall embedment level and the waterproofing of the excavation, as well as ensuring that the bottom uplift does not occur due to water pressure. This article presents a new method to analyse the uplift of the jet-grouting plugs, based on an analytical calculation of the wall-plug system, assimilating the behaviour of the jet-grouting plug to a thick beam subjected to uniformly distributed pressure. Also, a study of the same problem has been carried out using numerical modelling through the finite element method, that confirms that both numerical and analytical models result in similar stress fields at the wall/ jet-grouting plug interface.

RÉSUMÉ: La construction de bouchons de jet-grouting est une pratique courante pour réaliser des travaux souterrains, tels que des lignes souterraines, des passages souterrains, des puits, etc. Souvent, ces constructions sont développées dans des sols argileux à faible capacité de résistance, où sont réalisées les excavations à ciel ouvert en dessous de la nappe phréatique. Cette situation nécessite de réaliser des murs très profonds pour éviter le soulèvement de la dalle inférieure. Afin de raccourcir la longueur des murs et de garantir la stabilité de la dalle de fond, il est possible d'exécuter des bouchons de colonne par jet-grouting, améliorant la rigidité du niveau d'encastrement du mur et l'étanchéité de l'excavation, en plus d'assurer que le soulèvement du fond ne se produit pas en raison de la pression de l'eau. Cet article présente une nouvelle méthode d'analyse du soulèvement des bouchons de jet-grouting, basée sur un calcul analytique du système mur-chevilles, assimilant le comportement du bouchon de jet-grouting à une poutre épaisse soumise à une pression uniformément répartie. En outre, une étude du même problème a été réalisée en utilisant une modélisation numérique par la méthode des éléments finis, qui confirme que les modèles numériques et analytiques aboutissent à des champs de contraintes similaires à l'interface mur/bouchon de jet-grouting.

Keywords: Jet-grouting plug; uplift; diaphragm wall/jet-grouting plug interface; analytical method; deep beam.

1 INTRODUCTION

The subject of this article is the checking of the design and the uplift of the bottom plug of the diaphragm wall (D-wall).

The chosen D-wall is located in the Llobregat Delta area, within soils with low resistance and a shallow water level. Thus, a bottom plug was executed, using jet-grouting columns, causing stiffening of the wall embedment, as well as waterproofing of the excavation.

The purpose of this article is, on one hand, to verify with an analytical calculation the thickness of the jet-grouting plug and the safety factor against the uplift due to water pressure. On the other hand, to compare and analyze the results, applying the finite element method using a 3D geotechnical model.

2 DESCRIPTION OF THE DIAPHRAGM WALL AND THE JET-GROUTING PLUG

The substructure of the extension of the Barcelona Airport was executed with diaphragm walls. These walls reach a depth of 33 m. The dimensions of the D-wall are 32.20 m length and 23.43 m span (see Figure 1). The thickness of the D-wall is 1.20 m and it is always below the water table. The bottom slab has a variable thickness between 2.00 m and 3.68 m.

The jet-grouting plug dimensions are 21 m wide with a variable thickness between 9.43 m and 7.43 m.

3 SOILS

3.1 Material

The D-wall construction area comprises the following geotechnical units:

- UG0: Made ground fill and organic soils. Thickness 1.5m.
- UG1: Continental clays and silts. Thickness 2 m
- UG2: Silty sands, fine to medium sands. Thickness 11 m.
- UG3: Clays, clayey silts of low plasticity with a high content of organic matter. Thickness 31m.
- UG4: Gravel and sand. Dense.

Table 1. Soil parameters.

Parameter	UG0	UG1	UG2	UG3	UG4	Unit
Unit Weight, γ	17.50	20.00	20.00	19.00	28.00	kN/m^3
Young Mod.	2000	16000	9600	3940	39100	kN/m^2
Poisson coef.	0.30	0.35	0.35	0.40	0.33	
Fric. Angle, δ	22	24	32	26	38	(°)
Cohesion,c	0	10	5	15	0	kPa

Table 2. Jet-grouting plug parameters.

Parameter	Value	Unit
Unit Weight, γ_j	19	kN/m^3
Young Mod., E_j	$2\cdot10^6$	kN/m^2
Poisson coef., ν_j	0.3	
Fric. angle, δ_j	34	(°)
Cohesion, c_j	930.5	kN/m^2
Simple comp. strength, σ_c	3500	kN/m^2

Table 3. Jet-grouting plug/D-wall interface parameters.

