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# Influences of soil hydraulic and mechanical parameters on land subsidence and ground fissures caused by groundwater exploitation*

CHEN Xing-xian (陈兴贤)
School of Earth Sciences and Engineering, Hohai University, Nanjing 210098, China
Bureau of Geology Mineral Resources Prospecting of Jiangsu Province, Nanjing 210018, China,
E-mail: js_cxx@sina.com
LUO Zu-jiang (骆祖江), ZHOU Shi-ling (周世玲)
School of Earth Sciences and Engineering, Hohai University, Nanjing 210098, China

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**Abstract:** In order to study the influences of hydraulic and mechanical parameters on land subsidence and ground fissure caused by groundwater exploitation, based on the Biot's consolidation theory and combined with the nonlinear rheological theory of soil, the constitutive relation in Biot's consolidation theory is extended to include the viscoelastic plasticity, and the dynamic relationship among the porosity, the hydraulic conductivity, the parameters of soil deformation and effective stress is also considered, a three-dimensional full coupling mathematical model is established and applied to the study of land subsidence and ground fissures of Cangzhou in Hebei Province, through the analysis of parameter sensitivity, the influences of soil hydraulic and mechanical parameters on land subsidence and ground fissure are revealed. It is shown that the elastic modulus $E$, the Poisson ratio $\nu$, the specific yield $\mu$ and the soil cohesion $c$ have a great influence on the land subsidence and the ground fissures. In addition, the vertical hydraulic conductivity $k_z$ and the horizontal hydraulic conductivity $k_s$ also have a great influence on the land subsidence and the ground fissures.

**Key words:** Biot's consolidation, viscoelastic plasticity, groundwater, land subsidence, ground fissure

## Introduction

Serious geological disasters related with the land subsidence and the ground fissure were caused by excessive exploitation of the groundwater in China's north China plain and the Yangtze River delta since the 1980s. The land subsidence and the ground fissure caused by the groundwater excessive exploitation was shown to be a complex process in which the seepage interacts with the stress field[1]. The process is closely related to the soil hydraulic and mechanical parameters. Therefore, the influences of the soil hydraulic and mechanical parameters on the land subsidence caused by the groundwater excessive exploitation are the key to simulate and predict the land subsidence accurately. In China, the history of the model research of the land subsidence caused by the groundwater exploitation may date back more than 10 years, with Shanghai and Tianjin as representative research centers. However, in these models the groundwater flow model is almost a quasi three-dimensional model, with only the flow equation in the aquifer and without one in aquitard to simulate the water level change. It would be difficult to determine the land subsidence caused by the aquitard water release[2,3]. The land subsidence models are usually vertical one-dimensional linear elastic models, based on the Terzaghi theory, and they can not be used to simulate and forecast the soil horizontal deformation, and the occurrence of the ground fissure[4,5]. The dynamic relationship among the soil deformation parameters, the permeability and the stress fields is not well established[6-8], neither the full coupling between the seepage and the land subsidence. Thus it is difficult to accurately determine the

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**Biography:** CHEN Xing-xian (1963-), Male, Ph. D., Senior Engineer

influences of the soil hydraulic and mechanical parameters on the land subsidence by using these models. The objective of this paper is based on the Biot's consolidation theory combined with the nonlinear rheological theory of soil, to extend the constitutive relation in Biot's consolidation theory to include the viscoelastic plasticity, with consideration of the dynamic relationship among the porosity, the hydraulic conductivity, the parameters of soil deformation and effective stress, and to establish a three-dimensional full coupling mathematical model and to apply it to the study of land subsidence and ground fissures of Cangzhou in Hebei Province. On the basis of the model calibration and the analysis of parameter sensitivity, the influences of the soil hydraulic and mechanical parameters on the vertical displacement (land subsidence) and the horizontal displacement (ground fissures) are studied. It is shown that the elastic modulus $E$, the Poisson ratio $\nu$, the specific yield $\mu$ and the soil cohesion $c$ have a great influence on the land subsidence and the ground fissures. In addition, the vertical hydraulic conductivity $k_z$ and the horizontal hydraulic conductivity $k_s$ also have a great influence on the land subsidence and the ground fissures.

