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Study on compaction mechanism of overconsolidated soil and critical groundwater level in Cangzhou

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Abstract. Cangzhou area is facing increasingly serious land subsidence problem caused by groundwater overexploitation during a long time. In order to make effectively use of water resource and to limit the development of subsidence, it is necessary to establish the warning critical water level, that is, the subsidence rate will increase significantly as the water level depths exceeds the critical groundwater levels. In this paper, the 3rd aquifer group, the main groundwater exploitation layer, has been taken as a research object. The critical water level is calculated by stress analysis, and then determined by the correlation between the monitoring data of groundwater levels and subsidence. The calculated results indicate good consistency.

1 Introduction

In recent years, the North China Plain(NCP) is facing increasingly land subsidence problems caused by long-term overexploitation of deep groundwater resource. Cangzhou is a typical area of land subsidence in NCP, where the average groundwater levels had dropped by 80m, inducing severe land subsidence [1]. The government has taken a series of measures to restrict the exploitation of groundwater. In order to achieve the prevention, control and management of land subsidence, it's necessary to conduct reasonable regulation of groundwater resource and to ascertain the critical groundwater levels which could cause severe land subsidence.

Groundwater abstraction is the major reason for regional land subsidence in Cangzhou. In China, the concept of critical water level of overconsolidated soil layers in land subsidence control was first discussed in 1998 considering the mechanism of disaster-causing process. And it was used to establish warning groundwater levels of the 2nd aquifer group in Tianjin [2]. Then it had been proved that critical water levels of different soil layers are related to the storage coefficients through the study between overconsolidation values and critical water levels [3]. In the comparative research of land subsidence in different areas along Beijing-Shanghai high-speed railway, it had been proved that the critical groundwater levels did not exist in Beijing where the rate of land subsidence was linearly related to groundwater levels, while it could be discovered in Langfang, Cangzhou and other places where land subsidence is exponentially related to groundwater levels [4]. To provide services for the planning of subsidence prevention and control, the warning groundwater levels in Beijing had been defined in 2015 according to the threshold values of subsidence rate [5].

This paper focuses on issues associated with the critical groundwater level in Cangzhou City. At first, the way to calculate critical groundwater levels was improved through weighted average method by considering the consolidation characteristics of different soil layers. Then the critical groundwater level was evaluated with the monitoring data of subsidence and groundwater levels. Eventually, the results from these two methods were compared.

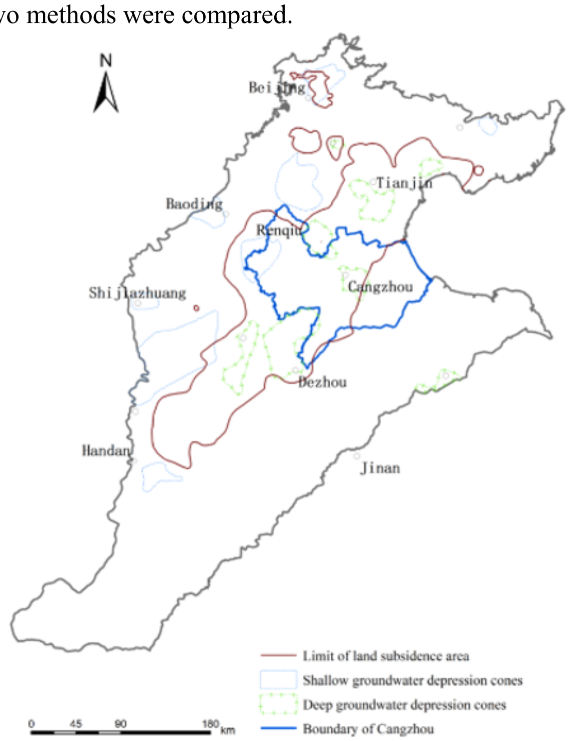

Fig. 1. Sketch map of Cangzhou area

2 Land subsidence and consolidation characteristics of aquifer system

Table.1. Four aquifer groups of Quaternary sediments

No.	Groundwater type	Lower confining boundary	Main recharge
1st	Unconfined	40-60m	Atmospheric precipitation
2nd	Micro-Confined Confined	120-170m	Infiltration Runoff
3rd	Confined	250-350m	Runoff, leakage
4th	Confined	350-550m	Runoff, leakage

2.1 Geological background

Cangzhou is located in the middle-east of the North China Plain(Fig.1), and its landscape belongs to coastal plain and tilts from southwest to northeast. There are many rivers and lakes in the city, the administrative area is 13491km^2, the average altitude is 8.7m, the maximum elevation difference is merely 12.7m. Previously research shows that the Quaternary sediments in Cangzhou have suffered several transgressions since the end of the Pleistocene, consequently, the fluvial-lacustrine system changes into littoral deposits from west to east. The thickness of Quaternary deposits in a range from 350-550m, which is composed of loose sediments and fine-grained interbeds with different hydrogeological properties. The stratigraphy can be roughly divided into 4 aquifer groups(Table.1) and the 3rd group is the main layer for groundwater abstraction.

