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# Characterization of semi-top-down excavation for subway station in Shanghai soft ground

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A B S T R A C T

Based on field instrumentation data and extensive comparison with bottom-up (BU) and top-down (TD) excavations, this study investigates performance characteristics of semi-top-down (STD) excavation for subway station in Shanghai soft ground. By taking advantage of its stronger propping system than BU and shorter excavation duration than TD excavations, the maximum lateral wall displacement, $\delta_{hm}$, of the STD was below half of BU and TD excavations featuring similar excavation geometry, supporting structure and subsurface condition. Rigid middle floor slab cast during excavation was effective in controlling time-dependent displacements of wall and ground as well as uplift of supporting structure. Rather than $\delta_{hm}$, the theoretical ground loss volume calculated from measured inward lateral wall displacement is the reliable indicator for assessing development of ground settlement. Despite its much smaller $\delta_{hm}$, ground settlement of the STD was comparable to that of the TD while smaller than that of the BU. However, ground settlement influence zone of the STD was in agreement with that of the BU, both much wider than that of the TD. These inconsistencies were proven to inherently correlate with their distinct $H_m$, where $H_m$ denotes the depth corresponding to $\delta_{hm}$. By obtaining $H_m$ near ground level, ground subsidence zone can be minimized considerably. This is vital to the performance of such deep excavations to ensure adequate safety against rotational push-in failure of earth retaining wall. Different from most BU and TD excavations, spatial corner stiffening behavior was not apparent for this STD excavation, which was the combined result of segmented construction procedure and narrow pit width.

## 1. Introduction

Design and construction of deep excavation is relatively challenging and requires careful consideration of geological condition, choice of retaining structure and use of numerical model well suited to handle complex soil-structure interaction problem. For excavation of subway station or tunnel located in urban environment, this challenge is further complicated by presence of structures and facilities nearby (e.g., Liao et al., 2009, 2013; Peng et al., 2011; Tan and Li, 2011; Pakbaz et al., 2013; Bai et al., 2014; Shen et al., 2014; Tan et al., 2015a; Wu et al., 2015; Xu et al., 2015; Verma et al., 2016; Tan and Lu, 2017a). Designer and contractor are not only confronted with the need to protect pre-existing structures and facilities, but also face the pressure of not interfering with ground traffic. Therefore, excavation of subway station commonly follows a performance-based design philosophy.

Because of its low cost, easy operation and short excavation duration, most subway stations in soft ground were excavated by bottom-up (BU) method (e.g., Tan and Wei, 2012; Chen et al., 2015; Tan et al., 2015b). During excavation, earth retaining walls were commonly braced with temporary struts. This made their earth supporting systems usually have insufficient stiffness for resisting excavation-induced lateral wall displacement, frequently accompanied by pronounced ground settlement and tremendous damage to adjacent structures or facilities (e.g., C. Xu et al., 2016; Y.S. Xu et al., 2016; Tan and Lu 2017b). In light of this, subway stations located in congested urban environment were traditionally excavated by top-down (TD) method (e.g., Liu et al., 2011; Tan and Li, 2011). Compared to BU method, TD method has the following major merits. First, it allows performing construction of underground structure and removal of soils simultaneously and consequently entire construction duration can be shortened. Second, rigid underground structure elements (e.g., floor slabs and beams) cast during excavation are strong for suppressing wall and ground movements; hence, risk of adjacent pre-existing structures and facilities to be damaged can be mitigated. Moreover, underground structure elements

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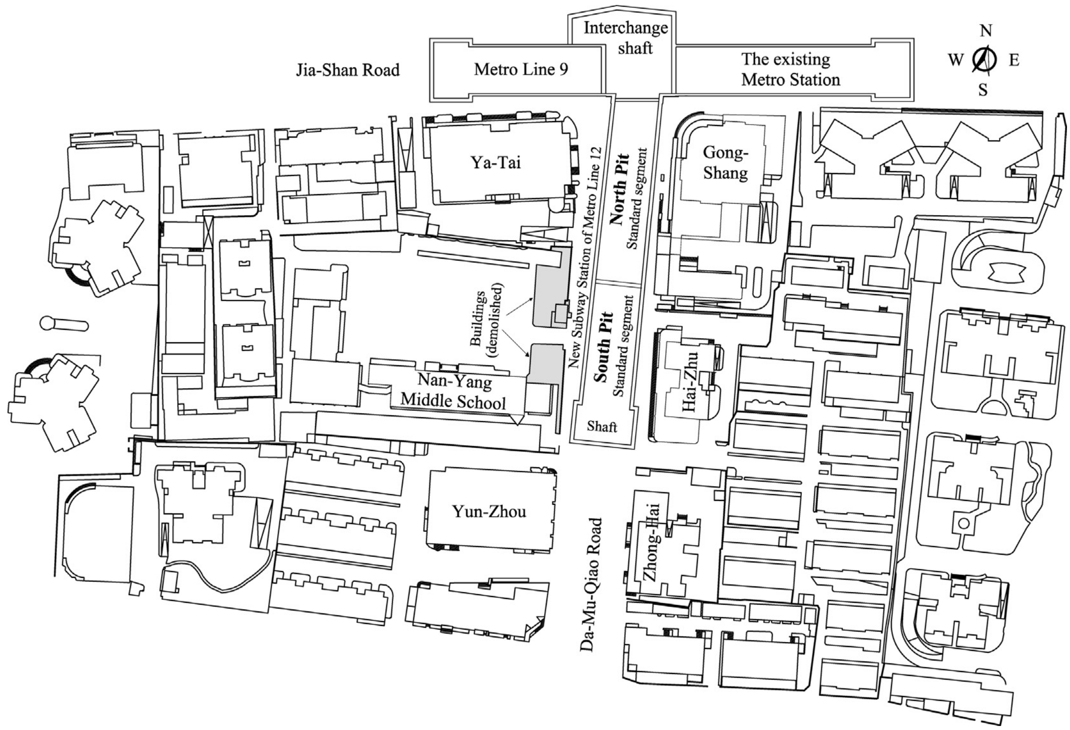


