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Numerical simulation of land subsidence caused by high-rise building, applied in Tanggu, China

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Abstract. Ground subsidence is aggravated and becomes a prominent phenomenon recently in Tanggu, China. The subsidence reached its most critic state because of intensive water over-extraction in 1980s. Thereafter, over-draft withdraw of groundwater has been strictly controlled. Consequently, the rate of settlement decreased in the subsequent period. However, in recent year, ground subsidence becomes a prominent hazard again in some high-rise building areas .GPS-based monitoring data indicated new cone of depression has been formed. After detail investigation and analysis, it was thought that the appearance of the new subsidence center is the direct consequence of the construction of high-rise building. In this study, based on acquired monitoring data of subsidence, a special software package of Adina computer programs was applied in this study and analysis of the mechanism of subsidence induced by buildings. The results indicate that this method is useful to manage the land subsidence problem to high-rise building group.

Introduction

Land subsidence consists on a gradual compaction of the ground surface, which is a common human-induced hazard affecting many cities in the world. The first occurrence emerged in Mexio(1891), however, the limited rate and no obvious hazards of the subsidence induced people pay no attention to this phenomenon. Recently, land settlement has already become a widespread hazard all over the word [1, 2]. As to China, land subsidence has been recorded over 96 cities, and Tianjin is one of the earliest cities in China that suffered serious land subsidence from 1959.Tanggu in the city of Tianjin had a maximum accumulated subsidence of 3.108m in 2003 [2]. It is well known that the land subsidence has a good correlation with the exploitation of groundwater [3, 4, 5]. To mitigate the land subsidence, the overdraft of water was controlled reasonably from 1985, and the rate of land subsidence decreased accordingly. However, this phenomenon has been in serious situation in recent year especially after 2005. After detail investigation and analysis, it was thought that this abnormality is related to municipal works and the construction of high-rise building.

Nowadays, there are several authors study the settlement caused by the over-draft of groundwater [3, 4, 5, 6], and the subsidence by effect of engineering constructions has also been studied by some authors [7, 8, 9]. However, most of them considered the subsidence caused by dewatering before the construction, the portion induced by the construction of buildings itself has not been attracted much attention to. Meanwhile the ground settlement problem under the building loads is not only confined to one building. As a new factor affecting the settlement and new type of subsidence, Shanghai has given attention to this problem in recent years [10]. But there is no system research and thorough analysis. Therefore, this paper preliminary discussed the characteristics of the subsidence induced by urban high-rise building group. The objectives of this paper was to make full use of monitoring data based on the Global Position System(GPS) and a special software package of Adina computer programs, trying to discuss the relationship between the land subsidence and high-rise building.

The study area

Tanggu, situated at the northern edge of the Great China plain in eastern China, stands on the coast of the Gulf of Bohai, and on the east of Tianjin (Fig.1). The marine and proluvial Quaternary deposits induce silt clay, clay and sand clay. The depth of silt-clay occupies more than 50% of the total deposits. It is well known that the mechanisms of silt clay are prone to compaction under pressure, so land subsidence especially caused by silt clay is a normal phenomenon in this area. Quaternary is about 400-500m in depth and consists of a layered sequence of marine sand and silt clay, in which four separate aquifer units have been identified. The uppermost aquifer is about 10-40m thickness and contains phreatic and semi-confines groundwater，and the buried depth of this aquifer is about 50-90m. The second to fourth aquifers are artesian groundwater and the buried depth are 168-204m, 280-300m and 397-420m, respectively.

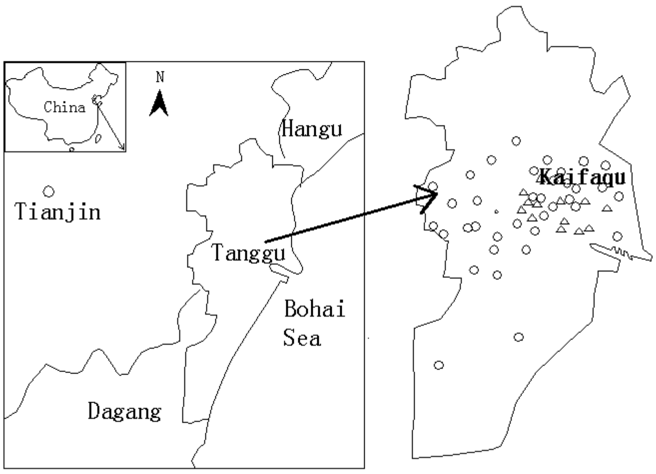

Fig.1: The situation of study area and location of GPS stations used in this work. Cycles and triangles indicate common stations and stations set on the buildings, respectively.