2.2 Land subsidence and consolidation characteristic of soil layers

The land subsidence in Cangzhou was observed in early 1970s and it is mainly caused by groundwater overexploitaion. At the beginning of 21th century, the local government has implemented a series of policies to restrict exploitation of groundwater. As a result of these efforts the annual subsidence rate decreased obviously, however, the area of land subsidence is still expanding. Numbers of groundwater depression cones and subsidence bowls have emerged so far.

Previous studies and monitoring data illustrate that the trigger mechanism of land subsidence in Cangzhou is the effective stress increasing with pore water pressure dissipation after groundwater exploitation, which leads to soil compression. During the development of the groundwater resource, aquifers consisting mainly of pebble, gravel and sand release water rapidly due to good permeability, while aquitards and clay interbeds within or adjacent to aquifers undergo head changes gradually. Compared with sandy soil, the clay layers in this study area account for more than 70% of total thickness and it is particularly susceptible to compaction with good compressibility. Therefore, the land subsidence in Cangzhou mainly results from the consolidation of cohesive soil layer, which shows obvious time-delay relative to the change of groundwater levels.

Besides, in the geological history of sedimentation of Quaternary system in Cangzhou, because of climate, transgression events, weathering and other factors, there are obviously differences in the soil consolidation among layers. These differences can be characterized by the preconsolidation pressure as P_c, which refers to the maximum consolidation stress in the stress history. According to the relation between preconsolidation pressure (P_c) and self-weight stress(P_0), the consolidation state of soil can be described by ORC(over-consolidation ratio) as ORC= P_c/ P_0, it can be divided into three types:

If ORC<1, the soil should be underconsolidated, which is naturally consolidated due to gravity.

If ORC=1, the soil should be normal consolidated, which is in equilibrium. Once additional stress exists, it will consolidate again.

If ORC>1, the soil should be overconsolidated, which has completed the natural consolidation. Only if the additional stress exceeds the preconsolidation pressure, can it turn to consolidate again.

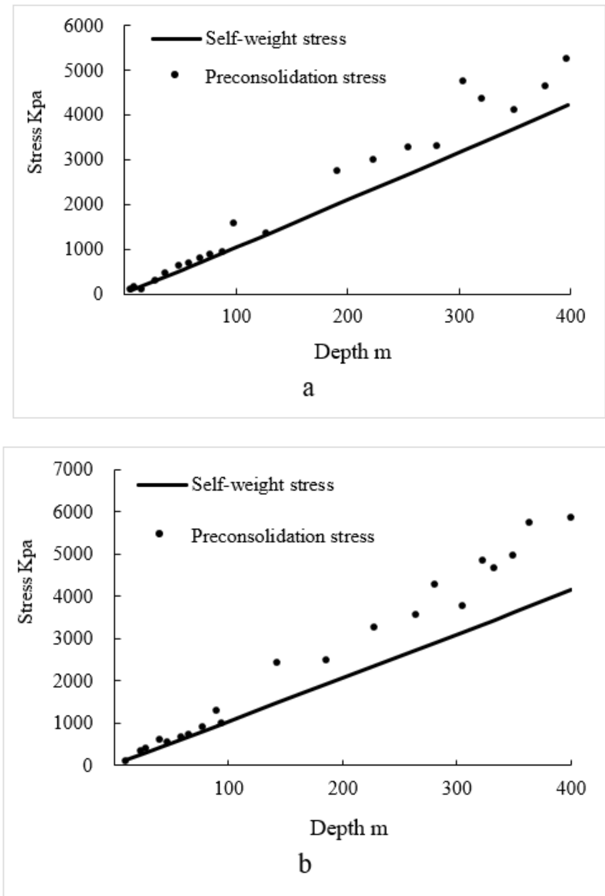

Fig. 2. Changes of Pc with depth in the downtown of Cangzhou(a) and Renqiu(b)

Overconsolidated soil is common in the Quatenary system in Cangzhou area because of geological factors and stress history. The results of geotechnical experiments on undisturbed soil samples show that (Fig.2) the underconsolidated soil is dominant within 0-140m, and the overconsolidated soil is dominant in layers below 140m. It also shows that the degree of soil consolidation increases gradually with depth. In summary, the land subsidence in Cangzhou is mainly induced by the compaction of cohesive soil layers due to overexploitation of groundwater in the 3rd aquifer group.

