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Impact of Continuous Groundwater Decline on Foundation Subsidence of Existing Buildings

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ABSTRACT: The drop in groundwater level can lead to uneven subsidence of the foundation and affect the safety of existing buildings. In this paper, a finite element model for the coupling of groundwater seepage and foundation consolidation of existing buildings is established, and the changes of groundwater and foundation with time at different head gradients are analyzed. The following conclusions were obtained: (1) the groundwater seepage velocity and flux increase with the depth of the foundation, besides, the softer and lower the strength of the soil, the greater the flow velocity and flux; (2) during soil consolidation, the shallow compression of the foundation soil is greater, and the foundation subsidence is higher near the low-water point, the hydraulic head gradient gradually spreads with time, and the gradient distribution tends to be stable; (3) Soil consolidation mainly causes the foundation to produce a uniform settlement, which grows more stable with time, while groundwater seepage causes non-uniform subsidence, which is very obvious at the beginning and grows slowly with time towards the later stage. The results of this paper can provide a basis for the analysis of non-uniform subsidence in existing buildings.

KEYWORDS: Groundwater seepage; Foundation subsidence; Soil consolidation; Fluid-solid coupling; Existing buildings.

I. INTRODUCTION

The development of cities requires large amounts of groundwater extraction, resulting in increasingly severe ground subsidence. Ground subsidence is an environmental geological phenomenon caused by the compression of the surface soil of the earth's crust due to natural and man-made factors. Hasanuddin applied a level and GPS to determine ground subsidence in Jakarta, the capital of Indonesia, which reached 160cm between 1991 and 1997, and showed by comparing hydrological data that Jakarta Ground subsidence in Jakarta is associated with over-abstraction of groundwater [1]. Ground subsidence is slow to occur, long-lasting and widespread, and is a geological hazard that poses a threat to urban construction, economic development, and people's lives [2].

Foundation subsidence due to groundwater drop is a complicated fluid-structure coupling process, which needs to consider the influence of groundwater seepage. Currently, many scholars have proposed various methods to predict the problem of foundation contraction and consolidation subsidence due to subsurface fluid extraction for different geological conditions and on-site subsurface fluid extraction practices. One of the earliest studies on this issue was the one-dimensional consolidation theory of K. Terzaghi. Later, Biot (1941) extended K. Terzaghi's one-dimensional consolidation theory to a true three-dimensional consolidation theory, laying the foundation for subsequent calculations of fluid-structure coupling.

Since the 1970s, with the development of computers, numerical analysis has been applied to the prediction of ground subsidence. The coupling of Darcy's law and Terzaghi's effective stress principle began to be considered, laying the foundation for one-dimensional ground subsidence simulations and groundwater resource calculations. Chen [3] studied the relationship between groundwater aquifers and ground subsidence in the Beijing Plain, China, exploring the positive correlation between groundwater level decline and the degree of ground subsidence, and providing implications for groundwater resource management and Jahangir [4] explored the problem of land subsidence due to groundwater over-exploitation in the Arak Plain, Iran, using an elastoplastic Mohr-Coulomb model to simulate land subsidence and provided technical measures to measure and predict land subsidence. sócrates [5] summarised the effects of groundwater over-exploitation in tectonic valleys in central Mexico on the impact of land subsidence. The study points out that the land gradually descends under the action of controlling geological formations, creating damage zones, topographic discontinuities, and slumping.

In this paper, a pore-elastic model is established to describe the interaction between groundwater seepage and foundation deformation. The model uses Darcy's law and Biot's principal structure relationship to describe groundwater seepage and foundation deformation respectively, and analyses the coupled interaction between groundwater flow and subsurface (matrix) deformation through pore-elasticity theory. Based on the model, the effect of continuous groundwater decline on the foundation settlement of an existing building is analyzed.

II. GROUNDWATER SEEPAGE AND FOUNDATION CONSOLIDATION COUPLING MODEL

Groundwater seepage is described by Darcy's law and conservation of mass

$$\frac{\partial}{\partial t}(\varepsilon_p \rho) + \nabla \cdot (\rho \mathbf{u}) = Q_m \quad (1)$$

$$\mathbf{u} = -\frac{K}{\mu}(\nabla p + \rho \mathbf{g}) \quad (2)$$

The governing equation for the deformation of the foundation soil during consolidation is

$$\nabla \cdot \sigma + \rho \mathbf{g} = 0 \quad (3)$$

where σ is the stress tensor, ρ is the total density and \mathbf{g} is the acceleration of gravity.

