The Use of Jet Grouting to Enhance Stability of Bermed Excavation

L'utilisation de Jet Grouting pour améliorer la stabilité d'une excavation avec risbermes

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ABSTRACT: Jet grouting has been widely used as a ground treatment method to improve the mechanical behaviour of soft soils in many different types of constructions. This technique has been used to facilitate the construction of the West Kowloon Terminus (WKT) of the Hong Kong section of the Guangzhou-Shenzhen-Hong Kong Express Rail Link (XRL) in Hong Kong. The construction sequence of the central portion of the deep excavation involves the formation of temporary cut slopes which serve to partially support the diaphragm wall until the core station structure is completed. The stability of the temporary cut slopes, hence the excavation, is affected by the presence of soft marine deposits. Jet grout columns are therefore constructed to enhance the overall stability of the temporary cut slopes before excavation. The paper discusses the design philosophy of the deep excavation supported by temporary cut slopes which have been pre-treated by jet grouting. The performance of the jet grout columns have been verified by post-construction coring together with in-situ and laboratory testing. Results of these verification measures and field monitoring data which demonstrate the overall performance of the excavation supported by slopes treated by jet grouting are also presented.

RÉSUMÉ : Le jet grouting a été largement utilisé comme une méthode de traitement du sol pour améliorer le comportement mécanique des sols mous dans de nombreux types de constructions. Cette technique a été utilisée pour faciliter la construction du Terminus West Kowloon (WKT) de la section située à Hong Kong de la liaison ferroviaire express Guangzhou-Shenzhen-Hong Kong (XRL). La séquence de la construction de la partie centrale de l'excavation profonde implique la création de talus temporaires qui servent à supporter partiellement la paroi moulée jusqu'à ce que la structure de la station de base soit terminée. La stabilité des talus temporaires, et donc de l'excavation, est affectée par la présence de dépôts marins mous. Des colonnes de jet grouting sont donc réalisées de manière à améliorer la stabilité globale des talus temporaires avant excavation. Cet article traite du concept de dimensionnement de l'excavation profonde soutenue par des talus temporaires pré-traités par jet grouting. La performance des colonnes de jet grouting a été vérifiée par un carottage post-construction associé à des essais in-situ et en laboratoire. Les résultats de ces mesures de vérification et de surveillance des données en place qui démontrent la performance globale de l'excavation soutenue par des pentes traitées par jet grouting sont également présentés.

KEYWORDS: Deep excavation, slope stability, soil berm, soft clay, diaphragm wall, jet grouting

1 INTRODUCTION

The West Kowloon Terminus (WKT) is the underground terminus of the Hong Kong section of the Guangzhou-Shenzhen-Hong Kong Express Rail Link (XRL). The multi-storey 10-hectare terminus, located at West Kowloon to the north of the West Kowloon Cultural District (WKCD), will be linked to the Kowloon Station and Austin Station and is expected to be commissioned in 2015. The entire station will be an underground structure with an iconic roof erected above it.

The construction of the underground terminus involves deep excavation of about 30m supported by a 1.5m thick reinforced concrete diaphragm wall. To meet the tight programme, a construction sequence involving open cut excavation supported by the diaphragm wall and temporary cut slopes formed in front of the wall – sometimes referred to as bermed excavation – was adopted at the central portion of the deep excavation as shown in Figure 1. The concept of using soil berm as lateral support for deep excavation can be dated back to 1960s (Peck, 1969). Various analysis methods have been discussed in Simpson and Powrie (2001). These methods have also been used to back analyse centrifuge model tests (e.g. Powrie and Daly, 2002).

The temporary cut slopes serve to provide lateral support to the diaphragm wall against earth and water pressures. The stability of the temporary cut slopes, hence the excavation, is adversely affected by the presence of soft marine deposits which is overlain by reclamation fill. To enhance overall stability of the temporary cut slopes and to reduce wall deflection during excavation, jet grout columns (JGCs) were constructed before excavation. The construction of jet grout columns involved the use of a high energy jet of fluid to break up and loosen the ground, and subsequently replaced the slurry by cement grout.

This paper discusses the design philosophy of the deep excavation supported by temporary cut slopes which have been pre-treated by jet grouting. The performance of the jet grout columns was verified by post-construction coring together with in-situ and laboratory testing. Results of these verification measures are also presented.

