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Quality control of double fluid jet grouting below groundwater table: Case history

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Abstract

A jet grout block created by overlapping columns aimed to convert the saturated silty sand soils into a safe space for breaking down four underground parking uplift piles along the tunnel alignment. Since the grouting platform was located on the mat foundation in the basement of underground parking and was under the groundwater table, a series of dewatering wells were installed before the 177 columns were constructed to prevent intrusion of the groundwater flowing upward from sandy soil to basement through grouting hole during wash boring and grouting stages from happening. Several quality control measures were undertaken prior to quality assurance testing. Two measurements of spoil return and spoil flow rate for each column were implemented. From a back analysis from the mean values of spoil density and spoil flow rate, the column diameter was estimated at around 1.56 m, slightly smaller than the design diameter by 2.5%. In addition, a control chart with upper and lower control limits, established from a large dataset of flow rate of spoil return, was a means to recognize the likelihood of sand boiling and to serve as an early warning indicator of abnormal conditions for the jet grouting works below the groundwater table. As the mean spoil density of the infill column was larger than perimeter column, an optimal grouting sequence for clusters was suggested in this paper. The jet grout block exposed during the breakdown process of the piles showed safe working conditions as required and a shield machine then passed through as planned.

Keywords: Double fluid jet grouting; Spoil density; Spoil flow rate; Column diameter; Infill column

1. Introduction

There are three jet grouting systems to choose from: a single, double, and triple system. The single system injects grout only at high pressure. This was the first system to be used: the resulting column diameter is limited and the boreholes sometimes become jammed, resulting in ground heave (Croce and Flora, 1998). The column sizes are small, usually less than 1 m in diameter.

The JSG (Jumbo-jet Special Grout) method is a jet grouting method with two fluids, neat cement grout and air (Yahiro et al., 1982; Miki and Nakanishi, 1984). The cement grout is injected at high pressure and is aided by a cone of compressed air, which shrouds the grout injection. The air reduces the friction loss, allowing the cement grout to travel further from the injection point, thereby producing larger column diameters. The addition of the air shroud increases jetting efficiency

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dramatically, typically resulting in an increase of 30% or in the design diameter for the same jetting energy. Nevertheless, the presence of the air bubbles means that that the column is not as strong as those produced by the single-fluid method, and more spoil return is produced.

The triple system differs from the single and double systems in that the erosion of the ground is carried out by a high pressure water jet shrouded with air and the eroded region is replaced by cement grout with an additional low pressure grout line. The single and double fluids are in-situ mixing methods, not soil replacement methods like the triple fluid method.

As mentioned above, the double fluid jet grouting technique results in the partial replacement of in-situ soil within the grouted column, thereby improving strength and reducing permeability. Because the overlap of the column with previously constructed columns can be accurately controlled, low permeability can be secured, thus avoiding the risk of leakage of water or soil through the gap between jetted columns. The accuracy of any quality control technique to evaluate the actual diameter of jet grout column is thus of major concern to the grouting industry.

The jet grouting diameter is affected by soil properties and jet grouting parameters (the lifting speed and rotation frequency of the monitor, the grout volume, the grout pressure, and the nozzle diameter) (Malinin et al., 2010). Therefore, these parameters are required for manually monitoring and for the automatic data acquisition system. However, either of these procedures provide solid values with regard to improved strength and the diameter of jet column. Quality assurance (Wang et al., 2013) is therefore generally adopted by sampling grout cubes and spoil cubes and performing breaks on both, along with taking spoil density readings throughout the jet grouting process to check the strength compatibility with the trial test sections (Langhorst et al., 2007; Hurley, 2005; Stark et al., 2009). Similarly, Kauschinger et al. (1992) developed mass balance equations for the single fluid jet grout system, which can be adopted to estimate the size and composition (soil, water, and cement) of spoil and soilcrete (jet grout column) by measuring the densities of soilcrete, cement grout, and spoil.

Hydrophones were used by Langhorst et al. (2007) and Hurley (2005) to detect the vibrations in the tubes at defined radii during the trial grouting program. This gave qualitative indications that the desired column diameter was being achieved which, when combined with a back analysis of spoil return densities, provided the confidence to proceed with production work. However, the installation of tubes for hydrophones is costly and time consuming. This will limit hydrophone method only to trial grouting programs, and makes it impractical for quality control during production work using the jet grout column.

Langhorst et al. (2007) and Malinin et al. (2010) used an innovative measuring device which was made of two crossing bars moving apart against the wall of the column wall before the grout set. Although the measured diameters of the columns were well-matched with those observed from the exposed columns after excavation, this device is not effective with jet columns at greater depths. In addition, Ho (2011) used an analytical model to predict the cutting distance of air-shrouded jets in cohesive soil. The model variables were calibrated by back-analyzing jet grouting field trial results at a nearby site with similar soil conditions.

Flora et al. (2012) proposed a most promising jet grouting design method by conducting a statistical analysis to obtain the mean value and coefficient of variation of the column diameter and verticality based on the measured values from a jet-grouting field trial. Then the uplift safety factor of the water sealing barrier made by jet grouting at the bottom of open excavation (Croce and Flora, 2000; Croce and Modoni, 2007; Flora et al., 2007; Lignola et al., 2008; Modoni et al., 2006) was estimated by the Monte Carlo procedure by assuming the column diameter, column spacing, and a given risk level. This method is quite simple and also accurate, and is ideal for use as a quality control method for production work.

This study presents a case history where a double fluid jet grouting project was conducted to maintain safety when four underground parking uplift piles were broken (Xu et al., 2014) during subway tunnel construction. Since the grouting platform was below the groundwater table, there was a possibility that groundwater would flow upward from the sandy soil to the basement through the grouting hole during the wash boring and grouting stages. Such leakage may have led to a serious incident, such as sand boiling. Therefore, two measurements were taken: spoil return and the spoil flow rate for the soilcrete column. A back analysis from the mean values of spoil density and spoil flow rate was utilized to estimate the column diameter. A control chart with upper and lower limits was developed in this paper to provide an early warning indicator of water leakage from a sand boiling issue. Apart from that, an optimal grouting sequence in a cluster was suggested in this paper in order to have more infill columns than perimeter columns.

2. Site characterization

Two 6.5-m diameter bored parallel tunnels driven using Earth Pressure Balance (EPB) shields need to pass beneath an existing underground parking under where four uplift piles, indicated by the red circle in Fig. 1, are in the way of the alignment. Double fluid jet grouting at depths ranging from 23.27 to 34.91 m was undertaken to improve the strength and reduce the permeability of the silty sand layer below the mat foundation of the underground parking. The purpose of this exercise is to provide a safe place for excavating the soils around the piles and then removing these piles from the alignment (Figs. 1 and 2). To prevent substantial structure heaves or settlements from occurring during jet grouting, real-time monitoring was implemented using electronic beam sensors installed in the underground parking (Fig. 1).

As seen in Fig. 2, the soil succession at this construction site of Taipei City comprises a fill of about 1.35-m in thickness, sitting on a 2.9-m thick medium stiff silty clay underlain by 11.15-m thick loose silty sand then 7.35-m thick medium stiff silty clay which extends to a thick layer of medium dense silty