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Numerical modelling of shafts – comparison between SBE and EBS construction methods

Modélisation numérique des puits – comparaison entre les méthodes de construction SBE et EBS

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ABSTRACT: The use of underground space in urban environment has increased considerably in recent years due to the construction of tunnels and underground stations. Shafts appear as one of the main structures associated with these works because they permit direct access to the underground. Generally, the shaft construction methods can be divided into two main categories: SBE – where the support is placed before excavation; and EBS – where the excavation is performed before the application of a support. Having as reference the case of the Shaft WA2, built as part of the Dublin Port Tunnel project, and excavated using the SBE method, this paper investigates the advantages and limitations of each construction method by performing a numerical study. After the calibration of the model based on the results of the instrumentation, the shaft excavation is alternately simulated using the EBS method. The comparison of the achieved results shows that although both methods have merits, the construction using the EBS method was probably the most adequate solution given the soil conditions at the site. In this particular case, the use of the EBS method would permit to employ a thinner support while keeping the deformations of the ground induced by the excavation at very small values.

RÉSUMÉ: L'utilisation de l'espace souterrain en milieu urbain a considérablement augmenté ces dernières années en raison de la construction de tunnels et de stations souterraines. Les puits apparaissent comme l'un des principaux ouvrages associés à ces ouvrages car ils permettent un accès direct au sous-sol. Généralement, les méthodes de construction de puits peuvent être divisées en deux catégories principales: SBE – où le support est placé avant l'excavation; et EBS – où l'excavation est réalisée avant l'application d'un support. Ayant comme référence le cas du puits WA2, construit dans le cadre du projet de tunnel du port de Dublin et creusé selon la méthode SBE, cet article étudie les avantages et les limites de chaque méthode de construction en réalisant une étude numérique. Après l'étalonnage du modèle sur la base des résultats de l'instrumentation, l'excavation du puits est simulée en alternance à l'aide de la méthode EBS. La comparaison des résultats obtenus montre que, même si les deux méthodes présentent des avantages, la construction selon la méthode EBS était probablement la solution la plus adéquate compte tenu des conditions du sol du site. Dans ce cas particulier, l'utilisation de la méthode EBS permettrait d'employer un support plus fin tout en gardant les déformations du sol induites par l'excavation à des valeurs très faibles.

Keywords: Shaft excavation; numerical modelling; construction method.

1 INTRODUCTION

The use of underground urban space has increased considerably due to the construction of tunnels and underground stations. In this context, shafts appeared as one of the main structures associated with this type of works because they permit direct access to the underground. Shaft excavation methods can be classified in two main groups: SBE (Support Before Excavation) – where the support, such as diaphragm walls, is installed prior to the excavation; and EBS (Excavation Before Support) – where the excavation is performed and only after the support, such as shotcrete, is installed. The analysis of case studies (Faustin et al., 2018) shows that, depending on the design requirements and site conditions one technique may be more applicable than the other. However, in some cases, it is not clear which one would be the most appropriate and there are few well-documented cases in the bibliography that discuss the impact of adopting a certain constructive method on the behaviour of shafts. Having as reference the case of the Shaft WA2, built as part of the Dublin port tunnel project, this paper aims to evaluate through numerical analysis the advantages and limitations of adopting the abovementioned construction methods.

2 SHAFT WA2

The shaft WA2 was built in 2001 and served as a launching platform for the twin tunnel excavation of the Dublin Port Tunnel (DPT). The circular shaft with an internal diameter of 56.6 m has a depth of around 29.0 m and it was built following the SBE method, with the support being materialised by a 1.5 m-thick diaphragm wall. The depth of the wall varied slightly, but it was approximately 32.5 m, coinciding with the top of the bearing stratum, a Limestone layer. Beside the capping beam, a ring concrete beam with a section of 2.5x2.5 m^2 at the depth of 13 m was also executed. A 1 m-thick concrete base slab was built once the excavation reached its bottom. Figure 1 shows a photograph of shaft WA2 at the time of its completion where all the supporting structures can be seen.

Ground conditions at the site comprised the well-known Dublin boulder clays overlying a limestone layer. A complete description of the Dublin boulder clays can be found in Long & Menkiti (2007). At the site of shaft WA2, the Dublin Clays stratigraphy was composed of 2 m of the Upper Brown (UBrBC) layer, followed by the Upper Black (UBkBC) layer, which had a thickness of around 12 m. The third layer was the Lower Brown (LBrBC) layer, with a thickness of 11 m and, finally, the Lower Black (LBkBC) layer with 7.5 m thick was found. The stratigraphy and the shaft dimensions and support can be seen in Figure 2.

The performance of the shaft excavation was monitored by 9 inclinometers, which were installed inside the diaphragm wall panels.

3 MODELLING PROCEDURES

3.1 Dimensions and mesh

In order to simulate the shaft excavation, the finite element program RS2 was employed. All analyses were performed considering an axisymmetric model and a total stress condition given the nature of the materials simulated. Figure 3 presents the model adopted in the SBE analysis. A width of 200 m and a depth of 100 m were considered so that all stresses and deformations fields would not be influenced by the presence of the boundaries.