In this paper, COMSOL Multiphysics finite element software was used to modeling for the above problem. The dimensions of the model, boundary conditions, and mesh division are shown in Figure 1, and the calculation parameters are shown in Table 1.

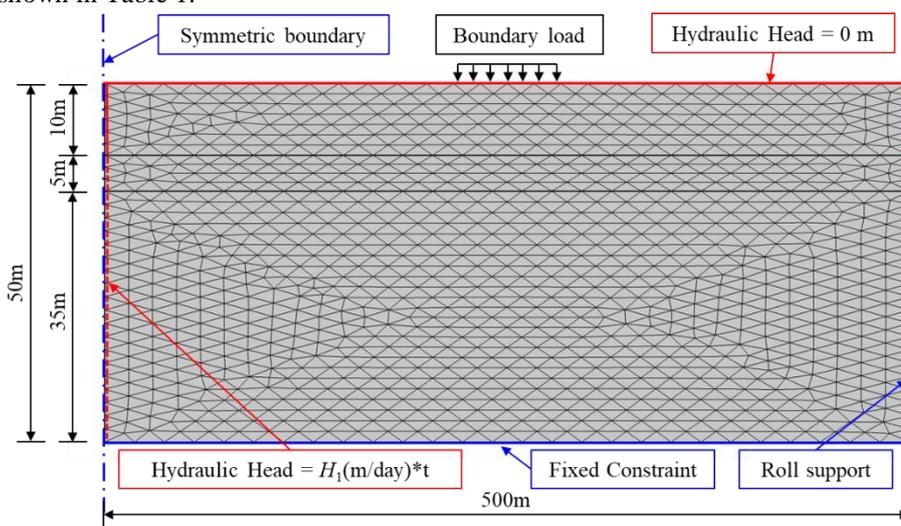


Figure 1 Geometry, boundary conditions, and mesh division of the model

Table 1 The physical parameters in the simulation

Variable	Value
Fluid density (kg/m ³)	1000
Soil density (kg/m ³)	2750
Hydraulic conductivity K ₁ (m/day)	25
Hydraulic conductivity K ₂ (m/day)	0.01
Biot-Willis coefficient	1
Initial hydraulic head H ₀ (m)	0
Low-hydraulic head H ₁ (m)	0, 0.01, 0.1, 1
Young' s modulus E ₁ (GPa)	800
Young' s modulus E ₂ (GPa)	600
Poisson' s ratio	0.25



III. RESULTS AND DISCUSSION

Figure 2 shows the distribution of the groundwater hydraulic head at one year of consolidation, as the distance from the low-water point increases, the flow rate becomes slower, as the depth of the foundation increases, the streamline becomes slower, at 0~10m the foundation subsidence is unchanged, at -5m~-40m, as the distance from the low-water point increases, the foundation subsidence starts to increase, at 400m it reaches about -25mm and tends to stabilize.

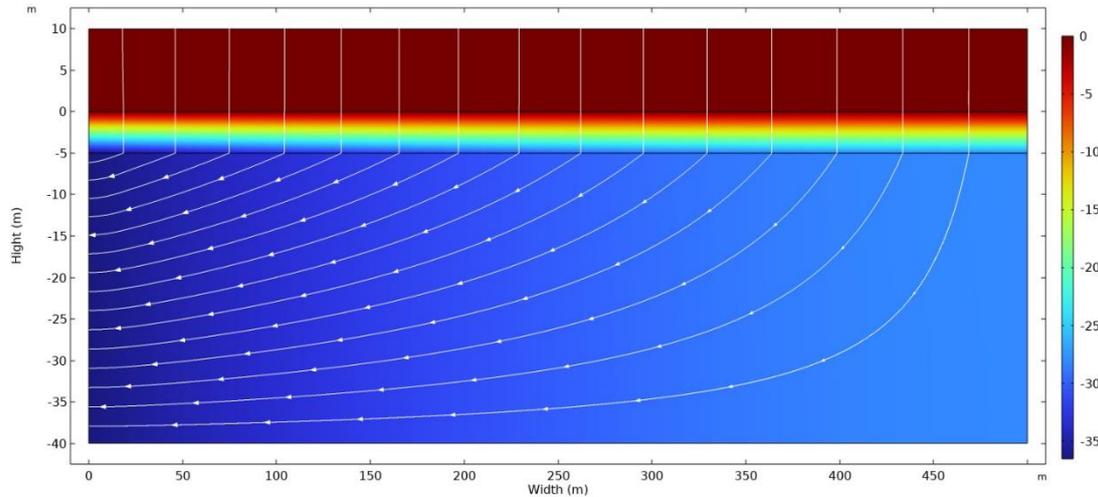


Figure 2 Distribution of groundwater hydraulic head (m) and streamlines (m/s) at 1 year of consolidation