After recognized the land subsidence problem of Tanggu in the late 1960s, a series of measures were extended to mitigate this hazard, however, subsidence still continues. Owning to the low-land landform of Tanggu, ground evaluation in some districts of the city has sunk near the mean sea water level, which made flooding protection more difficult and caused more economic lost. The maximum annual subsidence reached to 131mm during the period of 1977 to 1982, and 117mm of 1982 to 1985. After 1985, the subsidence was soon brought under control by the ending of aquifer over-exploitation and enlargement use of surface water, and the rate had an obvious decrease in that time accordingly. Recently, a subsidence monitoring system (Fig.1) based on GPS has been applied in Tanggu during the period of 2008 to 2010. The network consist 60 sites, to monitor the settlement caused by buildings, 12 monitor points were set on the top of typical buildings (Fig.1). The monitoring work took half year as a cycle and 5 period data have been collected. At the same time, the record of land subsidence was also obtained by other techniques including InSAR and Leveling over different and same time intervals, which were compared using a significant number of points. To analyze the change of this hazard before and after 2005, we selected two kinds of intervals, which cover the period of 2004 to 2005 and 2009 to 2010. Fig.2 shows the rate increased in the subsequent period and the subsidence affected area expanded with the growth of the city. Through direct monitoring data and detail investigation, there was new subsidence cone depletion in Kafaqu emerged, which had relation to the construction of the high-rise building group.

As for Tanggu, Land subsidence has brought about several problems, including seawater intrusion, localized flooding and damage to highways. For the development of the city, it is necessary to analyze this hazard and give reasonable advice to the construction of the city. Meanwhile, the high-rise building is a common construction in a large amount of cities, especially in metropolises, so the analysis of the effect of building to ground settlement is also critical to the similar region.

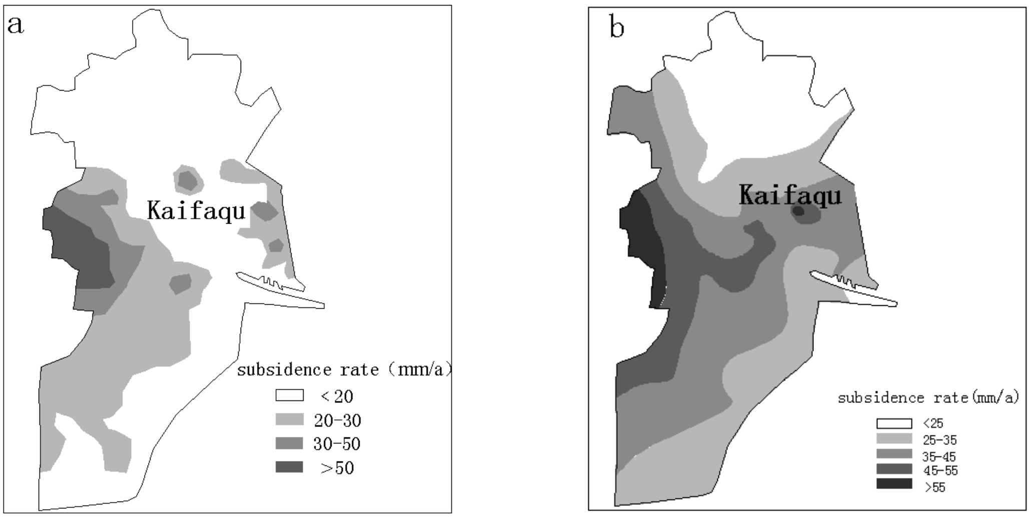

Fig.2: The annual subsidence rate of Tanggu for the period 2004-2005(a) and 2009-2010 (b).