Parameter	Value	Unit
Unit Weight, γ_{jp}	19	kN/m^3
Young Mod., E_{jp}	$2\cdot10^6$	kN/m^2
Poisson coef., ν_{jp}	0.3	
Fric. angle, δ_{jp}	34	(°)
Cohesion, c_{jp}	0	kN/m^2

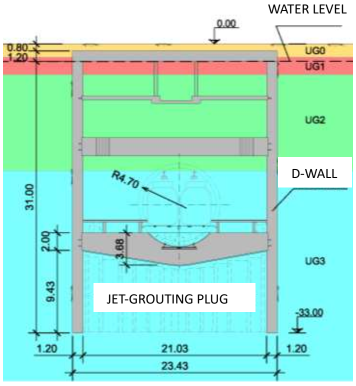

Figure 1. Cross-section of the D-Wall. Cross-section of the Barcelona subway structure executed with diapharfn walls and jet-grouting plug.

3.2 Geotechnical parameters

The geotechnical parameters of the soils are summarized in Table 1.

The jet-grouting plug is in the UG3 soil layer. The geotechnical parameters of the jet-grouting plug are presented in Table 2.

The jet-grouting plug/D-wall interface is considered only frictional, see parameters in Table 3.

4 ANALYTICAL METHOD

4.1 Theoretical base

For the first analysis the plastic balance of the plug and its jet-grouting plug/D-wall interface is considered, meaning that the plug does not uplift due to water pressure. Thus, the plug must prop-up against the D-wall, creating an axial compression force that should be equal to the characteristic compression resistance of the jet-grouting material (Table 2, σ_c).

To calculate the axial compression force, the concept of a deep beam with a uniform distributed load is used (Leonhardt, 1985). The jet-grouting plug is like a deep beam and the uniform load is the water pressure minus the plug weight.

Since the Airport substructure is a linear structure, a slice is analysed in a two-dimensional model using plane strain model. Therefore, considering the deep beam theory, a parabolic unloading arch is formed into the jet-grouting plug, that will have a minimum thickness for its propping up happen (Figure 2).

Once, it checked that the weight of the jet-grouting plug did not balance the water uplift pressure, there must be a shear strength between the D-wall and the jet-grouting plug that adds resistance against the plug uplift. This tangential strength can be obtained using the analogy of the deep beam supporting a uniformly distributed load.

Finally, it must also be verified that the axial unloading arch does not exceed the compression strength of the jet-grouting material (σ_c).

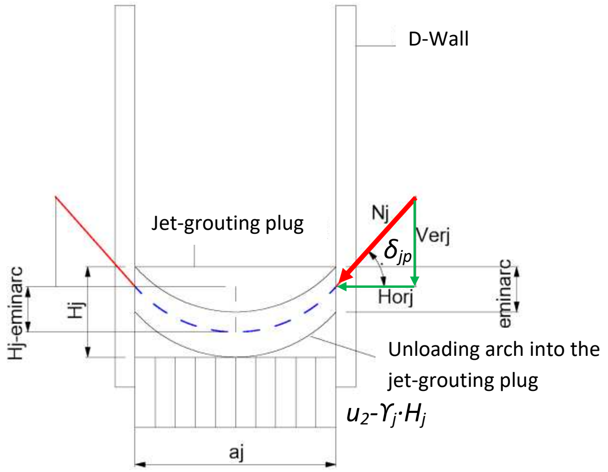

Figure 2. Deep beam analogy.
Sketch of the deep beam analogy for the jet-grouting plug
Where:

H_j:	jet-grouting plug thickness
a_j:	jet-grouting plug length
$emin_{arc}$:	minimum thickness of unloading arch
u_2:	uniform water pressure
δ_{jp}:	friction angle plug/wall interface
γ_j:	unit weight of the jet-grouting
N_j:	axial force on the unloading's arch developed into the jet-grouting plug
Hor_j:	Horizontal force on the jet-grouting plug
Ver_j:	Verical force on the jet-grouting plug

4.2 Practical application

The steps to use the analytical method to check or to pre-design the jet-grouting plug are as follows:

- Total water pressure on the bottom jet-grouting plug, U_2:

$$U_2 = u_2 \cdot a_j \tag{1}$$

- Jet-grouting plug weight, w_j:

$$w_j = H_j \cdot a_j \cdot \gamma_j \tag{2}$$

- Minimum thickness of the unloading parable (Leonhardt, 1985), so that the plug rests on the D-wall and it is in limit equilibrium, avoiding the uplifting of the bottom, $emin_{arc}$:

$$\tan \delta_{jp} = \frac{(H_j - emin_{arc})}{\left(\frac{a_j}{4}\right)} \tag{3}$$

- Vertical force (Ver_j) and horizontal force (Hor_j) on the plug for an uplift safety factor, SF:

$$Ver_j = \frac{(SF \cdot U_2 - w_j)}{2} \tag{4}$$

$$Hor_j = \frac{Ver_j}{\tan \delta_{jp}} \tag{5}$$

- Axial force on the jet-grouting plug, N_j:

$$N_j = \sqrt{\left(Ver_j^2 + Hor_j^2\right)} \tag{6}$$

- Compression stress on the jet-grouting plug, σ_{cj}:

$$\sigma_{cj} = \frac{N_j}{emin_{arc}} \tag{7}$$

where σ_{cj} should be lower than the compression carachteristic strength of the jet-grouting material (σ_c).