3 Study on the critical groundwater level

3.1 Study on critical groundwater level with soil consolidation

Terzaghi introduced the basic principle of effective stress that

$$\sigma_z = \sigma' + p \quad (1)$$

Where σ_z is the self-weight stress, σ' is the effective stress, and p is the fluid pore pressure.

The change in effective stress for a given change in groundwater head can be approximately expressed as [7]

$$\Delta\sigma' = -\rho_w g \Delta H \quad (2)$$

Where $\Delta\sigma'$ is the change in vertical effective stress (positive for increase), ρ_w is the density of water, g is the gravitational acceleration, and ΔH is the change in groundwater level.

If $\Delta\sigma' \geq Pc - P_0$, the subsidence rate becomes obvious due to inelastic compaction. The critical groundwater level can be expressed as [3]

$$\Delta H_c = \frac{P_c - P_0}{\rho_w g} \quad (3)$$

Where ΔH_c is the critical groundwater level.

The critical groundwater level of land subsidence can be calculated through weighted average method as

$$\Delta H_c = \frac{\sum_{i=1}^{n} \Delta H_{ci} * Z_i}{\sum_{i=1}^{n} Z_i} \quad (4)$$

Where n is the number of soil layers, ΔH_{ci} is the critical groundwater level of each soil layer, and Z_i is the thickness of each layer.

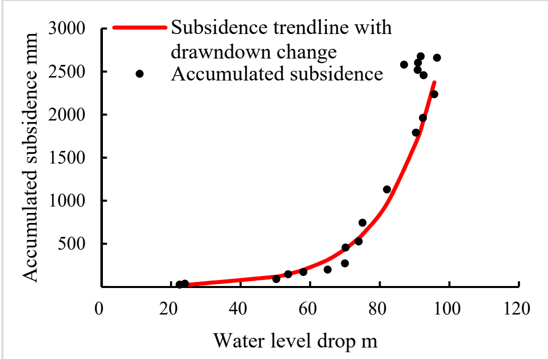

Fig. 3. The relation between accumulated subsidence and groundwater levels in the downtown of Cangzhou

3.2 Calculation of the critical groundwater level of land subsidence in Cangzhou

In this paper, the 3rd aquifer group is divided into 7 soil layers by considering the different physical and mechanical properties of soil samples. The preconsolidation stress of each layer has been calculated by the Casagrande method. According to Equation (4), the critical groundwater levels of all layers are calculated (Table.2), then the average critical groundwater level of the 3rd aquifer group is calculated as 64.3 m, which corresponds to a water depth of 66.8m.

3.3 Synthetical evaluation of the critical groundwater level by monitoring data

The critical groundwater levels can also be approximatively evaluated by analyzing the relation between the data of groundwater levels and land subsidence. Fig.3 shows the relation between accumulated subsidence and groundwater levels in the downtown of Cangzhou city. It indicates that in the water level depth of 60-70m, the development of land subsidence changes from stable stage into accelerated stage. Therefore, the average critical groundwater level can be calculated as 65m, which is basically consistent with previous calculated value of 66.8m.

Table 2. The critical groundwater levels of all soil layers for the 3rd aquifer group of Cangzhou

Layer number	Depth (m)	Thickness (m)	Pc (Mpa)	ORC	Compression index Cc	Expansion index Cs	Critical groundwater level(m)
L1	192.4	22.0	2.72	1.35	0.15	0.03	71.25
L2	223.5	31.1	2.98	1.27	0.27	0.04	64.76
L3	256.1	32.6	3.25	1.21	0.26	0.03	57.89
L4	281.2	25.1	3.32	1.12	0.21	0.05	37.55
L5	321.2	40.0	4.36	1.29	0.24	0.05	99.87
L6	349.4	28.3	4.07	1.10	0.26	0.03	39.19

4 Conclusions

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In this paper, according to the borehole data in the downtown of Cangzhou and Renqiu, the depth of 140m has been regarded as a boundary between normally consolidated soil layers and overconsolidated soil layers.

Two different methods are used for calculating the critical groundwater level. The method for calculating the critical groundwater level by preconsolidation stress has been improved by weighted average summation, and the calculated critical groundwater level depth is 66.8m. Meanwhile, based on monitoring data of groundwater levels and land subsidence, it is indicated that the development of land subsidence changed from stable stage into accelerated stage in the water level depth ranged from 60m to 70m, which has the average value of 65m. It shows that the evaluated critical groundwater level by two different methods is close to each other.

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