Biot's consolidation theory and the ADINA system

Consolidation is a process that soils decrease in volume. Generally three parts, that are water, gas and solid particles, make up of soil mass. According to the effective stress principle (Terzzaghi, 1925), the total stress of overburden (σ^T) is resisted by a combination of the pore pressure (p) and the effective stress in the soil mass (σ'). If the groundwater was removed or external load was applied on the soil mass, according to the equilibrium equation (1), the additional pressure was transferred to the effective stress. In this process, the soil structure aquifer system especially the clay layer was deformed, which caused the land subsidence on the surface. In a word, land subsidence is a common phenomenon after the consolidation of soil body.

$$\sigma^T = p + \sigma' \tag{1}$$

To calculate the magnitude caused by compaction, based on the principle of effective stress, Terzaghi described analytically the one-dimensional consolidation of a soil column. In 1941 Biot generalized Terzaghi's theory to three-dimensional porous media, which could calculate three-dimension displacement of soil body and has obvious advantages compared with the former [11]. But for practical engineering application, it is difficult to get the analytic solutions

Nowadays, the numerical simulation of soil mechanics problems has become a routine part of engineering practice as well as a focus for fundamental research [13, 14, 15]. The ADINA system has been developed in recent years into a complete system for the analysis of solid, fluid and coupled problems. They can be incompressible, slightly compressible, compressible flows and flows in porous media, and have a strong theoretical foundation based on the pioneering work of K.J.Bathe in the field of computational mechanics [11, 12, 16]. Most importantly, solid models created in ADINA can be coupled with any fluid model (ADINA-F) and its theoretical foundation is the Biot's consolidation.

The Biot's consolidation problem for homogeneous, isotropic and porous medium filled with water, meanwhile under the effect of consolidation the solid particles and water is incompressible. Although the consolidation theory has been developed, and many new methods have applied into use, the Biot's consolidation is still used today in a great variety of fields. Incorporating the effective stress concept, the equilibrium equation for an elastic solid mass can be expressed by the equitation (2). As to the fluid filled with the framework of solid particles, the fluid mass balance is prescribed by the continuity equation (3) [11, 12, 13].

$$-\mu\Delta\hat{u}-(\lambda+\mu)\nabla div\hat{u}+\nabla p=c \qquad (2)$$

$$\frac{\partial}{\partial t}div\hat{u}-\frac{k}{r_w}\Delta p=f \qquad x\in\Omega,\quad 0<t\leq T \qquad (3)$$

Where λ and μ are the lame constant, c the body force, $\hat{u}$ the medium displacements , p the fliud pressure , k permeability, r_w unit weight and t time.

In fact, to calculate the compaction of soils mass also needs the boundary and initial conditions. Meanwhile, the flow of the fluid must be coupled with the Darcy's Law [11].

Compared with other similar numerical simulation software, the ADINA has obvious advantages [16]. To discuss the problem caused by high-rise building, we rely on Adina computer programs to simulate the effect of building to subsidence, which can use the data from monitoring to testify the reliable of the model.

Numerical model

The engineering characteristics of soils are controlled by the history of consolidation and its correlation with underground water level. Most correlated model simplified the layered condition [13, 14, 15], which is difficult to realize the actual condition and the time delay. For conquering this problem and considering the effect of boundary, we gave a more complicated layer sequence 23 layered composited by aquifers and aquitards in 500m depth (Fig.3). The related mechanical parameters came from laboratory experiments, field experiments and report of Tianjin Survey Institute of Geologic and Minerals.

For the building load is a local load, the characteristics of the ground subsidence caused by it is different from that caused by pumping groundwater. The latter mainly affects the limited scope. To simplify the simulation ,we selected a typical region covered 2.25km^2(1500×1500m). This area was enlarged to minimize boundary effects as suitable hydraulic boundaries were poorly defined.

High-rise buildings was applied on the ground surface, the foundation bearing stratum was silt layer under the surface, the length of foundation was 50m and width 20m, the model use the 8-node element and was divided to 14076 units in total.

