Numerical Simulation of Ground Subsidence Induced by Dewatering in Excavation

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Abstract
Dewatering associated with deep excavations can induce ground subsidence. Many approaches have been used to predict and calculate ground subsidence induced by pumping groundwater. The Finite Layer Method (FLM) is introduced as a new way to numerically model ground subsidence. This paper summarizes the current approaches first, then briefly describes the FLM, and then presents the calculating process with FLM. A case study is used to show that the FLM can properly reflect the behavior of ground subsidence induced by dewatering in deep excavation.

Key words: ground subsidence, underground water, dewatering, finite layer method

Introduction
In China, land subsidence mainly occurs in 17 provinces located in the eastern and central regions, including Shanghai, Tianjin, Jiangsu, and Hebei provinces (Xie, 2006). More and more high-rise and super high-rise buildings are being constructed in China, which require deep excavation. Soft ground is widely distributed in some of these areas. These soft soil deposits generally have high groundwater tables; when a deep foundation pit is excavated, it is necessary to pump groundwater out during excavation in order to ensure safety. This groundwater pumping causes the transient flow of groundwater, forming a drawdown cone around the pit. Drawdown of the groundwater level increases the effective stress of soil outside the pit. Consequently, the soft clay consolidates and settlement will occur around the pit. In this study, the settlement around such a pit due to the withdrawal of groundwater will be analyzed.

Computing Ground Subsidence using the Finite Layer Method
Many researchers have used different methods to predict land subsidence, based on the hydrogeological conditions and groundwater withdrawal practices. The main predictive approaches of land subsidence are statistical, 1-D numerical calculations, quaisi-3D methods, 3-D seepage models, and 3-D fully-coupled models (Shen et al., 2005). Given the increasingly serious problem of land subsidence induced by pumping groundwater, and the many shortcomings of the existing land subsidence models in rationality and calculating requirements, it is important and urgent to establish a reasonable numerical model for ground subsidence that has greater calculating efficiency. The finite layer method (FLM) is introduced in land subsidence analysis as a new numerical model to solve ground subsidence problems caused by pumping groundwater in layered media.

Most land subsidence models are based on the finite element method. There are several difficulties in using this approach to calculate land subsidence caused by such factors as the huge scope of the calculation, the complex interaction of pumping wells, and the layered condition of the aquifer system. To cope with this problem, the FLM should be considered. It is highly efficient in calculating ground water effects and simulating soil deformation, and also can be used to model the three-dimensional situation. Yet, until now, no one has published on applying FLM to ground subsidence caused by dewatering. It also demonstrates how the FLM can be used to solve quasi three-dimensional ground water problems and predict soil deformation in one dimension.

Governing Equation of Ground Subsidence Model Based on FLM

The ground water and soil equilibrium equations are shown below; soil consolidation has not been taken into account here:

$$
\begin{cases}
\dfrac{\partial}{\partial x}\left(K_x\dfrac{\partial s}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(K_y\dfrac{\partial s}{\partial y}\right)+\dfrac{\partial}{\partial z}\left(K_z\dfrac{\partial s}{\partial z}\right)-\dfrac{s}{\lambda^2}+q(x,y,z,t)=S_s\dfrac{\partial s}{\partial t} \\
\qquad\qquad\qquad\qquad t>0,\ 0\le x\le a,\ 0\le y\le b \\
s(x,y,z,t)=0 \quad t=0,\ 0\le x\le a,\ 0\le y\le b \\
s(x,y,z,t)\Big|_{\substack{x=0\\x=a}}=0 \quad t>0,\ 0\le y\le b;\quad s(x,y,z,t)\Big|_{\substack{y=0\\y=b}}=0 \quad t>0,\ 0\le x\le a \\
\dfrac{\partial s(x,y,z,t)}{\partial x}\Big|_{\substack{x=0\\x=a}}=0 \quad t>0,\ 0\le y\le b;\quad \dfrac{\partial s(x,y,z,t)}{\partial y}\Big|_{\substack{y=0\\y=b}}=0 \quad t>0,\ 0\le x\le a
\end{cases}
\tag{1}
$$

