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Land subsidence and pore structure of soils caused by the high-rise building group through centrifuge model test

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ABSTRACT

In the urban area of Shanghai, the dewatering of groundwater was controlled strictly and the engineering–environment effect of the high-rise building group became to be the main cause of land subsidence in Shanghai. Based on the high-rise building group in the soft soil area in Shanghai, the mechanism of land subsidence was studied in this paper by the centrifuge model test. The central area of the building group has larger subsidence and the subsidence superimposition effect is obvious. It can exceed the allowance and cause land subsidence hazard. The land subsidence affected by the different building distances was also studied. For smaller building distances, the subsidence superimposition effect is more obvious. The engineering characteristics of soils are controlled by the state of pore structure of soils to a great extent. The parameter of specific subsidence was put forward as a tie to analyze the relationship between land subsidence and pore structure of soils. The pore structure of each soil layer was studied by the mercury intrusion porosimetry test (MIP) and the pore distribution of each soil layer was studied by the fractal theory. There are mainly macropores in silty clay of layer no. 4, clayey soil of layer no. 8, silty sand of layer no. 7 and layer no. 9 in Shanghai. The ink-bottle effect exists in the intrusion stage in the MIP test. There are four different fractal dimensions in silty clay of layer no. 4 and clayey soil of layer no. 8 and three different fractal dimensions in silty sand of layer no. 7 and layer no. 9.

1. Introduction

In recent years, land subsidence occurred in over 90 cities and counties in China, including Shanghai, Tianjin, Jiangsu Province and Shanxi Province, etc. The total area of subsidence reached 93,885 km^2 (Cui, 2008). Shanghai is one of the earliest cities that suffer seriously from land subsidence in China (Tang and Cui, 2008a,b). Before the 1960s, the main cause of land subsidence was the irrational withdrawal of groundwater. But from the 1960s, the withdrawal of groundwater was controlled reasonably. Especially, from the end of the 1970s, the pumping of groundwater was strictly controlled in the urban area in Shanghai. The quantity of water recharged into the subsurface was always greater than that of the pumping and the extracted aquifers were gradually adjusted. As a result of these measures, the subsidence caused by pumping and recharging kept smooth and gentle in the urban area. During the period of the 1990s, a variety of municipal works and high-rise buildings were constructed on a large scale (Gong, 1998; Yan, et al., 2002). At the same time, land subsidence accelerated again in Shanghai and the average yearly subsidence was more than 4 times that of the previous period (Cui et al., 2010a,b). Through the monitoring data, the subsidence caused by high-rise building groups is obvious (Cui, 2008), and it is important to deeply study the land subsidence caused by the engineering–environmental effect of the high-rise building group.

The engineering characteristics of soils are controlled by the state of pore structure of soils to a great extent (Gong et al., 2009). Mercury intrusion porosimetry (MIP) has been routinely used to evaluate the pore size distribution of powdered and bulk materials with open and interconnected pore structures. Recent applications of mercury intrusion porosimetry in geotechnical engineering included the following: the effect of soil microstructure on the compressibility of natural Singapore marine (Low et al., 2008); the compressibility effect in evaluating the pore size distribution of kaolin clay (Penumadu and Dean, 2000); the differences between the pore size distribution in laboratory and field compacted soil (Prapaharan et al., 1991); the feasibility of correlating permeability with the pore size distribution of clays (Lapierre et al., 1990); the effect of air-drying and critical-point drying on the porosity of clay soils (De Kimpe, 1984); permeability as a function of the pore size distribution of silty clay (Garcia-Bengochea et al., 1979) and the pore size distribution in clays (Diamond, 1970).

This paper discusses the relationship between the land subsidence and the pore structure of soils caused by the high-rise building group under the typical geological subsurface of Shanghai by the centrifuge

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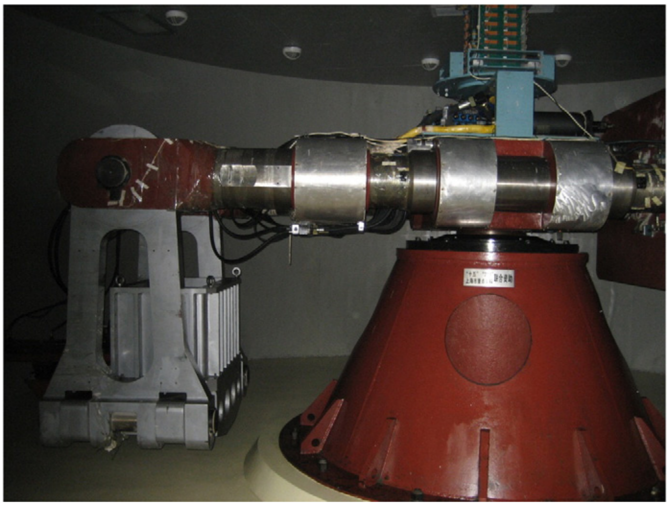

Fig. 1. The 150 *gt* geotechnical centrifuge.

model test. The problems studied, include the influence of high-rise building group on land subsidence of its central and circumjacent areas, the land subsidence affected by the different building distances, the deformation characteristics of different soil layers and the pore structure of each soil layer.