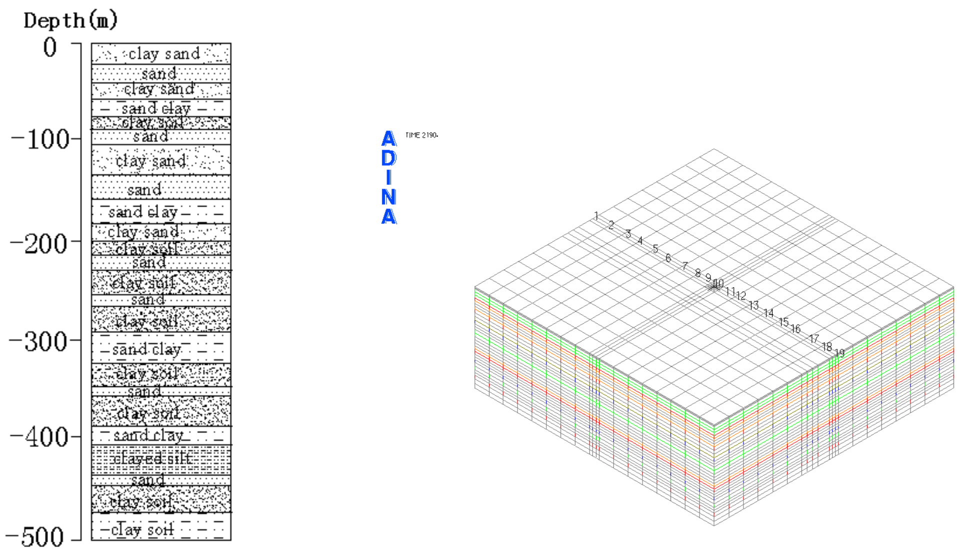

Fig.3: Stratigraphical sections and the numerical simulation model of Tanggu

The edge of model was taken as no-flow boundaries, as it had enough distance to the building and the effect of building to the edge could be omitted. Based on there no interbed inflow between aquifers below and above, the below boundary was taken as no-flow too. And the upper boundary was free boundary, which could accept recharge from rainfall (Fig.3). Because of the effect of primary state of stress to the mechanism of soil mass is major, we exerted gravity force before the simulation.

Results and Discussions

The effort of different buildings The scope of the ground subsidence caused by the building load was limited in 200 meters, while there was almost no obvious ground subsidence 200 meters away from the buildings. The depth of the affected soil increased with the building load. The maximum subsidence and the load had good positive correlation: 8-story, 20-story, 65-story buildings caused the maximum subsidence of 14.2, 30.7 and 76.0 cm respectively after they had been constructed ten years (Fig.4).

Applied load changes the effective stress of soil mass. The disturbed soil mass was extremely easy to creep, and the surface, shallow and deep soil mass showed vertical and horizontal displacement [11]. With the increase of the load, the soil lateral extrusion pressure increased, which leaded to adjacent ground uplift inevitably, and brought a series of problems subsequently, such as crack of the floors and walls, damage of underground pipelines and facilities.

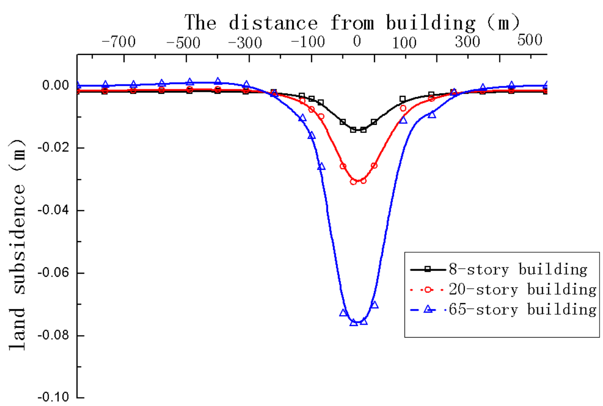

Fig.4: The ground settlement curve under different building loads

In this calculation, the surface appeared subsidence phenomenon only under 8-story and 20-story buildings. While a large amount of soil mass generated horizontal displacement under the load of 65-story building, and emerged an obvious uplift area distance the building about 300m-700m (Fig.4).

Table.1 Accumulative land subsidence under different loads

load	1st a (mm)	2ed a (mm)	3rd a (mm)	4th a (mm)	5th a (mm)	6th a (mm)	7th a (mm)	8th a (mm)	9th a (mm)	10th a (mm)
8-story	8.2	9.6	10.6	11.3	11.9	12.4	12.9	13.4	13.8	14.2
20-story	19.8	22.8	24.7	26.0	27.0	27.9	28.7	29.4	30.1	30.7
65-story	55.2	62.5	66.5	69.1	71.0	72.4	73.5	74.5	75.3	76.0

The complete compressive deformation of the soil mass was due to a period of time in generally. When the load is applied on the surface, soil body is compressed gradually and part of pore water is squeezed out until deformation became stable. At the same time, part of pores water pressure turns to effective stress [11, 12, 15]. According to the analysis of monitor point No.9 located at high building (Fig.3), land subsidence caused by high building mainly happened in 3-4 years after the building was built. And the consolidating time decreased with the increase of load (Table.1).