Where K_x, K_y and K_z are permeability coefficient along the direction *of* x, y and z; $s(r, z, t)$ is drawdown settlement; t is time; a is boundary condition in x direction; b is boundary condition in y direction.

$$
\begin{cases}
d_1\dfrac{\partial^2 u}{\partial x^2}+d_5\dfrac{\partial^2 u}{\partial y^2}+d_6\dfrac{\partial^2 u}{\partial z^2}+\left(d_2+d_6\right)\dfrac{\partial^2 v}{\partial x\partial y}+\left(d_3+d_5\right)\dfrac{\partial^2 w}{\partial z\partial x}=0 \\
d_6\dfrac{\partial^2 v}{\partial x^2}+d_1\dfrac{\partial^2 v}{\partial y^2}+d_6\dfrac{\partial^2 v}{\partial z^2}+\left(d_2+d_6\right)\dfrac{\partial^2 u}{\partial x\partial y}+\left(d_3+d_6\right)\dfrac{\partial^2 w}{\partial y\partial z}=0 \\
d_5\dfrac{\partial^2 w}{\partial x^2}+d_5\dfrac{\partial^2 w}{\partial y^2}+d_4\dfrac{\partial^2 w}{\partial z^2}+\left(d_3+d_5\right)\dfrac{\partial^2 u}{\partial x\partial z}+\left(d_3+d_6\right)\dfrac{\partial^2 v}{\partial z\partial x}+Z(s)=0 \\
\text{A Boundary condition } u\Big|_{\substack{x=0\\x=a}}=0 \quad 0\le y\le b \\
\qquad\qquad v\Big|_{\substack{y=0\\y=b}}=0 \quad 0\le x\le b \\
\text{B Boundary condition } v\Big|_{\substack{x=0\\x=a}}=0,\ w\Big|_{\substack{x=0\\x=a}}=0 \quad 0\le y\le b \\
\qquad\qquad u\Big|_{\substack{y=0\\y=b}}=0,\ w\Big|_{\substack{y=0\\y=b}}=0 \quad 0\le x\le b
\end{cases}
\tag{2}
$$

Where $Z(s)$ is the equivalent load due to water level change; $u,v,\ w$ are deformations along x,y, and z;X^0, Y^0, Z^0 are equivalent loads due to initial strain; d_1,d_2,d_3,d_4,d_5,d_6 are coefficients in an elastic matrix. Based on equation (1) and (2), we can get the ground subsidence equation based on FLM:

$$
\begin{cases}
\left[G\right]_{mn}\{\Phi\}_{mn}+\left[B\right]_{mn}\dfrac{d}{dt}\{\Phi\}_{mn}+\{Q\}_{mn}=0 \quad (m=0,1,2\cdots M;n=0,1,2\cdots N) \\
\left[K\right]_{m'n'}\left\{\tilde{\delta}\right\}_{m'n'}=\left\{\tilde{F}\right\}_{m'n'} \qquad\qquad (m'=0,1,2\cdots M;n'=0,1,2\cdots N)
\end{cases}
\tag{3}
$$

Where $[G]$ is the total permeability matrix; $[B]$ is the total storage matrix; $\{Q\}$ is the total water vector; $\{\phi\}$ is undetermined parameters; $[K]$ is total matrix; $\tilde{\delta}$ is flexibility matrix, and $\tilde{F}$ is load vector. This, very briefly, is how one can calculate ground subsidence induced by dewatering using FLM. The relevant program is written in Fortran language. More details can be found in Wang (2007).