Figure 1. Shaft WA2 (Looby and Long, 2007).

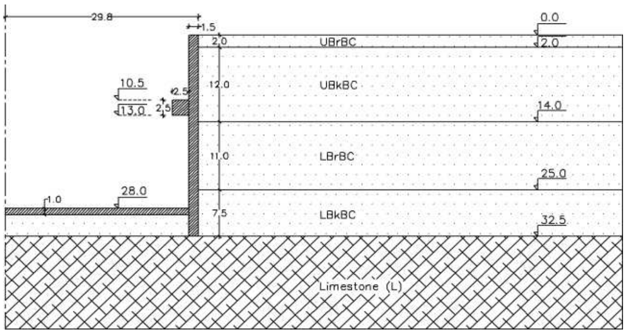

Figure 2. Stratigraphy and geometry of WA2 shaft.

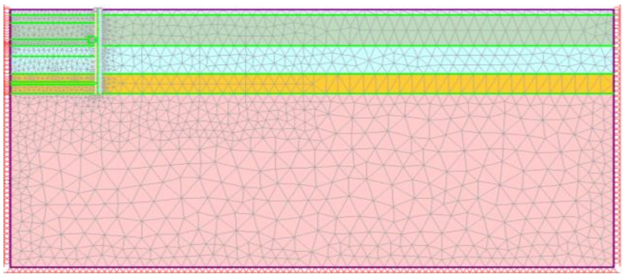

Figure 3. Mesh employed in the SBE numerical model.

The shaft dimensions, its support and ground profile were simulated accordingly with Figure 2. The mesh is constituted by isoparametric triangular finite elements with 6 nodal points and has a total of 1961 elements, with a refinement in the shaft vicinity. Boundary conditions were assumed as standard for axisymmetric conditions: free at surface, only vertical displacements allowed in the vertical boundaries and all movements restrained at the base of the model. Elastic interface elements were considered between the soil and the diaphragm wall so that relative movements could occur. The diaphragm wall was considered to be elastic while for the soil layers a linear elastic-perfectly plastic constitutive model with a Tresca failure criterium was adopted.

3.2 Construction sequence

The definition of the construction sequence followed the description presented by Cabarkapa et al. (2003), so that the obtained results could be compared against the inclinometer data. A total of 6 stages were considered in the SBE shaft excavation: 1) initial stress state, considering geostatic conditions and a K_0 profile; 2) installation of the diaphragm wall as wished-in-place; 3) excavation up to a depth of 13m; 4) installation of the ring beam; 5) final excavation of the shaft to a depth of 29m; and 6) construction of the base slab.

3.3 Calibration of the numerical model

A class A prediction of the shaft performance was presented by Cabarkapa et al. (2003), where a coupled-consolidation analysis to simulate the short-term behaviour of the excavation was employed. The final horizontal displacements obtained by Cabarkapa et al. (2003) are presented in Figure 4. Superimposed in the figure are also the results of the inclinometers (and its envelope) to facilitate the comparison. The results show that both the trend and magnitude of the displacements are not correctly captured by the analyses, with the authors claiming that the parameters adopted for the materials at the design stage were very conservative and also justifying that the poor connection between the diaphragm panels permitted a cantilever deflection in the upper part of the shaft, which is not possible to simulate in the numerical model.

Having as reference the inclinometer data and also the extensive geotechnical characterisation on the Dublin boulder clays performed by Long & Menkiti (2007) and Long et al. (2013) a back analysis study was performed in order to calibrate appropriately the mechanical parameters of the Dublin boulder clay layers. The obtained final horizontal displacements are also presented in Figure 4, where it is possible to observe that, although the displacements near the surface are smaller than those measured at site, overall, a reasonable agreement, well within the inclinometer's envelope, is obtained. As mentioned previously it should be noted that with an axisymmetric model it is not possible to simulate the poor connection of the panels and therefore to improve the adjustment near the ground surface.

The parameters adopted as reference for the Dublin boulder clay layers in the analyses are presented in Table 1. For the structural elements (diaphragm wall, ring beam and base slab) a linear elastic behaviour, characterised by a Young's modulus of 25 GPa, Poisson's ratio of 0.15 and unit weight of 25 kN/m³, was adopted. For the interface elements, an elastic model was assumed with normal and shear stiffness of 1×105 kPa/m and 1×104 kPa/m, respectively.

Table 1. Soil parameters adopted in the analysis.

Material	γ (kN/m³)	S_u (kPa)	E_u (MPa)	ν	K_0
UBrBC	21	60	60	0.49	1.5
UBkBC	22.5	225	450	0.49	1.5
LBrBC	22	375	750	0.49	1.35
LBkBC	22.5	375	750	0.49	1.2
L	26	500	1000	0.3	1.0

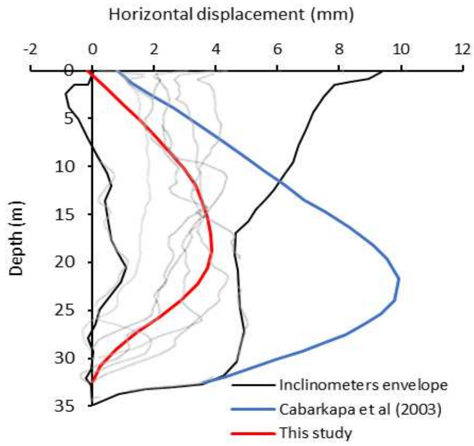

Figure 4. Calibration of the numerical model having as reference the inclinometer data.

