Calculation and field monitoring on ground settlement caused by groundwater pumping

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ABSTRACT: Based on 2-D steady flow theory, the space character of conic surface of lowed water table caused by construction pit dewatering is deduced, then derived from Effective Stress Principle (ESP); the ground settlement calculation model is suggested. Then, it is simplified in the form of Laminated-Settlement-Accumulation model, which is recommended in the current Chinese National Code. The analysis reveals that the ground settlement is in direct proportion to the two-time-power of value of water table lowing. In the practical cases, the lowing of water table, calculated ground settlement and practical surveyed settlement are compared. It is supposed that the scope of ground settlement is rather smaller than the water lowering influence area, and their relationship is obscured by the variation of compression modulus of site soil. At the same time, the heaped load and traffic load in the adjacent area of construction pit play important role in the ground settlement.

1 INTRODUCTION

In China, more and more buildings are constructed in the downtown area, and deep construction pits have to be dug at the initial stage of construction. For the convenience of excavation, groundwater pumping is carried out before digging, and the watertable lowering leads to adjacent ground and existing buildings settlement. Plenty of practical cases show the catastrophic effects of groundwater pumping. So, it is significant to find a way to predict the scope of settlement area and the magnitude of maximum settlement.

Usually, the settlement of adjacent ground and building is caused by both groundwater lowering and the deformation of pit wall. However, in Zhengzhou, a Central China metropolis, on the Yellow River, with the east-west and north-south backbone national railways crossing through it, enough practical surveys show that the pit wall deformation is no more than dozens of millimeter, and is not able to propagate far away. So, in this paper, it is taken for granted that the adjacent ground and building settlement are caused by the groundwater pumping, i.e., the pit wall deformation is neglected in the following discuss. A calculation model for lowed groundwater table is suggested, and the corresponding ground settlement prediction model is put forward.

2 2-D STEADY FLOW THEORY

2.1 *Declined Watertable*

In China, the most common form of water pumping associating with the pit construction is well-point unwatering, and the calculation model is based on the 2-demintion steady flow theory. The privilege algorithm (Darcy, 1856) for watertable and the distance from well-point is:

$$\frac{S_{nw}}{S_w}=\frac{\lg R-\lg(r+D)}{\lg R-\lg r} \quad (1)$$

Where, S_w-the watertable lowering depth under the bottom of pit (m);

S_{nw}-the watertable lowering depth at a concerning location on the rivage of pit (m);

R-radius of pumping effective area. From the centre of pit

$R=R_1+r$;

R_1-the reference effective radius of the single well pumping testing;

r-equivalent radius of pit;

When the pit is in shape of circle or nearly a square, then $r=\sqrt{\frac{F}{\pi}}$;

When the pit is in shape of rectangular

① $\frac{a}{b}\le 2$, $r=0.3(a+b)$ and ② $\frac{a}{b}>2$, $r=\frac{b}{\sqrt{\pi}}$;

F -the area of pit bottom;

a,b -the long and short side of rectangular pit;

D -the distance between the concerning location and the edge of pit.

For a particular construction pit, when all the parameters are known, based on Equation (1), the declined watertable is determined.

2.2 *Determination of* R

(1) When the thickness of aquifer is known, the reference effective radius of the single well pumping testing R_1 may be obtained as

$$R_1 = 2S_w\sqrt{K \cdot M} \tag{2}$$

K -the permeability factor of aquifer (m/d);

M -the thickness of aquifer (m).

(2) When the thickness of aquifer is unknown, the radius of pit has to be taken into consideration. then

$$R = 10 \cdot S_w\sqrt{K} + r \tag{3}$$

3 FUNDAMENTALS FOR SETTLEMENT CAUSED BY UNWATERING

3.1 *Mechanism of adjacent ground settlement*

Groundwater pumping is the main reason for adjacent area settlement, it changes the route of groundwater permeating, and results in a conic-shaped declined groundwater table (called artificial watertable in the following part), whose peak is located on the center of pit. The pore water pressure of soil between natural watertable and artificial watertable evanesces, and the effective stress increases, then the soil condenses, which leads to the settlement S_1. At the same time, the effective stress of soil beneath the artificial watertable rises because of unwatering, then it leads to the settlement S_2. So the settlement of adjacent ground consists of two parts:

$S = S_1 + S_2$

According to the Effective Stress Theory (Terzaghi, 1925), representing the total stress of certain point in the soil as σ, the effective stress on the surface of skeletal grains as σ', and pore water pressure as u, then $\sigma = \sigma' + u$. When the watertable declines, the total stress keeps the same, so $\Delta\sigma' = -\Delta u$ (shown in Fig 1).