Case Study

To assess the effectiveness of the proposed method, one case was calculated using the FLM, and the result was compared with observed data. The aquifer profile included fill soil, mud-silty clay, clay, and silt. The area of the excavation project was 3730 m^2 and the depth was 14.5 m. The designed water level decline was 16 m below the ground surface. The initial water level was 1 m from the surface. A fully penetrating well with a depth of 40 m was determined to be necessary. The number and the

layout of the penetrating well system is shown in Figure 1. The permeability coefficient was 22 m/d and the average storage was 0.005 L/m. Only confined water was pumped.
Based on the mentioned parameters on soils, groundwater and penetrating well system, the case is computed with made program using FLM method. The results are demonstrated in Figure 2. From the comparisons between calculated results and the measured data, it could be found that they have a good agreement. The distribution of ground subsidence along the horizontal direction is logical according to the observed data. That shows the correct of this method in computing the ground subsidence induced by dewatering in excavation using FLM method.

Figure 1 *The layout of the penetrating well system*

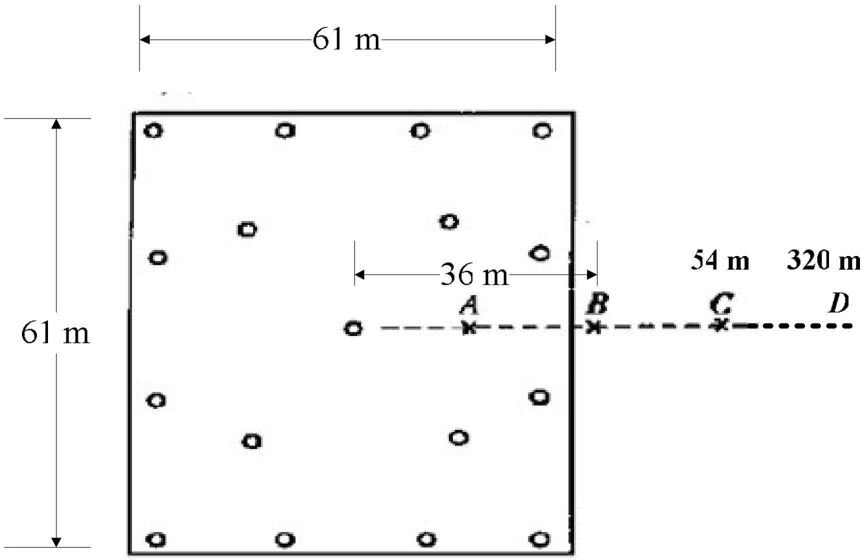
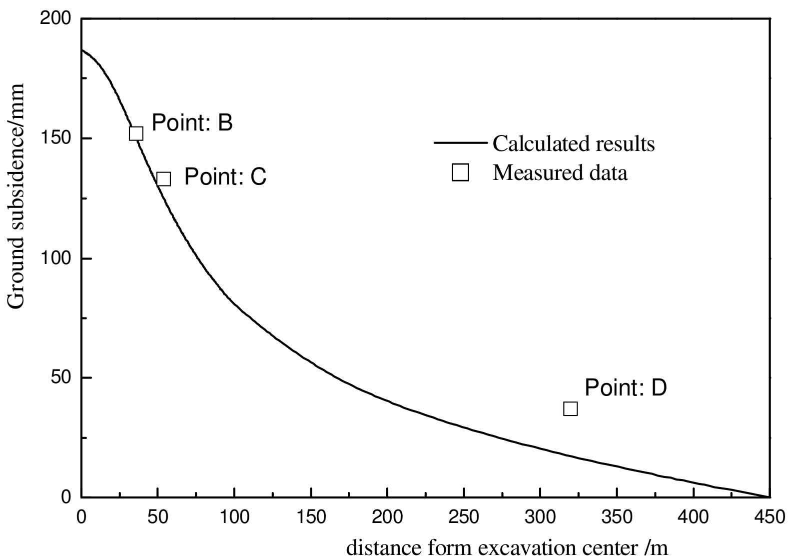


Figure 2 *The calculated results and measured data*



Conclusions

In this paper, the FLM was used to comput the ground subsidence induced by dewatering in excavation. The advantages of FLM in solving this problem were demonstrated by one case study. It appears that the FLM provides a new and effective way to effectively and rationally calculate ground subsidence.

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