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Investigation on performance of a large circular pit-in-pit excavation in clay-gravel-cobble mixed strata

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ABSTRACT

A unique pit-in-pit (PIP) excavation, which comprised a large diameter circular pit outside and a smaller deeper rectangular pit inside, was constructed in clay-gravel-cobble mixed strata. To guarantee project safety as well as characterize behavior of PIP excavation, investigate influence of inner pit excavation on outer pit performance and explore lateral earth pressure mobilized in discrete geomaterials, this project was extensively instrumented throughout construction. Field data indicated that it performed distinctly from those excavations in literature. This excavation caused relatively smaller wall and ground displacements, both of which featured distinctive profiles; current empirical and semi-empirical approaches for predicting excavation performance were not applicable to this case any more. To control performance of PIP excavation, it is of paramount importance to limit lateral wall movement of inner pit. Contrary to previous recognition, basal rebound due to excavation took place not only in soft clay, but also in stiff to hard clay, clay-gravel-cobble mixtures, and even decomposed bedrock. Different from those in fine grained soils, magnitudes of lateral earth pressures against retaining wall in clay-gravel-cobble mixtures showed a wide range of scattering and their thrusts were transferred to wall mainly via contact force of rock particles. Classic Rankine theory substantially underestimated while current empirical apparent earth pressure (AEP) diagrams highly overestimated magnitude of lateral active earth pressure of clay-gravel-cobble mixtures. For design of PIP excavation, the ground between inner and outer retaining walls should be treated as the passive state during excavation of outer pit, while as the active state during subsequent excavation of inner pit when greater increment of deflection occurred to inner wall than outer wall. Casting head of inner wall inside base slab of outer pit prior to excavation of inner pit was a cost-effective solution for enhancing excavation performance; socketing wall toe into underlying decomposed bedrock significantly mitigated potential risk associated with wall kicking.

1. Introduction

It has been widely recognized that excavation performance is closely related to subsurface condition. To date, vast amounts of studies have been contributed to excavations in clayey and sandy strata (e.g., Clough and O'Rourke, 1990; Ou et al., 1993, 1998; Whittle et al., 1993; Lee et al., 1998; Long, 2001; Moormann, 2004; Hashash et al., 2008; Pakbaz et al., 2013; Tan and Wang, 2013a,b; Finno et al., 2015; Hong et al., 2015; Shi et al., 2015; Tan et al., 2017, 2018a,b, Tan and Li, 2011; Tan and Wei, 2012; Tan and Lu, 2018). In contrast, few studies regarding excavations in mixed strata were known in literature, e.g., soft soils underlain by stiff residual soils or weathered rocks in Singapore (Wong et al., 1997), residual soils or sandy soils overlying soft to hard rocks in South Korea (Yoo, 2001; Seo et al., 2010), sandy deposit overlying karst in Guangzhou, China (Elbaz et al., 2018), decomposed geomaterials in Hong Kong, China (Leung and Ng, 2007), and boulder clay in Dublin, Ireland (Long et al., 2012). Their investigations indicated that there were considerable scatters in excavation performance for different mixed strata. Moreover, excavation performance in mixed strata differed from those in homogeneous soils and current empirical or semi-empirical approaches could rarely make reliable predictions on them.

A large-sized excavation was conducted in the clay-rock mixed strata overlying decomposed bedrock in Jiangsu Province, China. Because of its unique features, this excavation differed from most excavations reported worldwide. It had a pit-in-pit (PIP) configuration in

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plane, i.e., it consisted of a circular pit outside and a smaller deeper rectangular pit inside; consequently, influence from excavation of the inner pit was uncertain. This excavation was conducted in clay-gravel-cobble mixed strata, of which no similar case could be found in literature for reference; the presence of the mixed soils further complicated the project. Unlike the aforementioned excavations in mixed strata in rectangular shape and supported by anchored or propped earth retaining walls, the outer pit of this case had a large diameter circular geometry in plane and was supported by unpropped diaphragm wall (DW) panels (completely self-supported). Apart from excavation-induced structural and ground deformations, lateral earth pressures both in front of and behind the outer circular DW as well as those behind the inner rectangular continuous-bored-pile-wall (CBPW) were monitored in this case. Such instrumentation arrangements provided a rare opportunity to explore the role of the ground between the outer and the inner walls at various stages of excavation. As for lateral earth pressure against buried underground structures, most published studies just focused on propped or anchored earth retaining walls of rectangular pits (e.g., Terzaghi and Peck, 1967; Tschebotarioff, 1973; Wong et al., 1997; Yoo, 2001; Ng et al., 2012; Tan and Wang, 2013b) or tunnel linings (e.g., Chen and Peng, 2018), and none was known for unpropped circular earth retaining wall. With respect to lateral earth pressure in clay-gravel-cobble mixtures, neither field nor experimental data was reported. Hence, the relevant field measurements presented in this study can assist understanding earth pressure mobilized in mixed soils, which plays an essential role in design of earth supporting system (Tan and Wang, 2015a,b).

Because of the uncertainties above, a long-term field instrumentation program was implemented throughout the construction to safeguard project by providing immediate feedbacks on excavation performance to engineers. With the aid of numerical simulations, this study intends to characterize complex behaviors of PIP excavation in clay-gravel-cobble mixtures by analyzing field instrumentation data and comparing with relevant findings in literature. The major objectives of this study are to: (1) characterize lateral earth pressures mobilized in clay-gravel-cobble mixtures, (2) check applicability of current empirical and semi-empirical approaches for predicting performance of PIP excavations, (3) examine potential influence of inner pit excavation on performance of completed outer pit, (4) verify potentially variable states (passive, active, or at-rest) of the soil mass between outer and inner retaining walls throughout excavation, and (5) develop apparent earth pressure (AEP) diagrams for calculating lateral earth pressures against retaining wall in clay-gravel-cobble mixture. The findings and lessons learned from this study will be practically helpful for upgrading current state of design and construction for PIP excavation.