2. Centrifuge model test

Because of the ability to reproduce the same stress levels in a small-scale model, as those present in the full-scale prototype, centrifuge modeling is a useful tool for the investigation of geotechnical problems (Sharma and Bolton, 1996; Abdoun et al., 2003; Powrie and Daly, 2007).

2.1. The geotechnical centrifuge

The geotechnical centrifuge of Tongji University (Fig. 1) used for the model tests has a single arm with the nominal radius of 3 m. The capacity of the centrifuge is 150 *gt* and its maximum acceleration can reach 200 g.

The strongbox used for the model tests has dimensions of 500 mm × 800 mm × 550 mm in width, length and height. Three side walls and the bottom of the container are made of high strength stainless steel plates to protect against possible corrosion and to reduce the friction between the soil and the container surface. The front wall of the container is made of a 40 millimeter thick Plexiglas plate.

2.2. Soil property and pile

Shanghai is situated on the Yangtze River delta where the alluvial deposits generally reach 250–300 m in the urban area (Cui et al., 2010a). In recent years, records indicate that the main subsidence below 70 m is related to pumping/recharge while the soil deformation above this depth is mainly caused by engineering works. In this upper horizon there were three distinct thick layers of soft soil and Cui et al. (2010a) summarized the geological layer above 70 m in detail.

According to the geological and hydrogeological background in Shanghai, the soil layers from the top downward are brown-yellow clay layer, silty clay layer, silt sand layer, clayey soil layer and silt sand layer. The foundation soil of the model test is silty clay of layer no. 4, silt sand of layer no. 7 and clayey soil of layer no. 8, respectively, obtained from the site in Shanghai. The soil properties are summarized in Table 1.

The model used pile foundations, as this is the normal type of foundation for high-rise buildings in Shanghai. However, it is not intended to study the characteristics of pile foundations and they are used in the model simply to take the building load. In order to simplify the model, steel bars are used to make the 230 mm model piles and steel plates are used to make the 100 mm × 100 mm model pile caps.

2.3. Preparation of soil layers

To minimize side friction, the container wall was covered with a thin layer of smooth plastic membrane. The procedures of preparing soil layer were as follows.

(1) The silt sand obtained from the site was used to construct the bottom sand layer (layer no. 9), 50 mm in thickness;
(2) Layer no. 8 (150 mm in thickness) was constructed by the clayey soil obtained from the site. This layer was divided by several sub layers. After the first sub layer constructed, the second sub layer was subsequently constructed;
(3) Thirdly, layer no. 7 (75 mm in thickness) was also constructed by silt sand;
(4) The silty clay was used to construct layer no. 4 (200 mm in thickness). Its construction way was the same as that of layer no. 8;
(5) Lastly, 25 mm thick upper layer was constructed.

After soil layers were constructed, the model was consolidated at 200 g for about 3 h.

2.4. Instrumentation and test procedures

Fig. 2 shows the location of the instrumentation. Linear variable differential transformers (RMWY-50) were installed on the pile cap of one building and at various points in the foundation soils in order to measure the building and land subsidence as well as the deformation of different soil layers.

The model consisted of four high-rise buildings (Fig. 3), using a scale of 1 to 200. The original plan dimensions of each building were 20 m × 20 m, with the 22 floors reaching a height of 65 m. The bearing stratum of the pile tip was the silt sand of layer no. 7.

Two centrifuge model tests were conducted to study the land subsidence affected by the different building distances. The distance between two adjacent buildings in the building group was 20 m and 30 m in the prototype, and the running time of the centrifuge was 6 h and 8 h, respectively. The acceleration stage of the centrifuge needs 8 min, then the centrifuge reaches the stable acceleration.

3. Land subsidence

3.1. Land subsidence of different positions in the building group

In the increasing stage of the acceleration, the subsidence of different positions all increases quickly. In the stable acceleration stage of the acceleration, the subsidence keeps increasing and the velocity decreases. Fig. 4 shows variations of subsidence with time at three different positions in the building group.

The central area of the high-rise building group experiences larger subsidence, so the superimposition effect of the high-rise building group

Table 1
Physical and mechanical properties of soils for the centrifuge model test.

Soil	Water content (%)	Bulk density (kN/m^3)	Initial void ratio	Compression modulus (MPa)	Cohesion (kPa)	Internal friction angle (°)
Silty clay of layer no. 4	43.58	18.89	1.075	2.48	12.0	12.5
Silt sand of layer no. 7	9.95	13.81	1.142	9.04	5.0	24.8
Clayey soil of layer no. 8	38.79	18.88	1.001	2.13	15.8	14.5