4.3 Analytical results

Table 4 and Table 5 summarize the results of the analytical calculation of the jet-grouting plug presented in Figure 1.

In this case, the minimum thickness of the unloading arch is 3.85 m, which requires a minimum thickness of the jet-grouting plug of 7.43 m for the development of the unloading arch, see Table 4.

Once the value of the $emin_{arc}$ has been obtained, the *SF* is calculated, being the multiplier of the total water pressures (U_2) that create the maximum compression stress of the plug (Table 5).

Thus, the geometric design of the jet-grouting plug that balances the water pressure depends exclusively on the plug dimensions and the angle of friction of the jet-grouting plug/D-wall interface.

Table 5 shows the safety margin of the simple compression resistance of the jet-grouting needed to prevent failure, presenting a maximum safety factor of 2.7, reaching the maximum simple compression strength of the jet-grouting material.

Table 4. Design of the plug. Analitical results.

H_j (m)	a_j (m)	w_j (kN/m)	u_2 (kN/m^2)	$emin_{arco}$ (m)
7.43	21.03	2968.8	310	3.85

Table 5. Safety Factor. Analytical results.

FS	σ_{cj} (kN/m^2)	σ_c (kN/m^2)	$\sigma_{cj} < \sigma_c$
1	826.5	3500	Yes
1.3	1280		Yes
2.0	2339		Yes
2.7	3398		Yes

5 NUMERICAL METHOD

5.1 Model

The 3D model of the D-wall has the next dimensions: 124 m long x 25.10 m wide x 55 m depth (Figure 3). The number of zones is 55033.

For both the soil layers and the jet-grouting plug, the drained Mohr Coulomb elastoplastic model has been used, applying the parameters of Table 1 and Table 2 respectively.

The jet-grouting plug/D-wall interface has been simulated using a frictional Mohr Coulomb model, see parameters in Table 3.

The D-walls and middle struts have been simulated using zones and the linear elastic model of concrete, see Table 6.

The upper struts are pipes Φ355.6x14 mm separated 3.85 m. These structures have been modeled with beam elements, whose characteristics are presented in Table 7.

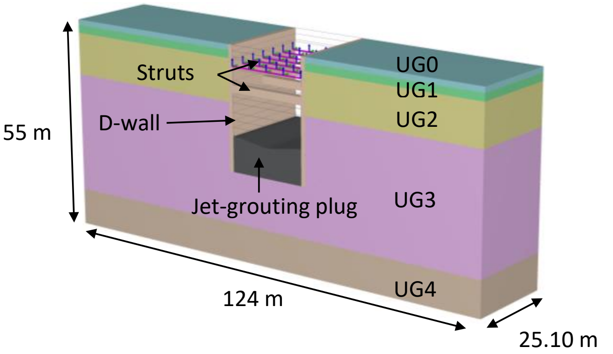

Figure 3. Geometry of the 3D model. Geotechnical 3D Model of the D-Wall and jet-grouting plug.

Table 6. Concrete parameters.

Parameter	Value	Unit
Unit Weight	21	kN/m^3
Young Mod.	$30 \cdot 10^6$	kN/m^2
Poisson coef.	0.2	

Table 7. Struts parameters.

Parameter	Value	Unit
Material model	Elastic	
Unit Weight	78.5	kN/m^3
Young Mod.	$200 \cdot 10^6$	kN/m^2
Area	0.015	m^2
Moment inertia	$0.278 \cdot 10^{-3}$	m^4
Elastic yield, σ_e	275	MN/m^2

5.2 Results of the critical phase

Figure 3 presents the critical construction phase of the construction process, the end of the excavation before execution of the bottom slab. In this case the total excavation depth is 24 m.

Figure 4 shows the principal stresses direction into the jet-grouting plug, where the unloading arch obtained with the analytical method has clearly been developed, as indicated in Figure 2. Figure 4 shows the unloading arch showed in Table 4.

Figure 5 shows a band of shear plastic points in the jet-grouting plug/D-wall interface, where the maximum friction is mobilized. This shear plastic band has a thickness of 4 m. In this way, the thickness of the interface plastic area equals the unloading arch minimum thickness, $emin_{arc}$, 3.85 m obtained with the analytical method (Table 4).