2. Geological conditions

Fig. 1 presents typical ground profile along with the measured soil properties at this site. Its subsurface soils comprised of 37 m thick superficial deposits underlain by decomposed bedrock. The superficial deposits were composed of successive layers of fill in the upper 1 m below ground surface (BGS), very stiff alluvial silty clay at 1–11 m BGS, stiff to very hard limnetic silty clay at 11–20 m BGS, and a pluvial stratum at 20–37 m BGS. This pluvial stratum contained 10–50% clay with the remaining constitutes predominantly classified as sub-angular gravels and cobbles with particle sizes of 3–20 cm, which were termed as clay-gravel-cobble mixtures. The bedrock consisted of moderately to highly weathered siltstone, mylonite, cataclasite, sandstone and tectonic breccia. Across the site, there existed some small secondary fault zones in the bedrock.

The observed long-term phreatic water level was located at about 0.5 m BGS. One confined aquifer was detected in the clay-gravel-cobble mixtures with water head near ground surface; another one existed in well-watered tectonic fissure zone of the bedrock with water head at 5.58 m above ground surface. These two aquifers imposed a high risk of piping failure to this PIP excavation, i.e., the weight of overlying soil strata could not suppress the underlying upward artesian pressures during excavation. The excavation depth, H_{piping}, where piping failure could take place, can be estimated by:

$$\gamma_{soil} \times (H_e - H_{piping}) = \gamma_{water} \times H_{artesian} \quad (1)$$

where, γ_{soil} = soil unit weight = 19 kN/m^3; γ_{water} = water unit weight = 9.8 kN/m^3; H_e = final excavation depth; $H_{artesian}$ = artesian pressure head. For the outer pit, its H_e = 16 m and underlying $H_{artesian}$ = 20 m + 0 m = 20 m; for the inner pit, its H_e = 32 m and underlying $H_{artesian}$ = 37 m + 5.58 m = 42.58 m, refer to Fig. 1. Thus, the estimated H_{piping} was 5.68 m for the outer pit and 10.04 m for the inner pit, i.e., if no water pressure relief was carried out during excavation, the upper aquifer in the clay-gravel-cobble mixtures could cause piping failure once excavation went downwards to 5.68 m BGS or deeper and the lower aquifer in the weathered bedrock could incur piping failure once excavation proceeded to 10.04 m BGS or deeper.

3. Construction

Figs. 2a and 2b present configurations of this PIP excavation in plane and Fig. 3 shows its vertical cross-section. It had an outer circular pit (103.4 m in diameter and 16 m in depth) and an inner rectangular pit (54 m in length, 40 m in width and 32 m in depth). The outer pit was excavated in the stiff to hard silty clay, which was retained by 1.2 m thick and 45–50 m high unpropped circular DW; the inner pit extended completely through the upper silty clays and into the clay-gravel-cobble mixtures, which was supported by 1.2 m diameter and 25 m high CBPW. One level of steel reinforced concrete struts was cast at 24 m BGS against the inner CBPW. Both the outer DW and the inner CBPW were tipped into the decomposed bedrock, i.e., rock-socketed. The DW head was encased in a circular concrete capping beam (1.5 m thick and 2.2 m wide) and the CBPW head was cast within the base slab (1.0 m thick) of the outer pit at 16 m BGS prior to the commencement of the inner pit excavation.

The following sequential construction steps were adopted at this project: (1) construction of the outer circular DW, (2) excavation to 13 m BGS, (3) construction of the inner CBPW, excavation to 16 m BGS and casting of the base slab at 16 m BGS, (4) excavation of the inner pit to 25 m BGS accompanied by casting of the concrete struts at 24 m BGS, (5) excavation to the final level at 32 m BGS followed by casting of the base slab at 32 m BGS, and (6) construction of underground structures. To prevent soil loss, shotcrete was paved on the exposed inner face of the CBPW right after each soil removal at the inner pit. Detailed construction schedules can refer to Fig. 4.

As mentioned previously, the existence of the two confined aquifers in the clay-gravel-cobble mixtures and the weathered bedrock would endanger excavation safety to some extent, e.g., piping of deep soil layers, or gushing of tectonic fault zones and fault fracture zones (e.g., Chow and Ou, 1999; Tan and Lu, 2017; Tan et al., 2018a). In light of these potential risks, the bedrock had been treated by fissure grouting prior to excavation; in addition, pressure heads of the aquifers were reduced to safe levels by deep discharging wells during excavation. Relevant technical information regarding aquifer, water discharging and grouting treatment can refer to Shen et al. (2013), Wu et al. (2015), Njock et al. (2018) and Tan et al. (2018b).

4. Field instrumentation

To investigate performance of this PIP excavation and assist safeguarding the project, the site was extensively instrumented. Figs. 2a and 2b present the instrumentation layouts for the outer and the inner pits; Fig. 3 shows instruments along depth. The monitored items included: (1) lateral deflections of the outer DW panels at P01 to P12 and the inner CBPW at P13 to P20; (2) ground settlement development along 16 arrays of aligned survey sections behind the outer pit (G1-