In between the natural watertable and the artificial watertable, $\Delta\sigma' = \gamma_w h$; and beneath the artificial watertable, $\Delta\sigma' = \gamma_w \Delta H_n$.

Where, h -the depth of soil from the natural watertable downward to the concerning point;

ΔH_n -the depth of watertable declines;

3.2 *Simplified Laminated Settlement Accumulation Method*

The Laminated Settlement Accumulation (LASA) method is a privilege strategy which is

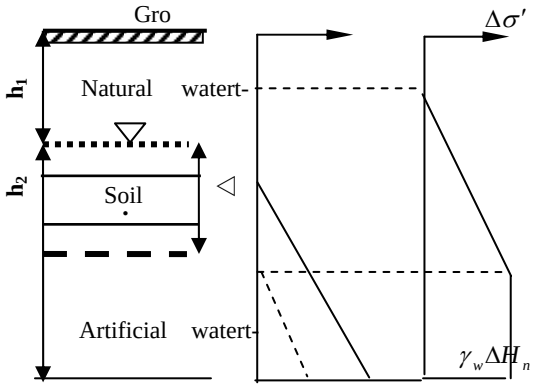

Fig.1 Pore water pressure and increment of effective soil stress

recommended in the Chinese National Code to calculate soil settlement. When LASA method applied to the practical project with sandwich layer structure, the result is close to the survey one and the algorithm is rational and practical. Therefore, a simplified LASA method is put forward to analysis the settlement caused by the groundwater pumping. For the infinitesimal in soil layer i, the condensing may be determined as:

$$\Delta S_i = \frac{\Delta\sigma'_h}{E_{si}}\Delta h_i \tag{4}$$

Where, ΔS_i -the settlement (condensing) of a infinitesimal in soil layer i (mm) ;

$\Delta\sigma'_h$ - the additional stress at soil cell with the watertable declining value as h, i.e. the increment of effective stress (*kPa*);

E_{si} - the confined compressive modulus for layer i (*MPa*);

Δh_i -the thickness of soil infinitesimal in layer i (m);

The settlement cause by groundwater pumping consists of two parts, which may be determined as following.

(1) Settlement of Drainage Stratum

The soil layers between the natural watertable and artificial watertable are called the drainage stratum. Integrating the condensing of all the infinitesimal in drainage stratum, and substitute $\Delta\sigma'_h = \gamma_w h$ into Equation (4), then

$$S_1 = \int_0^{\Delta H_1} \gamma_w \frac{h}{E_{s1}}dh + \int_{\Delta H_1}^{\Delta H_2} \gamma_w \frac{h}{E_{s2}}dh + \cdots + \int_{\Delta H_{n-1}}^{\Delta H_n} \gamma_w \frac{h}{E_{sn}}dh$$

$$= \sum_{i=1}^{n} \frac{\gamma_w}{2E_{si}}(\Delta H_i{}^2 - \Delta H^2{}_{i-1}) \tag{5}$$

Where, ΔH_i -watertable declining value for layer i (m), and $\Delta H_0 = 0$;

n - the total number of layers in the drainage stratum.

(2) The settlement of bed stratum

The soil layers beneath the artificial watertable are called the bed stratum. For each layer in bed stratum, the increment of effective stress is a constant, namely, $\Delta\sigma' = \gamma_w \Delta H_n$, then

$$S_2 = \sum_{j=n}^{m} \frac{\gamma_w \Delta H_n}{E_{sj}} (\Delta H_j - \Delta H_{j-1}) \quad (6)$$

Where, m - the number of soil layers which condensed beneath the artificial watertable.

In fact, the increment of effective stress at artificial watertable is not able to transfer to deeper soil without dissipation, and it is difficult to determine the adequate depth of bed stratum. For the more, there are a lot of practical problem for the calculation of S_1. First, groundwater drainage does not take place instantaneously, it takes a rather long period. During this period, the characteristic of soil is changing gradually. Therefore, the exact value of settlement in drainage stratum is difficult to obtain. Second, because of the complication of geological constitution, the real watertable is not the same as the calculated one.