Figure 6 shows the variation of the angle of friction mobilized along the thickness of the interface during the critical phase. It is observed that in the upper 0.6 m thickness there is a tension plastic band, caused by the rotation and support of the D-wall in this band. Thus, this band should not be considered as shear resistance. Therefore, the plastic shear area develops from 0.6 m to 4.8 m, mobilizing the maximum friction angle 34° (Table 3).

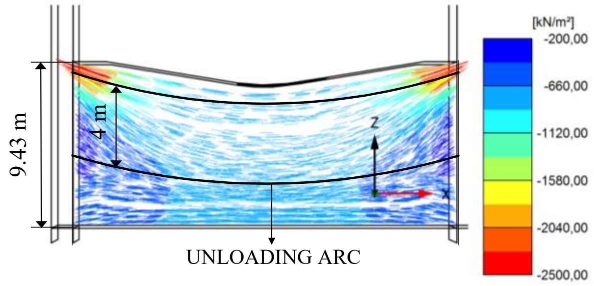

Figure 4. Principal stresses into the jet-grouting plug. Principal stresses direction into the jet-grouting plug, where the unloading arch has been developed.

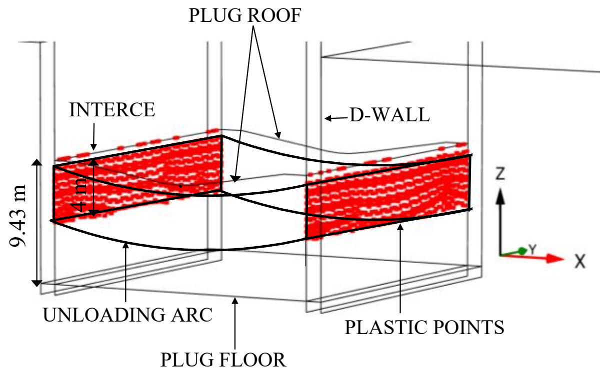

Figure 5. Shear plastic points in the plug/wall interface. Shear plastic points in the jet-grouting plug/D-wall interface, where the maximum friction is mobilized.

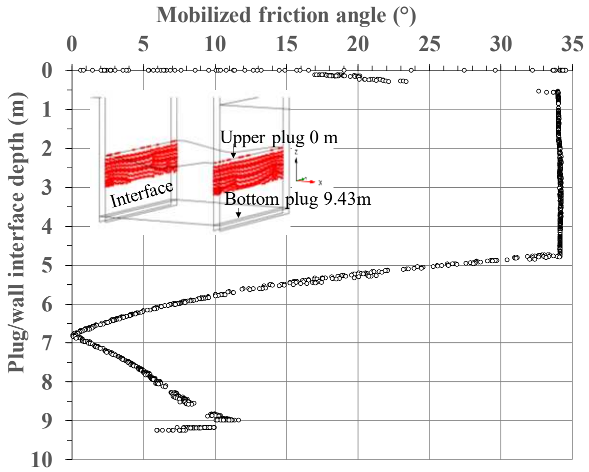

Figure 6. Shear plastic points along the jet-grouting plug/D-wall interface. Variation of the angle of friction mobilized along the thickness of the interface during the critical phase

6 CONCLUSIONS

This paper presents a structural analysis of jet-grouting plugs for the open excavations constructed with diaphragm walls. This model considers the behavior of the jet-grouting plug as a deep beam with uniform distributed water pressure. This pressure is resisted via the mobilization of the frictional strength when the jet-grouting plug props-up against the diaphragm wall. The following conclusions are obtained:

- Fitting the plug geometrically, the analogy of a deep beam bearing a uniform load can be used, assuming the equilibrium limit state against the upward forces.
- The uniform loading on the plug is resisted by the formation of a structural unloading arch in equilibrium with the reaction at the jet-grouting plug/D-wall interface.
- It is very important that the prop-up effect between the jet-grouting plug and the D-wall develops, in order to ensure that the shear resistance prevents the uplift of the jet-grouting plug. In many cases this resistance becomes more important than the value of the unit weight of the jet-grouting. Thus, during the construction process, it must be guaranteed that the jet-grouting and the D-wall contact is continuous, otherwise the system may fail due to lack of friction.
- It is important to consider the width/thickness ratio of the plug. The greater ratio, the more extended the unloading arch, and the greater horizontal stresses are developed, which can exceed the simple compression resistance of the jet-grouting.

Verification using a numerical model yields the following conclusions:

- The principal stresses develop within the jet-grouting plug in an arch-shaped form as considered in the analytical study.
- At the jet-grouting plug/D-wall interface, a plastic zone develops, that corresponds to the jet-grouting/diaphragm wall propping-up area, and it is similar to the minimum thickness of the parabolic unloading arch obtained in the analytical method.
- Therefore, the analytical method provides a preliminary design of a jet-grouting plug, verifying the minimum conditions of the plug and the uplift safety factor.

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