**Fig. 1.** Plan view of construction environment.

are combined tightly with retaining wall via in-situ casting (i.e., supporting system of TD excavation has much better structural integrity than that of BU excavation); thus, TD excavation is less susceptible to stability failure of earth supporting system. Typical failure cases of BU excavations involved with collapse of earth supporting system can be found in Ishihara (2011) and Chen et al. (2015). Third, since floor slabs, beams and side walls of substructures cast during excavation function as struts, fewer temporary struts are needed. Fourth, soil removal and cast of substructure elements are operated by turns and weight of cast substructure is transferred into deep bearing strata via interior columns atop end-bearing bored piles. As a result, upheaving of the soil strata below excavation level, which arises from vertical stress relief (excavation), is restrained by the embedded bored piles and then the incidence relevant to buckling of propped struts caused by differential vertical displacement of interior columns and retaining wall is reduced. Fifth, excavation below completed ground level floor does not disrupt ground traffic and other urban activities; furthermore, TD excavation is not affected by weather change. Despite these merits, TD method has three primary drawbacks: (1) large amounts of interior columns and underlying bored piles (load bearing elements) are essential for supporting heavy floor slabs, which means much higher project cost of TD excavation than BU excavation; (2) because of restricted work space, it is difficult to excavate and dispose soils below ground floors; (3) subsequent soil removal cannot commence until poured substructure elements has cured. As the result of (2) and (3), it will usually take TD method much longer than BU method to finish excavation.

Relevant practice in soft ground (Tan et al., 2015b) indicated that apart from supporting system stiffness, excavation duration is one of vital factors in determination of excavation performance. Longer excavation duration commonly led to significantly larger time-dependent lateral wall displacement and associated ground settlement, particularly at deep excavation level (high unloading stress level). Despite its much greater supporting system stiffness, TD excavations in soft ground did not exhibit better performance than BU excavations (Tan and Wang, 2013a, 2013b), largely resulting from TD's much longer excavation duration. In light of this, an innovative excavation procedure, termed as semi-top-down (STD) method, has been gradually adopted in recent years for excavation of several subway stations in the congested downtown area of Shanghai. During STD excavation, soils above middle floor of substructure are excavated in accordance with a BU procedure. Thereafter, middle floor slab is cast. Once the poured slab gets cured, soil removal continues to final level, followed by casting base slab and other underground structure elements. Because excavation of its upper pit follows a BU procedure, STD excavation has shorter excavation duration than that excavated by TD method. Meanwhile, since rigid middle floor slab is cast prior to excavation of the lower pit, it has stronger supporting system than that excavated by BU method. Because of these two merits, STD excavation was assumed to have better performance than both BU and TD excavations.

Advances in deep excavations are often initiated by field observations from previous excavations (e.g., Peck, 1969; Clough and O'Rourke, 1990). As such, well-documented case histories are critical in the field of deep excavation. In the last decades, many researchers and practitioners have contributed amounts of field data to both BU and TD excavations (e.g., Ou et al., 1993; Hashash et al., 2008; Karlsrud and Andresen, 2008; Tan and Wang, 2013a, 2013b; Bolton et al., 2014; Finno et al., 2014; Tan et al., 2015b). In contrast, there were very few field data of STD excavation reported in literature. This excluded the possibility of comprehensively characterizing behavior of STD excavation and quantifying its potential advantages over BU and TD excavations. The construction for Jiashan Road Station of Shanghai Metro Line 12, which lasted from 2011 to 2013, provided this rare opportunity for investigation. This 24.8–25.2 m deep excavation was extensively instrumented and its performance was closely monitored throughout construction. By analyzing its field monitoring data and comparing its performance with those of BU and TD excavations, deformation characteristics of STD excavation were comprehensively investigated and its advantages over BU and TD excavations were quantified. With the aid of numerical analyses, the key role of the depth, $H_m$, corresponding to the maximum lateral wall displacement, $\delta_{hm}$, in affecting ground subsidence zone was identified and then associated risks (e.g., damage to pre-existing structures or facilities in the proximity of excavation) could be mitigated in the future by preparing appropriate countermeasure or remedial measure in advance. The relevant findings presented in this