For simplification, with a suitable precision remaining, it is suggested that the adjacent ground settlement may be calculated by the theoretical final artificial watertable, and the magnitude may be obtained by multiply an adequate factor ψ to S_1, while the factor ψ may be determined by local experience and the features of the project. Finally, the following analytical model is set up to predict the settlement caused by groundwater pumping.

$$S = \psi \sum_{i=1}^{n} \frac{\gamma_w}{2E_{si}} (\Delta H_i^{\,2} - \Delta H^{2}_{i-1}) \quad (7)$$

Where, ψ - the amendment factor for settlement prediction caused by groundwater pumping.

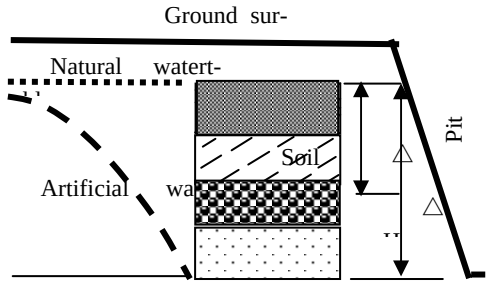

Fig .2 Variables for calculation of dewatering settlement

3.3 *Procedure of Settlement Prediction*

For a construction pit, if its dimension, depth of watertable declining at the pit bottom, compressive modulus and permeability characteristics of soil are all known, then the adjacent ground settlement may be evaluated through the following steps:

(1) Define the Relative Distance to the pit as

$$\lambda = \frac{D}{S_w}$$

Where D-the distance of concerning location to the pit wall;

S_w-the watertable declining value at pit bottom (m).

Then, the watertable decline value may be determined by Equation (1)

$S_{nw} = f(\lambda)$.

(2) Rough Settlement Determination

Base on the soil characteristics obtained from the in-situ reconnaissance, the rough settlement may be evaluated by Equation (5).

(3) For a certain area, based on enough historical survey parameters, the amendment factor ψ may be obtained by statistics works, then Equation (7) may be applied to get the final settlement.

For further study, vast amount of pore water pressure, practical artificial watertable and ground settlement monitoring are needed, in order to set up an adequate amendment factor ψ for local area application.

Equation (7) reveals that if the confined compressive modulus is a constant in the adjacent area (in fact, it varies drastically from point to point, and from surface layer to bed layer), the ground settlement descends with the relative distance increases, and it descends in proportion to the two times powder of watertable declining value. However, practical experience shows that the adjacent building settlement is constrained by its foundation, and the final magnitude is related to the foundation form, rigidity and other factors.

4 CASE STUDY

4.1 *Engineering Background*

The main building is 26-story shear wall commercial building, with one-story basement as equipment floor, located in Zhengzhou. The foundation is situated on -5.0m silt layer. Before pit excavation, geological reconnaissance shows that the natural watertable is -3.4m. The distance from constructed pit to Huanghe Road is 18.2m, and its inside corner to the Yaozai Road is 11.9m, while the closest wall to Yaozai Road is only 3.8m. The west margin to the neighbor's house is 7.0m. The depth of pit is 5m, and the watertable declining depth at bottom is 4.5m. According to Equation (1), r = 32m, $R = 10 S_w \sqrt{K} + r$ = 66m. The settlement monitoring points are shown in Fig3, and the geological background is shown in Table 1

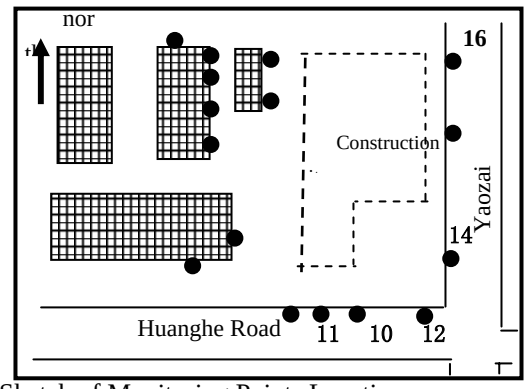

Fig.3 Sketch of Monitoring Points Locations

Table 1 Description of Typical Geological Boring Hole

Layer	1	2	3	4	5	remarks
type	silt	silt	Silty clay	silt	silt	Comprehensive equivalent permeability K =0.58m/d
E_{si}	4.2	6.0	4.2	6.0	10.0	
h_i	0.8	1.8	1.5	1.6	2	
ΔH_i	0.8	2.6	4.1	5.7	7.7	

4.2 *Calculated Artificial Watertable and Calculated Ground Settlement*

Because the watertable decline and ground settlement are not of the same order of magnitude, in order to compare their features, a relative magnitude of watertable declining and ground settlement are shown in Fig 4, in which the maximum watertable declining and ground settlement are taken as 1.0 at the edge of pit.