Figure 3 illustrates the coupling of groundwater-foundation flow and consolidation at 1 year of consolidation. The mass flux remains essentially constant at $2 \times 10^{-9} \text{ kg}/(\text{m}^3 \cdot \text{s})$ at the depth of 0m to 10m; when the depth of the foundation is at -5m to 0m, the soil is relatively loose and low strength, and the groundwater mass flux reaches a maximum of $12 \times 10^{-9} \text{ kg}/(\text{m}^3 \cdot \text{s})$; with the depth of the foundation at -40m to -5m, the flux is higher, at about $9 \times 10^{-9} \text{ kg}/(\text{m}^3 \cdot \text{s})$ at the low water level.

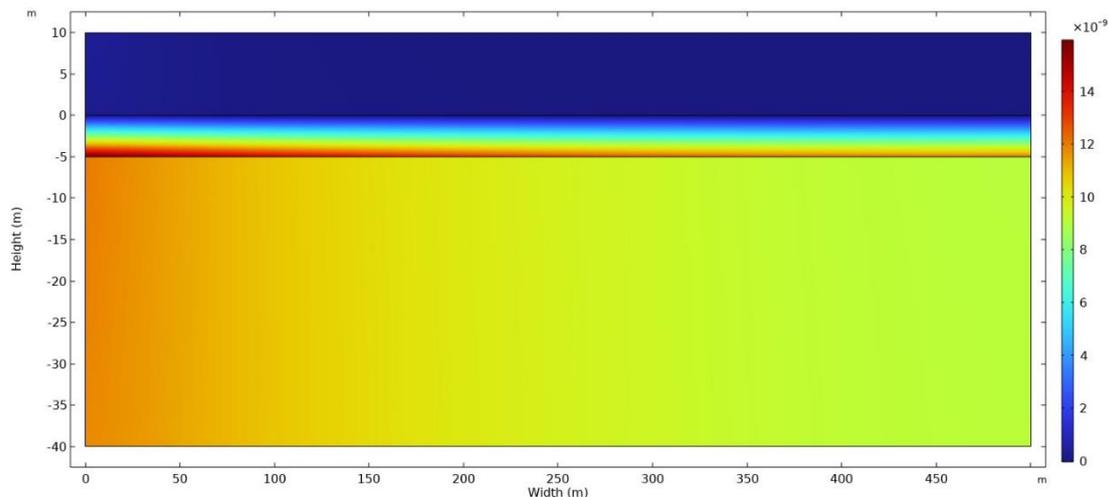


Figure 3 Coupling of groundwater - foundation at 1 year of consolidation

It can be seen in Figure 4 that after 1 year of consolidation of the foundation soil, the foundation compression increases with the increase of the foundation depth, and the foundation compression reaches 21.18mm at the foundation depth of 0m to 10m, at the foundation depth of 0m to -5m, the foundation compression is between 10.95mm and 16.8mm, and at the foundation depth of -5m to -40m, the foundation The compression amount is between 0mm and 12.41mm at the depth of -5m to -40m.