Figure 1. Deep excavation at West Kowloon Terminus (WKT).

2 DESIGN OF THE DEEP EXCAVATION

The 30 m deep excavation at WKT has a plan area of approximately 550 m by 220 m, and is surrounded by high-rise residental and commerical buildings in West Kowloon – an urban area of Hong Kong. Construction of large diameter bored piles and rock-socketted steel H-piles for supporitng the station structure and the perimeter diaphragm wall was carried out before excavation commenced. The diaphragm wall serves as the temporary retaining structure for the deep excavation, the permenent wall of the station structure, as well as a load bearing wall to support the vertical load from the superstructure. This Section describes the ground conditions of the site, the construction seqenence and the design considerations of the deep excavation.

2.1 *Ground conditions*

The solid geology within the site area comprises Kowloon Granite from the Cretaceous Period of the Mesozoic Era which is a monzogranite pluton centered on Kowloon and Hong Kong Island. The superficial deposits include fill and transported materials such as alluvium, colluvium, marine deposits, estuarine deposits and the like.

Reclamation fill has been placed on the site following the West Kowloon reclamation works carried out in the 1990s. The fill comprises the reclamation deposits and the remnants of the old seawalls, old breakwaters, revetments, old ferry pier and existing layers of building debris and rock fill. The in-situ deposits include weathered rock and the soil derived from the weathered rock such as saprolite and residual soil (i.e. the Grade VI material according to GEO (1988)). Variably jointed rock and soil masses with different proportions of rock and soil are present within the in-situ deposits.

The site topography prior to the bulk excavation is generally characterised as flat and the average ground level is at about +5.5 mPD. The available groundwater level records from standpipes and vibrating wire piezometer indicate that the highest recorded groundwater level ranged from +1.56 mPD to +3.60 mPD and the lowest groundwater level recorded ranged from -1.29 mPD to +1.94 mPD.

2.2 *Construction sequence*

Excavation and construction of the station structure is carried out by two separate contractors who adopt different construction methods. The contractor on the northern side adopts open cut excavation (see Figure 1) which is then followed by bottom-up construction. On the southern side, the contractor adopts top-down construction for the top two levels of slabs and then changes to bottom-up construction for lower levels.

The focus of this paper is the open cut excavation carried out near the northern part of the site. Upon completion of the foundation works and diaphragm wall construction, jet grouting was carried out at locations where soft marine clayey deposits are present which adversely affect the stability of the bermed excavation. After sufficient strength had been gained in the jet grouted material, temporary cut slopes at a gradient of 1 on 2 were formed in front of the diaphragm wall. This was followed by bottom-up construction of the central core of the station structure. Construction of the entire structure would then be completed by top-down method between the diaphragm wall and the core station structure where the temporary slopes are gradually removed and replaced by reinforced concrete slabs connecting the diaphragm wall to the core station structure.

2.3 *Design considerations*

Figure 2 shows a simplified design scenario which illustrates the design concept. The diaphragm wall and the soil berm are to support an excavation with a maximum depth of approximately 30 m. Since the diaphragm wall is designed as a foundation element for vertical loading, the wall is founded on the bedrock with a nominal embedment of 300 mm. The sufficiency of the embedment depth of the wall has been checked by trial wedge methods. For areas with a shallow rockhead, mini piles, denoted as shear pins, were constructed beneath the base of the diaphragm wall to increase the resistance against overturning.

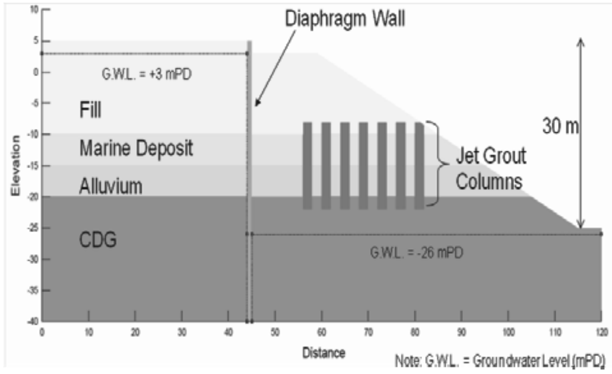

Figure 2. Simplified design scenario of bermed excavation design with ground treatment by jet grouting.