4 EBS SHAFT EXCAVATION

The EBS shaft excavation followed the typical principles of a sequential excavation. An excavation step of 2 m was adopted, which resulted in a total of 15 excavation stages until a depth of 29 m was reached (the last stage was only 1 m deep). Support for the excavation was provided by a shotcrete layer with a thickness of 0.5 m. For ease of comparison the parameters of the shotcrete were considered as equal as those of the diaphragm wall. In total, 31 stages were simulated in the EBS model. After the initial stress state, the first 2 m excavation step was performed followed by the installation of the shotcrete. These 2 stages were then repeated continuously until the bottom of the excavation was reached and the base slab installed.

5 COMPARISON OF THE RESULTS

The comparison between the main results obtained for the final stage of the excavation of the SBE and EBS models is presented in Figure 5. Although the horizontal displacements (a) obtained with the EBS model show a similar trend to the displacements obtained from the SBE, they are considerably higher as a consequence of the soil decompression which is inherent to the unsupported excavation performed. Is also interesting to verify that, had the excavation been performed without support (blue line) the horizontal

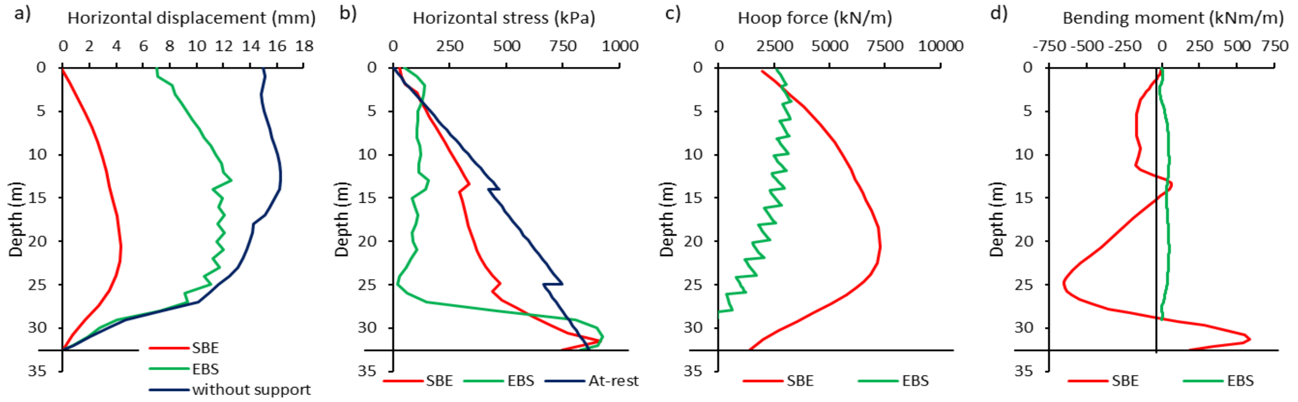

Figure 5. Comparison between the SBE and EBS methods: a) horizontal displacement; b) horizontal stress; c) hoop force; d) bending moment.

displacements would have been only slightly larger than those observed in the EBS model, implying that the ground strength is very high. Nevertheless, given that the overall movements do not surpass 16mm they can be considered very small. The results of the horizontal stress (b) are in agreement with the horizontal movements with the EBS model showing a much smaller final stress as consequence of the soil decompression. In the SBE a much smaller soil decompression is observed with the horizontal stress values being much closer to those adopted in the initial stress state. The structural forces in the diaphragm / shotcrete wall show that with SBE methodology much higher forces, both hoop (c) and bending moments (d) are to be expected. Those come as consequence of small reduction of horizontal stresses that are allowed due to the installation of the diaphragm wall before the beginning of the excavation.

6 CONCLUSIONS

Having as reference the case of the WA2 shaft in Dublin the following conclusions can be drawn:

- A SBE construction reduces considerably the decompression of the ground during the excavation process, which results in very small deformations. As a result, this method is ideal to minimize the impact of shaft excavation on nearby infrastructure. However, since the soil decompression is not allowed, the forces in the support, both hoop and bending moments, are expected to be very high and demand a robust support;
- The almost exact opposite was observed in the EBS model, where the excavation without support allowed for a maximum soil decompression, which resulted in higher horizontal movements but much smaller horizontal stresses and structural forces;
- Based on the achieved results for the case of WA2 shaft, the application of the EBS method would be feasible and highly competitive, as it would allow to considerably reduce the volume of materials used and the execution time, without significantly increasing the ground deformations or compromising the shaft stability.

It should be noted that these conclusions relate to the specific case of the WA2 shaft and should not be directly generalised to other projects where the geotechnical conditions would be different.

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