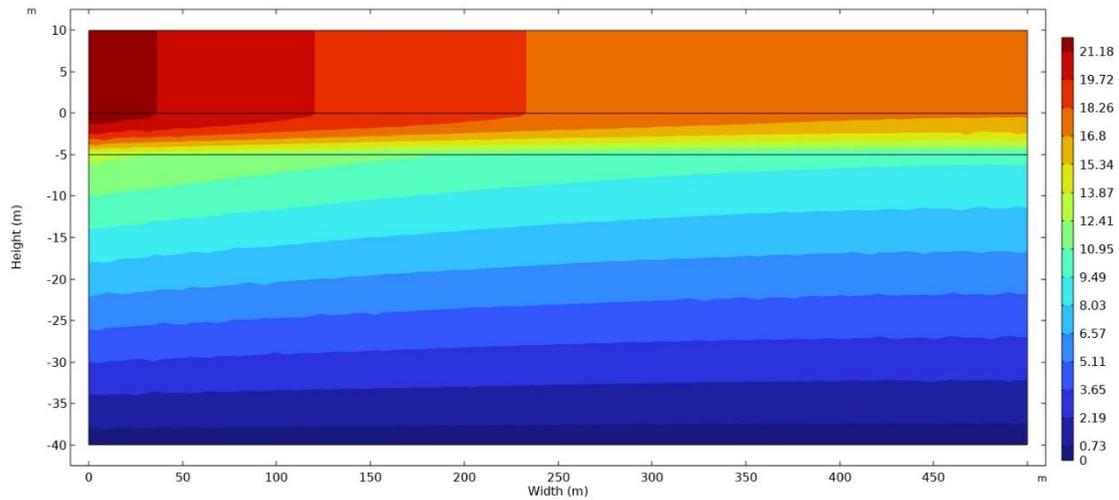


Figure 4 Foundation compression at 1 year of consolidation (mm)

Figure 5 shows that the hydraulic head gradient varies greatly with the growth of consolidation time, the amount of hydraulic head change is small at 0.1 years of consolidation, the hydraulic head height is about -3m, and at 1 year the hydraulic head height is about -29m, but the hydraulic head gradient is small, at 5 years the hydraulic head height at the -5m depth position reaches about -152m, with a significant increase of the hydraulic head gradient, at the 10 years the hydraulic head height at the -5m depth position reaches -308m above. Meanwhile, the foundation soil subsidence is not only related to time but also affected by the existing building load and groundwater seepage. From Figure 5, it can be found that at 0.1 years of consolidation, the foundation building subsidence is small and the maximum amount of subsidence of the upper layer of soil is 3cm, which is mainly generated by the foundation consolidation, and is more uniform overall, only the subsidence near the existing building is slightly larger with other locations. At 1 year of consolidation, the maximum amount of subsidence of the upper foundation soil was 4.2cm, but it was obvious that the amount of subsidence at the low water level was greater and that the impact of groundwater on the foundation subsidence was significant, leading to the occurrence of non-uniform subsidence. At 1 year of consolidation, the maximum amount of settlement of the upper foundation soil was 16.4cm, and the phenomenon of non-uniform subsidence was very remarkable.

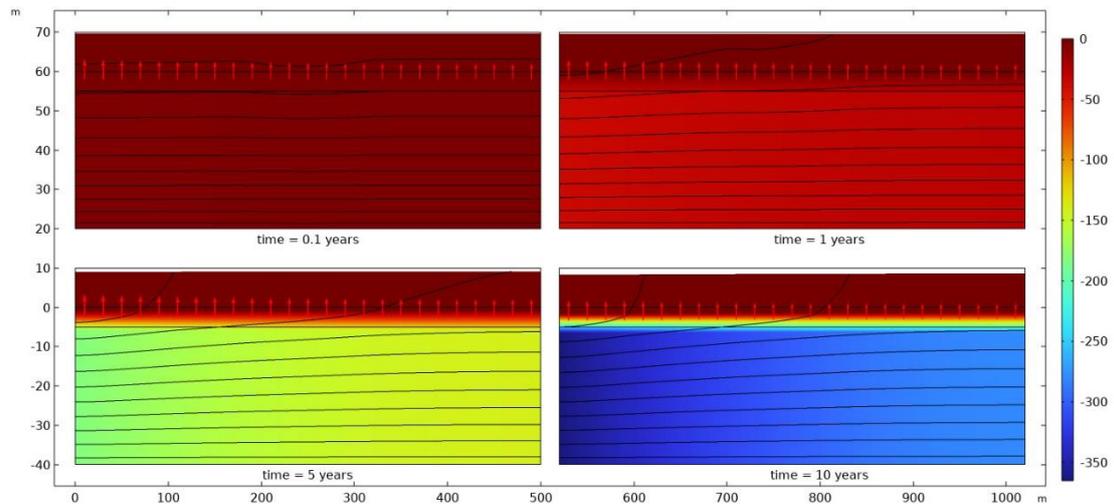


Figure 5 Comparison of groundwater head distribution, hydraulic head gradient, and subsidence of foundations for consolidation times of 0.1, 1, 5, and 10 years respectively.