The trial wedge method considers the soil berm as a passive support as far as stability of the embedded wall is concerned. The stability of the soil berm has to be considered separately. The marine deposits sandwiched between the reclamation fill and alluvium consist of interbeded cohesive and granular materials. The cohesive portion typically comprises of clay and in places silt with various proportion of sands and gravels. The undrained shear strength ranged from a few kilopascals to >200 kPa. A general design value of 30 kPa was adopted, except for marine clay at shallow depths where a lower value of 20 kPa was used.

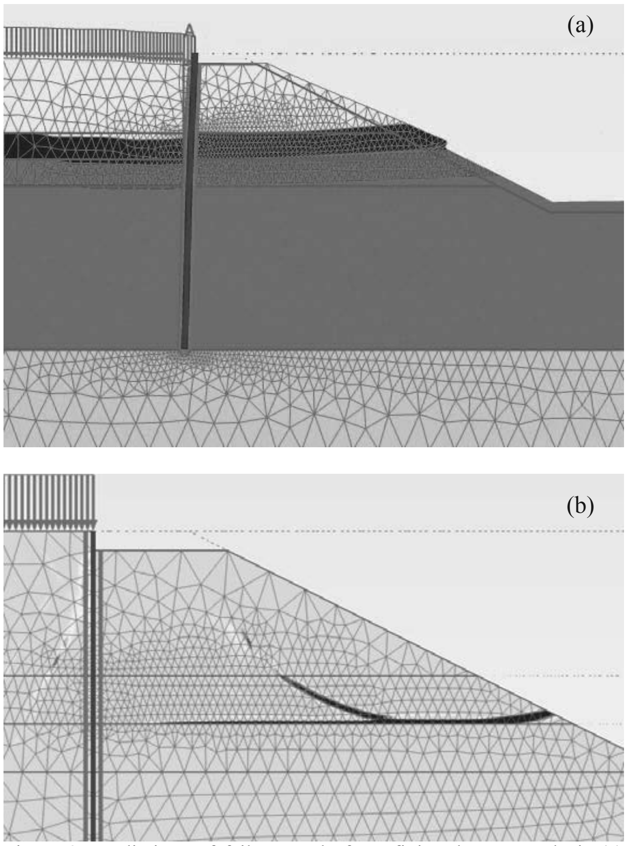

Figure 3. Predictions of failure mode from finite element analysis (a) total deformation, (b) incremental shear strain distributions

Finite element analyses have been conducted using Plaxis to predict the behaviour of the bermed excavation for the simplified design scenario shown in Figure 2 if ground treatment is not carried out. In the absence of ground treatment, equilibrium solutions could not be obtained and the likely failure mechanisms are shown in Figure 3. The predicted failure mechanism involves concentrated shear strains mobilised along the base of the marine clay layer due to the constant strength assumption. The overall stability is directly dictated by the elevation of the soft marine clay layer which controls the overburden pressure exerted on the potential failure soil mass.

To enhance the overall stability, jet grouting works was proposed. The potential working principle of the jet grout columns has been studied by finite element analyses. The technique of strength reduction has been used in the analysis to quantify the margin of safety and to identify the most critical failure mechanism of the design scheme. In the analyses, several rows of 2 m diameter discrete jet grout columns which pass through the marine clay and alluvium layers are assumed. The uniaxial compressive strength (UCS) and the Young's modulus of the jet grouted material are assumed to be 2 MPa and 300 MPa respectively. Due adjustment of these parameters have been made in the plane strain models.

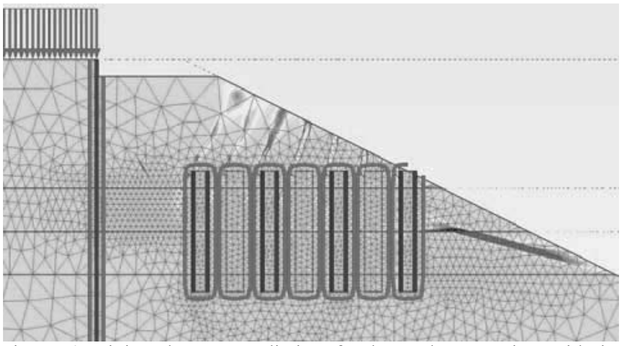

Figure 4. Finite element prediction for bermed excavation with jet grouting - incremental shear strain distributions at failure.

