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Research Paper

Design procedure for the modelling of jet-grout column slabs supporting deep excavations

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ABSTRACT

Overlapping jet-grout columns are often used to form a grout slab at the bottom of deep excavations to support the retaining structures. Columnar geometrical imperfections, spatially varying strength and stiffness and the post-peak behaviour of the grout, render the simulation of the jet-grout column slab a very complex issue. In practice, these aspects are not taken into account and simplified models are commonly used, in conjunction with the application of a strength reduction factor. With the aim to improve the existing design process and extend its applicability to serviceability limit state analysis, a consistent design procedure is presented.

1. Introduction

Soil reinforcement through jet grouting at the bottom of deep excavations has been applied in many projects to prevent the development of excessive retaining wall deflections and settlements of adjacent buildings. The method is more often used in the case of deep excavations realised by the '*top-down*' construction method, where the permanent structure elements of the basement are built along with the excavation from the top to the bottom. The combination of this method with temporary steel props is, for technical reasons, very rare and therefore reinforcement with jet grouting of the soil zone below the excavation bottom is an effective alternative. The reinforced zone serves as a lateral strut, providing stress and deflection control on the diaphragm walls and reducing ground displacements (Eramo et al. [6], Lee et al. [11], Nakagawa et al. [18], Ochmański et al. [19], Shen et al. [22–24], Tanaka [26] and Wang et al. [27]).

Overlapping jet-grout columns are constructed with the aim to form a mass slab of appropriate thickness, of usually 2.00–4.00 m. Nevertheless, untreated zones often remain within slab and these can severely affect the overall behaviour of the slab and the supported retaining walls. The presence of these soil pockets leads to stress concentrations, which in turn lead to yielding and stress redistribution in the surrounding zones, particularly when the soil pockets are connected [12]. Decreasing the spacing between the jet-grout columns in conjunction with the use of triple jet grouting apparatus may reduce the effect but at significant cost increase. However, even in this case, the presence of untreated soil pockets cannot be avoided, especially in deep excavations that exceed the depth of 15.0 m [16]. According to Modoni et al. [14,15] geometrical imperfections and spatial variation of the mechanical properties of a jet grouted material are unavoidable, even if very strict controls are maintained during treatments.

The major reasons for the presence of soil pockets among the grout columns are the unavoidable deviation of the column from the prescribed axis position and the column diameter variability. A deviation on the order of 0.5% from the theoretical axis, which is considerably less than the requirements of many drilling guidelines, leads to a shift of the grout column position of 0.10 m at a depth of 20.0 m, which may be further increased if a deviation in the opposite direction is observed to the adjacent column.

The variation in grout column diameter can take place horizontally, from column to column, or vertically along a given column. According to the findings of several studies, the grout column average diameter is related to the consistency of the soil medium (higher diameters can be achieved in sandy than in clayey soils), and that a lower diameter is developed as the soil shear strength increases. The injection system (single, double or triple), the applied grouting pressure and other relevant parameters of jet grouting are related to the achieved grout column diameter [7]. Various prediction models are available in the literature, [20], for estimating the column diameter using soil mechanical properties and injection hydraulic properties (e.g. Corce and Flora [5], Modoni et al. [13], Flora et al. [7], Shen et al. [25], Ochmański et al. [19]. However, it has been observed that even for homogeneous soil conditions and unchanged jet grouting parameters the column diameter still varies both vertically and horizontally. This can be attributed to the fact that soil heterogeneity can be induced by the high-pressure grout flow (300–500 times greater than the