The effort of high-rise buildings group Because 30 floors residential buildings were popular with Tanggu, we selected the designed building height of this calculation was 30-story. The buildings were placed abreast, gable pitch selected 20m, and the vertical distance between buildings was 50m. Under the conditions of single, two in a row, a row of four and twelve in three rows building were used to calculate the land subsidence.

With the result, we found that the settlement caused by buildings did not simplify equal to the sum of the subsidence that caused by each single building. The change of ground elevation was correlated to the layout of building group. The larger plot ratio will cause larger range of ground settlement (Fig.5). The zone that was less than about 200m away from the building belonged to the settlement area, and a limit area which was more than 200m belonged to an upper lift area (Fig.5). If the plot ratio increased, the depth of pressured soil would increase accordingly. Taking 5cm as a threshold settlement, the depth of compressed soil caused by single building and twelve in three rows buildings were 100m and 380m.

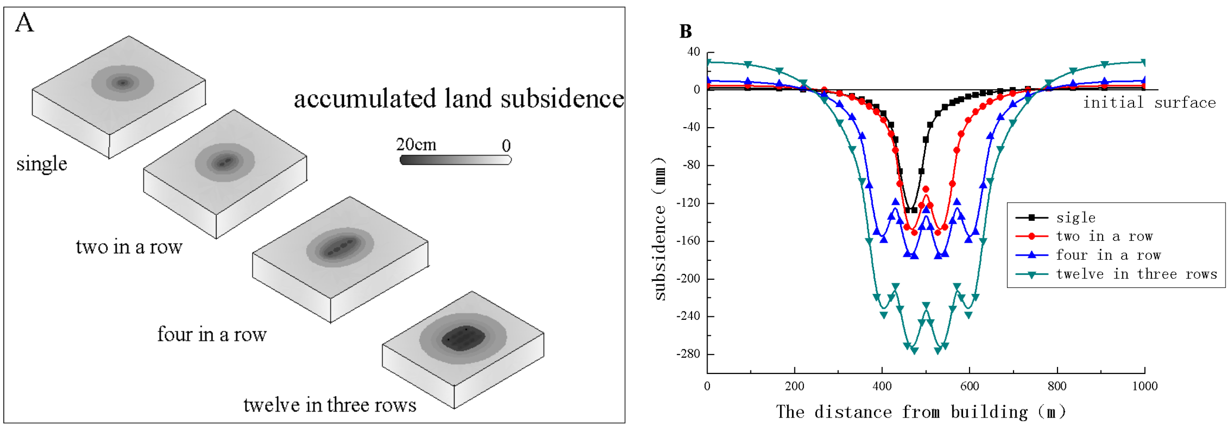

Fig.5： Accumulated land subsidence induced by buildings in 10 years after it built(A).The ground settlement curve line under different building group(B).

Conclusions

(1) Tanggu is located in the coastal plain, and its low-land landform makes the hazard of subsidence more serious. The depth of silt clay takes more than 50 percent of the total Quaternary deposits. The silt clay has low strength and large void ratio, so they would cause great ground subsidence with the building loads. Monitor data indicated new subsidence cone depletion emerged in Kaifaqu, which has relation to the construction of the high-rise building group.

(2) In the scope within two hundred meters with the building, the settlement and load value have a good positive correlation. With the increase of distance to the building, land subsidence caused by high-rise building and its relation to the load become unobvious. Meanwhile, higher buildings would cause a larger value of land subsidence while the time of consolidation stable would be much shorter.

(3) The settlement caused by building group is not simple equals to the sum of the settlement that caused by every building. The change of ground elevation has relation to the layout of the high-rise buildings. The larger plot ratio will cause larger range of ground settlement. If the plot ratio increases, the depth of pressured soil would increase, the time of soil consolidation and the amount of compression would increase accordingly.

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