## 1. Biot's consolidation theory

For a saturated soil, assuming that the soil skeleton deformation is linear elastic and small, the seepage satisfies the Darcy's law, the water is incompressible or with a micro compression, the three dimensional Biot's consolidation equation can be expressed as follows[9]:

$$-G\nabla^2 w_x - \frac{G}{1-2\nu}\frac{\partial}{\partial x}\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_y}{\partial y}+\frac{\partial w_z}{\partial x}\right)+\frac{\partial u}{\partial x}=0 \tag{1a}$$

$$-G\nabla^2 w_y - \frac{G}{1-2\nu}\frac{\partial}{\partial y}\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_y}{\partial y}+\frac{\partial w_z}{\partial x}\right)+\frac{\partial u}{\partial y}=0 \tag{1b}$$

$$-G\nabla^2 w_z - \frac{G}{1-2\nu}\frac{\partial}{\partial z}\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_y}{\partial y}+\frac{\partial w_z}{\partial x}\right)+\frac{\partial u}{\partial z}=-\gamma \tag{1c}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_y}{\partial y}+\frac{\partial w_z}{\partial z}\right)-\frac{1}{\gamma_w}\left\{\frac{\partial}{\partial x}\left(k_x\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left[k_z\left(\frac{\partial u}{\partial z}+\gamma_w\right)\right]\right\}=0 \tag{2}$$

where $G$ is the shear modulus, $\nu$ is the Poisson ratio, $w_x$, $w_y$ and $w_z$ are the displacement components in the $x, y, z$ directions, $u$ is the pore water pressure, $k_x$, $k_y$ and $k_z$ are the hydraulic conductivities in the $x, y, z$ directions, $\gamma$ is the specific weight of soil, $\gamma_w$ is the specific weight of water.

## 2. Constitutive model of soils

The constitutive relationship concerns the mechanical properties of soils, and is the mathematical expression of the relations among the stress, the strain, the strength and the time. For soils, with the rheological properties, the deformation features are mainly reflected in the deformation and time relation at a stress level, as in a kind of visco-elastic-plastic medium. The total strain increment for this kind of soil $\mathrm{d}\varepsilon_{ij}$ is composed of three parts: the elastic-plastic increment $\mathrm{d}\varepsilon_{ij}^{ep}$, the visco-elastic increment $\mathrm{d}\varepsilon_{ij}^{ve}$ and the visco-plastic increment $\mathrm{d}\varepsilon_{ij}^{vp}$, therefore, at an arbitrary point in the soils at any moment, the strain increment can be expressed as follows[10]

$$\mathrm{d}\varepsilon_{ij}=\mathrm{d}\varepsilon_{ij}^{ep}+\mathrm{d}\varepsilon_{ij}^{ve}+\mathrm{d}\varepsilon_{ij}^{vp} \tag{3}$$

## 3. Visco-elastic-plastic finite element equation of Biot's consolidation

The Galerkin weighted residual method is used to discretize the equations. With the nonlinear characteristics of soils, the increment $\Delta t$ is used, and Eqs.(1) and (2) are discretized into an incremental form as[11]

$$\begin{bmatrix}\overline{K} & K' \\ K'^{\mathrm{T}} & \Delta tK+B\end{bmatrix}\begin{bmatrix}\Delta\delta \\ \Delta u\end{bmatrix}=\begin{bmatrix}R-R_t \\ \Delta t\Delta Q\end{bmatrix} \tag{4}$$

where $\Delta\delta$ is the displacement increment at the node, $\Delta u$ is the pore pressure increment at the node, $\overline{K}$ is the solid stiffness matrix, $K$ is the seepage discharge matrix, $K'$ is the strain-seepage coupling matrix, $\Delta Q$ is the flow increment matrix, $B$ is the free surface integral matrix, $R$ is the equivalent joint load, and $R_i$ is the load balanced by the displacement at time $t$.

Because the seepage flow depends on the distribution of the total pore pressure, rather than the distribution of the pore water pressure increment, so the pore pressure must be expressed by the total pressure. We denote the total pore pressure in the element node $i$ at time $t_n$ and $t_{n+1}$ as $u_{i(n)}$ and $u_{i(n+1)}$, moreover, $\Delta u_i = u_{i(n+1)} - u_{i(n)}$. Equation (4) can be expressed in the following form