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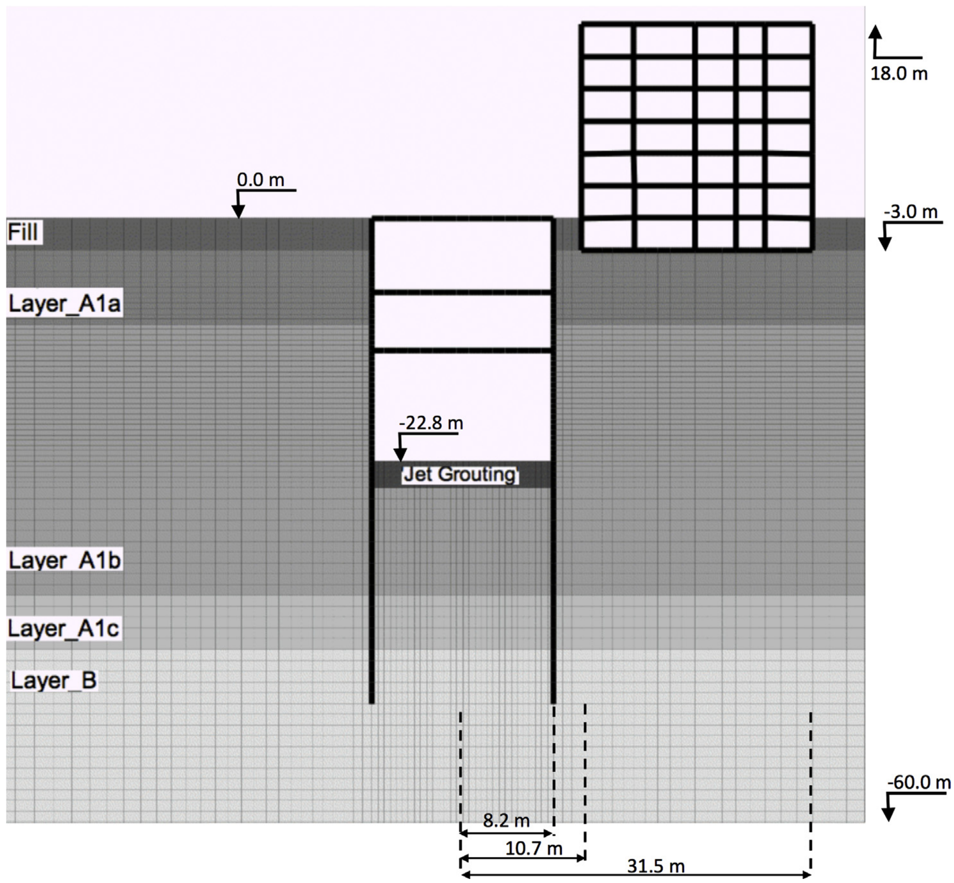

Fig. 1. Illustration of soil stratigraphy with the Analipsis' underground station and an adjacent building.

atmospheric pressure) that causes a substantial but variable degradation in treated zones. This observation has prompted many researchers to consider random variation of column diameters or soil pockets using the simple Gaussian distribution [14], or even the more complex approach of artificial neural networks [19].

Although jet-grout column positioning has been identified as the major influencing factor on the slab response and resistance [12], the stiffness and the strength of the individual materials (the grout and the soil) have the same or even greater effect on the composite strength and stiffness of the slab in the horizontal direction that supports against inward movement of the retaining walls. It is noted that the post-peak strength reduction and the associated stress release in yielding zones may lead to local collapse, depending on the strength of the grout column. For this reason, when the design of such structures is based on simplified analysis that does not take into account the non-linear response and the post-peak behaviour of the grout slab, reduction factors on both strength and deformation modulus need to be introduced.

The objective of this paper is to present a consistent design procedure for '*top-down*' excavations that accurately models the behaviour of the jet-grout base slab, taking into account the spatial variation of material properties and the post-peak grout behaviour. The case of a diaphragm wall excavation with a jet-grouted base slab, for the construction of the Analipsis' Station of the Thessaloniki Metro is used as a study case. The analysis presented in the following paragraphs includes the following steps:

(1) The geometrical imperfections of the jet-grout columns are first evaluated from the in-situ test program that is carried out to define the appropriate values for the various parameters to be applied in the jet-grouting process. Based on this evaluation, the geometrical spatial variation is statistically determined,
(2) The mechanical properties of the grouted zones are determined using laboratory test results and their spatial variation is statistically estimated. Both the evaluation of geometrical imperfections and the mechanical properties can be verified and re-adjusted, if necessary, during the in-situ control process of the slab construction,
(3) The aforementioned statistical variations are then introduced into three dimensional (3D) numerical analysis with the aim to estimate the reduction effect on the equivalent Young's modulus of the composite slab arising from the presence of soil pockets among the grouted zones,
(4) A two-dimensional (2D) analysis is carried out, in which the multistage '*top-down*' excavation is simulated, taking into account the spatial variability of the slab strength and the Young's modulus, the post-peak behaviour of the slab and the non-linear behaviour of the soil,
(5) The range of probable responses and the effects on the displacement field and stress development in the diaphragm walls and the slab are assessed through Monte-Carlo simulations.

The simplified case where the slab is considered as a linear elastic material is also presented for comparison purposes.

2. Project description

The Analipsis' station, is part of the Thessaloniki Metro Main Line. It is 210 m long and 16.4 m wide and was constructed using the "top-down" method. Diaphragm walls of $t = 1.20$ m thickness and $L = 44.0$ m length were constructed around the perimeter and a jet-grout slab was formed beneath the maximum excavation depth. The basement of the station is 22.82 m below the ground surface. The