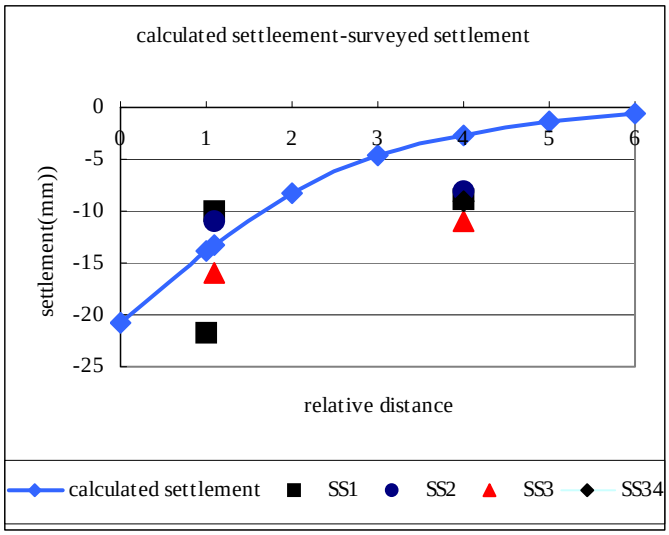

Fig.4 Calculated watertable-calculated settlement-relative distance

4.3 *The Calculated Ground Settlement and Surveyed Settlement*

In order to verifying the proposed algorithm, field survey is carried out for more than half a year, and the final ground settlements are shown in Fig 5. Although there are 16 monitoring points, they are roughly distributed on two concentric circles, with the center of circle on the centre of pit. So, the corresponding relative distances are two values: 1.2 and 4.0.

5 CONCLUSIONS

(1) Groundwater pumping leads to the watertable declining, forming a conic surface, with the peak locating on the center of pit. Theoretic analysis shows that the ground settlement is in proportion to the two times order of watertable declining value, i.e., the radium of ground settlement is rather smaller than that of watertable declining. However, the characteristics of field soil, especially the confined compressive modulus, play important role on settlement distribution. The variance of compressive modulus perturbs theoretical relationship between watertable declining and ground settlement.

(2) In phreatic area, the ground settlement may be determined by the Simplified Laminated Settlement Accumulation (LASA) method. Case study shows that the suggested strategy is applicable. However, because of the complication of geological background, the calculated results are not able to match the surveyed ones exactly. Lots of work has to be done to set up the local Amendment Factor.

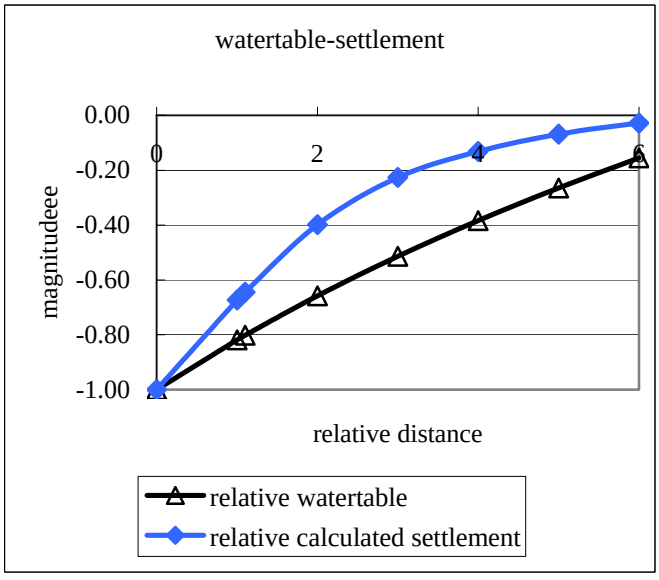

Fig. 5 Calculated settlement- surveyed settlement-relative distance

(3) The circumstance of pit is usually complex, and the activities of construction (heaping load, transportation and so on) affect the maximum magnitude and distribution of ground settlement. Usually, the monitoring points setting on road surface get to steady quickly, at the same time, their magnitudes are often bigger than the points setting on adjacent building (with the same relative distance). It reveals that the traffic load enlarges the settlement of

ground, and the foundation of building restrains the settlement of buildings.

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