Figure 4 shows the incremental shear strain distributions at failure when soil strengths have been reduced by a factor of 1.45 through strength reduction calculations. It can be seen that the most critical failure mechanism no longer involves a sliding plan along the base of the marine clay layer due to the presence of the jet grout columns. Instead, a local failure in the marine clay and alluvium is observed.

In the analysis, the jet grout columns are modeled as a non-porous elastic perfectly plastic material, with the maximum shear strength governed by the Mohr-Coulomb failure criterion. Jet grouted material is brittle and therefore the mobilised shear strains in the jet grout columns have been calculated to ensure sufficient strength can be mobilised at small deformation. A limiting criterion of maximum shear strain of 0.5% has been adopted.

The design scenario depicted in Figure 2 is a gross simplification of the actual site conditions. It conservatively considers the adverse effects of the presence of soft marine clay on the overall stability. The actual characteristics of the marine clay, including its strength, thickness and elevation, may vary across the site. The finite element analyses merely confirm the feasibility of the design scheme under an extreme condition. The actual amount of jet grout columns to be installed is determined by considering the local ground conditions, excavation profiles and the characteristics of the marine clay. The key design criteria are the overall safety margin of the excavation including the slope in front of the wall, the mobilised deformation in the jet grouted material as well as the structural forces induced in the diaphragm wall. Verification of the assumed material parameters for the jet grout columns is described in the next section.

3 PERFORMANCE VERIFICATION

Although jet grouting has been used widely in many parts of the world, it has not been common in Hong Kong. Therefore, not much field data was available. As such, a site trial was carried out before commencement of the actual jet grouting works. The purpose of the site trial is to determine the control parameters of the grouting operation, for example, the grout pressure, nozzle size and lifting rate, etc. In addition, the site trial serves to confirm that the assumed design strength and stiffness of the jet grouted materials can be obtained. A total of twelve trial jet grout columns were constructed using different combinations of operation parameters. A photo showing the jet grouting works is shown in Figure 5. The entire process is fully automated with all the operation parameters shown on a digital display panel.

Figure 5. Plant used for jet grouting works with fully automated control system.

A comprehensive post-grouting investigation was carried out. This included multiple full-depth coring in the trial jet grout columns, laboratory testing of the core samples and in-situ pressuremeter tests in the core holes. Core samples were obtained at differnet depths and at different locations in order to confirm that an effective diameter of 2 m could be acheived. The core samples were tested to obtain the Young's modulus and the UCS of the specimens. In-situ pressuremeter tests were conducted in the core holes to measure the stiffness of the grouted zone. The final operation parameters of the jet grouting works were determined according to the results of site trial.

For working jet grout columns, full-depth corings were obtained at a particular sampling frequncy as a quality control measure. Typical cores are shown in Figure 6.

