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Model test on partial expansion in stratified subsidence during foundation pit dewatering

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ABSTRACT

Partial expansion was observed in stratified subsidence during foundation pit dewatering. However, the phenomenon was suspected to be an error because the compression of layers is known to occur when subsidence occurs. A slice of the subsidence cone induced by drawdown was selected as the prototype. Model tests were performed to investigate the phenomenon. The underlying confined aquifer was generated as a movable rigid plate with a hinge at one end. The overlying layers were simulated with remolded materials collected from a construction site. Model tests performed under the conceptual model indicated that partial expansion occurred in stratified settlements under coordination deformation and consolidation conditions. During foundation pit dewatering, rapid drawdown resulted in rapid subsidence in the dewatered confined aquifer. The rapidly subsiding confined aquifer top was the bottom deformation boundary of the overlying layers. Non-coordination deformation was observed at the top and bottom of the subsiding overlying layers. The subsidence of overlying layers was larger at the bottom than at the top. The layers expanded and became thicker. The phenomenon was verified using numerical simulation method based on finite difference method. Compared with numerical simulation results, the boundary effect of the physical tests was obvious in the observation point close to the movable endpoint. The tensile stress of the overlying soil layers induced by the underlying settlement of dewatered confined aquifer contributed to the expansion phenomenon. The partial expansion of overlying soil layers was defined as inversed rebound. The inversed rebound was induced by inversed coordination deformation. Compression was induced by the consolidation in the overlying soil layers because of drainage. Partial expansion occurred when the expansion exceeded the compression. Considering the inversed rebound, traditional layer-wise summation method for calculating subsidence should be revised and improved.
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1. Introduction

Groundwater extraction plays a direct role in land subsidence by causing the compaction of susceptible aquifer systems (Galloway and Burbey, 2011). When ground water in underlying confined aquifers endangered excavation, the water level was lowered to ensure safety.

Subsidence induced by groundwater withdrawal has been recognized and cumulatively evaluated in a large number of situations (Modoni et al., 2013). Land subsidence is a serious environmental geological problem in China (Ye et al., 2016a,b). Various studies have been carried out to predict the subsidence induced by lowering water levels, such as statistical method (Holzer and Bluntzer, 1984), one-dimensional (1D) consolidation theory based on Terzaghi theory (Qian and Gu, 1981; Chai et al., 2005; Ye et al., 2011; Loaiciga, 2013; Ye et al., 2016a,b), quasi three-dimensional (3D) seepage method (Harada and Yamanouchi, 1983; Giao and Ovaskainen, 2000; Li et al., 2000a,b; Tan et al., 2015; Ye et al., 2015), model based on 3D groundwater seepage

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(Shen et al., 2006; Xu et al., 2007, 2012), model with 3D groundwater flow and 1D subsidence modules (Ye et al., 2005, 2011; Xue et al., 2008; Shi et al., 2008; Shen and Xu, 2011; Wu et al., 2010; Shen et al., 2013), model coupled with 3D groundwater flow, model with 3D aquifer system displacements (Kihm et al., 2007; Ye et al., 2016a,b), and model of visco-elasto-plastic compaction (Wu et al., 2010; Zhang et al., 2015). Budhu and Adiyaman (2010) presented a basic mechanics analysis of land subsidence due to groundwater pumping, together with a corresponding land subsidence prediction method. Shen et al. (2006) and Shen and Xu (2011) established a numerical model to predict the behavior of land subsidence in Shanghai because of groundwater pumping. Wang et al. (2012) suggested three ways to control seepage and discussed the combined effects of pumping, curtain, and recharging wells. Yoo et al. (2012) presented a case where excessive ground settlement occurred around a conventional tunnel. The excessive ground settlement was caused by tunneling-induced groundwater drawdown. A similar case of land subsidence was monitored and analyzed by Lopez-Fernandez et al. (2013) in a tunnel excavation. Wang et al. (2013a,b) investigated the influences of dewatering on deep excavation and surrounding deformation. Loaiciga (2013) proposed a new equation to calculate vertical consolidation settlement in aquifers caused by pumping, an equation that is viewed as a modification of traditional 1D consolidation theory. However, the subsidence predicted using consolidation theory was larger than the observed one for the multi-aquifer and multi-aquitard (MAMA) system in China. The predicted subsidence has to be revised through an empirical coefficient to match the observation. Field and laboratory experiments were performed to investigate the deformation law of layers (Burbey, 1999, 2001, 2003, 2006, 2008; Burbey et al., 2006; Zhang et al., 2012; Wang et al., 2013a,b,c,d; Li et al., 2014; Zhou et al., 2014; Minderhoud et al., 2015). However, the reason for the inaccurate prediction was not discussed.