Figure 6 shows the subsidence of the foundation soil at different consolidation times, from Figure 6(a), we can find that the groundwater seepage velocity at the low water level point is 0.1m/day, at 0 years of consolidation, the subsidence of the foundation soil is mainly governed by the groundwater seepage, the initial stage occurs near the low water level point, the amount of subsidence is about 2.5cm, the further away from the low water level point, the smaller the amount of subsidence, the subsidence caused by the soil consolidation is only 0.5cm; at the moment of 0.1 year and 1 year, the foundation displacement was influenced by consolidation and the overall downward displacement occurred, the subsidence was about 3.1cm at 0.1 year and 4.3cm at 1 year; by 10 years, due to the large period, the foundation displacement was influenced by consolidation and groundwater seepage, the foundation subsidence near the low water level point was about 15cm. Figure 6(b) shows the amount of foundation subsidence at different groundwater seepage rates H_1 for a consolidation time of 0.1 yr. When H_1 is 0m/day, the foundation subsidence is 2.8cm, which is mainly generated by soil consolidation; the amount of subsidence gradually increases when H_1 increases, and when H_1 is 1m/day, the foundation subsidence becomes more influenced by groundwater seepage, and when H_1 is 1m/day Subsidence from groundwater seepage reaches 2cm.

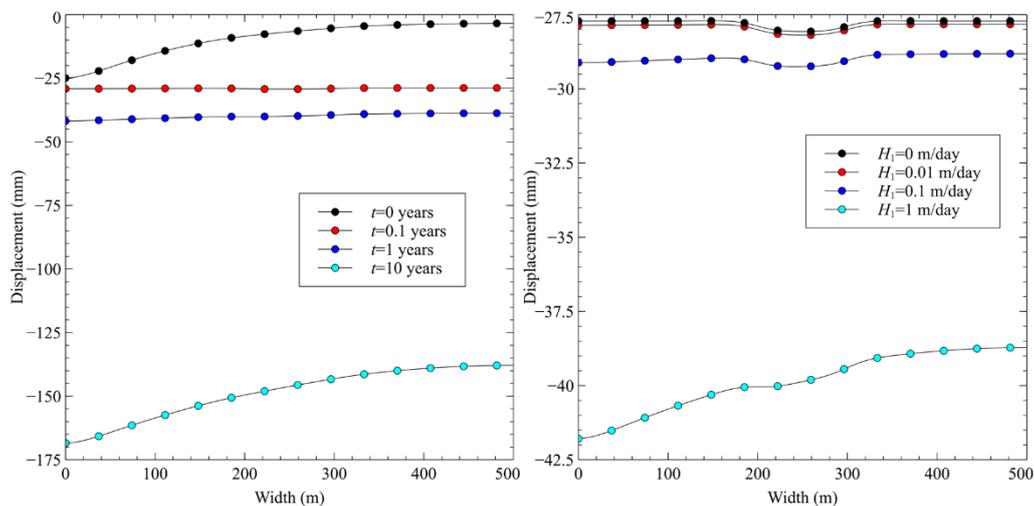


Figure 6 Displacement of foundations at different conditions. (a) Consolidation times are 0, 0.1, 1, and 10 years, respectively. (b) H_1 is 0, 0.01, 0.1, 1 m/day.

IV. CONCLUSION

Foundation subsidence during groundwater seepage can lead to non-uniform subsidence of existing building foundations and affect the safety of existing buildings. In this paper, a coupled model of groundwater seepage and foundation consolidation is established based on the finite element method, and the changes of groundwater and foundation with time at different head gradients are analyzed, and the following results are obtained:

- (1) The groundwater seepage velocity and flow rate increase with the depth of the foundation, and the looser and lower the strength of the soil, the greater the flux and velocity;
- (2) When the soil consolidates, the shallow compression of the foundation soil is greater, and the foundation subsidence is greater near the low water level; the hydraulic head gradient gradually spreads with time, and the gradient distribution tends to be stable;
- (3) Soil consolidation mainly causes the foundation to generate uniform subsidence, which grows more stable with time, while groundwater seepage causes the foundation to generate non-uniform subsidence, and the subsidence is very obvious at the beginning and grows slowly with time at the later stage.

The consolidation of the foundation during groundwater infiltration plays an important role in the safety of the whole building, while the lowering of the groundwater head will lead to consolidation of the foundation and thus non-uniform subsidence, which will have a certain impact on the normal use and safety of the building. With the accelerated development of infrastructure construction, the consequent subsidence of the foundation needs to attract the attention and concern of the construction personnel and construction designers. The results of this paper can provide a basis for the analysis of non-uniform subsidence in existing buildings.



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