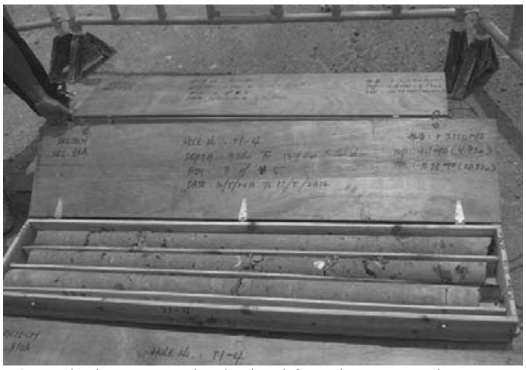

Figure 6. Typical core sample obtained from jet grout column

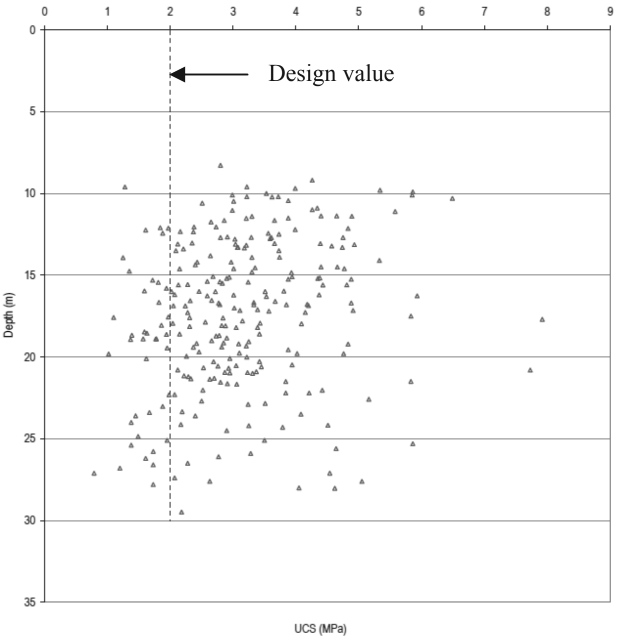

Figure 6. Measured uniaxial compressive strengths of the jet grouted materials.

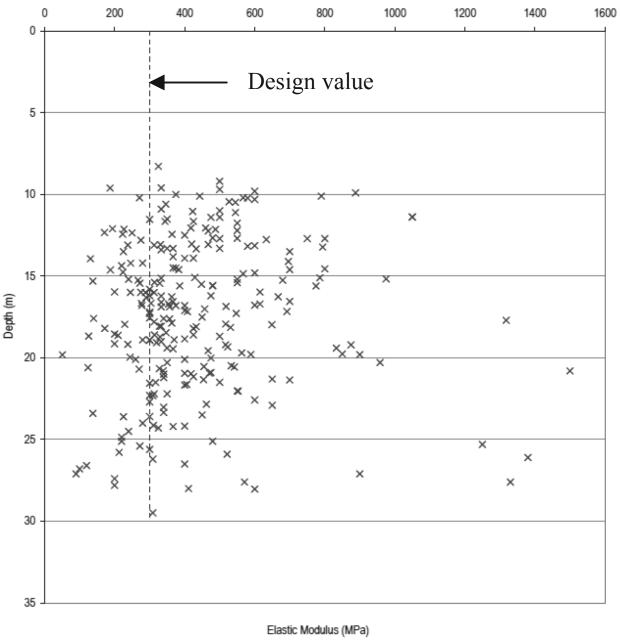

Figure 7. Measured Young's modulus of the jet grouted materials.

The UCS and Young's modulus measured from the core samples of the working jet grout columns are plotted in Figures 7 and 8. It can be observed that the mean values of UCS and Young's modulus are well above the assumed design values. For the cases where the measured UCS or Young's modulus of a particular jet grout column was below the design value, a design review was carried out. The design review assessed the likely behaviour of the excavation using finite element technqiues assuming that the strength or stiffness of the jet grout columns was reduced to the measured value. If the design criteria set out in Section 2.3 could still be met, the revised design was considered acceptable. On the contrary, additional jet grout columns were constructed to ensure that the excavation is of suffcient safety margin.

The purpose of coring and testing conducted on the core samples of the working jet grout columns was to verify the design assumptions made in the design analyses. It is important to monitor the actual performance of the construction through field instrumentation. A comprehesive instrucmentation plan has been adopted for such purposes. Inclinometers have been installed in the diaphragm wall as well as in some of the jet grout columns. The measured deflection is used to closely monitor the actual performance of the construction using the predictions made by finite element analyses as a reference.

4 CONCLUSIONS

The use of soil berm to support deep excavation is not uncommon and has been used for decades. However most of the previous cases involved excavation in stiff clay. The stability of the soil berm is therefore not a concern – at least for short term conditions.

This paper describes a case where bermed excavation is adopted in a geologically complex site. The overall stability is adversely affected by the presence of soft marine clay. Without ground treament, finite element analyses predicted a potental failure mechanism initiated from sliding along the base of the marine clay layer. In order to enhance the overal stability, jet grouting as a ground treatment method was introduced. Finite element analyses also showed that the jet grout columns could avoid the formation of a global sliding failure along the marine clay layer if sufficent strength of the jet grouted material can be mobilised at small deformation. Verification of the design parameters was done through a site trial which consisted of labortoary and in-situ tests. Quality control and verification of the acutal performance were achieved by obtaining core samples from the working jet grout columns together with a comprehensive monitoring scheme.

5 ACKNOWLEDGEMENTS

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