Partial expansion phenomenon was observed in a subway foundation pit close to an operating high-rise bridge by complicated monitoring measures under the demand of environment protection during foundation pit dewatering (Wang et al., 2009, 2013a,b,c,d; Zhu et al., 2015) in Shanghai China. This phenomenon may be one of the potential reasons for the inaccurate subsidence prediction. When the partial expansion phenomenon was first observed, it was suspected to be a monitoring error of the observation method using multipoint extensometers in soft soil. Reproducing the phenomenon in layered soil in the laboratory and observing the deformation was a key step to check its existence.

Model tests were performed in this study to check the existence and understand the mechanism of partial expansion phenomenon in a MAMA system during foundation pit dewatering. Numerical methods were introduced to reproduce the partial expansion and correct the results of model tests. The existence of partial expansion occurred in stratified settlements under coordination deformation and consolidation condition was confirmed. The mechanism of the phenomenon was explained by the model tests and numerical simulations, which can be used as references to revise and improve subsidence calculation method for foundation pit dewatering.

2. Background

Shanghai is located in front of the Yangtze River Delta plain. Besides sporadic residual volcanic rocks exposed in the southwest, all the bedrocks are covered with Quaternary strata. The layers of Shanghai are composed of typical MAMA system. According to generation time, genetic types, and main engineering geological features, the Quaternary strata in Shanghai area were divided into 16 engineering geological strata (Shanghai Geological Environmental Atlas, 2002). Seven major engineering geological layers are shown in Table 1.

Table 1
Seven major engineering geological layers.

Geological layers No.	Layer name	Depth (m)
1	Topsoil layer	0.0
2	The first sand layer	0.9–7.0
3	The first hard soil layer	1.0–5.0
4	The first soft soil layer	3.0
5	The second soft soil layer	18.0–22.0
6	The second hard soil layer	15.0–30.0
7	The second sand layer (the first confined aquifer)	27.0–30.0

The aquifer system underlying Shanghai is not a complete, independent groundwater system but rather a part of the water systems of the Yangtze Delta. The first sand layer corresponds to the phreatic aquifer in the hydrogeological section of the region, and the second to the sixth sand layers correspond to the first to fifth confined aquifers. Apart from the sixth sandy soil distributed in the northern region, the remaining sand layers in the region have relatively stable distribution. In some sand layers, clay lenses exist. Semipermeable aquifers composed of clay and silty clay are distributed between the sand layers. For normal foundation pit dewatering, only micro-confined, the first confined, and second confined aquifers were considered.

According to engineering geological and hydrogeological conditions, as well as the combinations of formation, the Shanghai area was divided into four landform partitions: lake plains, coastal plains, river sand and tidal flat (Fig. 1). Coastal plain partition was selected as the background of the model test. Most of the confined aquifers of dewatering engineering in Shanghai are concentrated in the first confined aquifer. The overlying strata include the topsoil, first sand, first hard soil, first soft soil, second soft soil, and second hard soil layers. According to the physical and mechanical properties of the overlying combined strata, the overlying strata were summarized into muddy clay, sandy silt, and silty clay layers. The confined aquifer was generalized as silty sand layer. Physical property indexes of the summarized layers are shown in Table 2.

The foundation pit of Yishan Road station, subway line 9 is a typical foundation pit in Shanghai. The geological and hydrological conditions of the pit can represent a type of geological partition and the pits in the city center of Shanghai. The description of layers is shown in Fig. 2(b). Due to the high request of environment protection, lots of monitoring and field experiments were performed here obtaining enough monitoring data, the pit was selected as the case for investigating the partial expansion phenomenon. Partial expansion phenomenon in the subsidence was observed in the foundation pit dewatering of the pit (Wang et al. 2009, 2013a,b,c,d; Zhu et al. 2015). The subsidence velocity of the bottom was larger than the top in an aquitard. There was a different subsidence acceleration for the bottom and top of an aquitard. Although the bottom and top of the aquitard were all subsided, the velocity of bottom was faster than that of top. Then the thickness of the aquitard was increasing and expansion occurred (Fig. 2).

3. Material and methods

3.1. Conceptual model

For a 3D subsidence cone induced by foundation pit dewatering, a slice was selected to represent the subsidence in that direction

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