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Numerical evaluation of ground settlements induced by groundwater inflow to the tunnel

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ABSTRACT

Tunneling beneath the groundwater table may result in unexpected groundwater inflow into the tunnel and cause unstable stress conditions near the tunnel and ground surface. Unlike the operational parameters of tunneling, the groundwater inflow to the tunnel results in the overall and widened settlement. The seepage forces in the ground surrounding a tunnel induce the change of effective stress. The groundwater drawdown also increases the effective stress by removing pore pressure near the surface. In this study, the numerical experiments are conducted with parameters such as the groundwater level, ground type, and the amount of inflow. The results are analyzed by comparing them with analytical solutions for groundwater drawdown and seepage. The contribution of groundwater inflow to the ground settlement is evaluated, and it is anticipated to serve the crucial role of predicting the settlement induced by the tunnel excavation.

1. INTRODUCTION

Tunnel construction in urban areas cannot help encountering unfavourable geological conditions to protect the adjacent structures and get a proper tunnel function. Among the geological factors, the tunnelling beneath the groundwater table may cause severe and widened ground deformation. As the groundwater inflows during tunnelling, it not only hinders the construction sequences but also disturbs the ground (Yoo, 2005; Yoo, 2016). The deformation characteristics of the surrounding ground are ruled by effective stress, which is controlled by pore water pressure. The change in pore water pressure distribution during the tunnelling can affect the tunnel and ground stability in the short and long term. The stress distribution change induced by groundwater inflow shows that two different aspects occurred simultaneously. One is the groundwater

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drawdown in the surrounding aquifer. The ground surface may result in settlements because the pore water pressure is removed and the effective stress drastically increased. The second is the seepage-induced ground deformation that occurred at excavated tunnel wall. This study investigates the settlement induced by groundwater inflow to the tunnel analytically. The numerical experiments are also conducted with parameters such as the groundwater level, ground type, and the amount of flow. The contribution of groundwater inflow to the ground settlement is evaluated, and it is anticipated to serve the crucial role of predicting the settlement induced by the tunnel excavation.

2. GROUND DEFORMATION INDUCED BY GROUNDWATER INFLOW

The ground deformation during the tunnel construction is controlled by the tunnel's internal pressure and radial displacement. Analytical solutions have been proposed to estimate the change in effective stress induced by seepage forces at the tunnel boundary (Bouvard and Pinto, 1969; Schleiss, 1986; Fernandez and Alvarez Jr., 1994). They assumed the rock mass as a homogenous, isotropic, porous, and elastic medium. The seepage-induced radial displacement at the tunnel wall is given by:

$$u\left(r=a\right)=\frac{1+\nu}{E}\cdot\Delta P_w\cdot a \tag{1}$$

From the radial displacement, the ground loss, which means a deformed area for a unit excavated area, is determined by multiplying the length of tunnel circumference. For the detailed evaluation, the ground is assumed as layered with homogeneous and isotropic layers. Simplifying the groundwater inflow occurred as steady-state flow beneath the phreatic surface, the pore pressure difference can be determined by considering that the hydraulic head of the flow path is identical to the hydraulic gradient multiplied by layer thickness. The layer including groundwater level is labelled as first, and the layer including the tunnel is labelled as n.

$$G_{flow}=a\gamma_w\cdot\Delta Q\cdot\sum_{i=1}^{n}\left(\frac{1+\nu_i}{E_i}\cdot\frac{H_i}{k_i}\right) \tag{2}$$

The seepage-induced settlement originated from the tunnel. However, the groundwater drawdown is the dominant factor because it removes the pore pressure for some depths. The drawdown-induced settlement is given by the pore pressure decrement and the sum of each layer’s deformation. Considering the ground as elastic as before, the settlement is:

$$S_{drawdown}=\gamma_w\cdot\sum\frac{H_i}{E_i}\cdot(drawdown) \tag{3}$$

3. NUMERICAL EXPERIMENTS

In this study, the FDM based numerical computational software FLAC3D was used. For the numerical simulation of groundwater inflow, the porosity and permeability of the ground, and the compressibility of water were applied. The ground deformation under undrained excavation was simulated by applying fixed hydraulic stress condition and calculating only mechanical behaviour. The deformation induced by pore pressure was simulated by the uncoupled process. It calculates the mechanical step and hydraulic step individually. The deformation caused by mechanical, plastic deformation, was simulated by coupled process. The process applied in this study was uncoupled analysis of phreatic groundwater surface.

The tunnel was simulated without mechanical nulling, it only functioned as drain path. However, the geometry concerns the mechanical boundary condition first, then evaluated by influence range of drawdown curve. As a result, the model geometry was selected as 90m (>H+4D) on y-axis (longitudinal direction to excavation), 90m (>H+4D) on x-axis (transversal direction to excavation), and 60m (>H+4D) on z-axis, considering the diameter of tunnel (D) and the cover depth of tunnel (H) (Lambrughi et al., 2012). All nodes were fixed with orthogonal direction to boundary.

The parametric study was conducted by changing the groundwater level (0m or 2m), the type of excavated rock medium (weathered rock; WR or soft rock; SR), and the inflow rate and flow time. The tunnel depth and diameter was fixed as 20m and 3.6m. The ground properties for parametric studies were as below:

Table 1. Ground properties for parametric studies (An et al., 2022)

	Type	Thickness [m]	Density [kg/m³]	Cohesion [kPa]	Internal friction angle [degree]	Elastic modulus [MPa]	Poisson's ratio	porosity	Permeability [cm/sec]
Layer 1	Fill	4.0	1,800	5	26	18	0.33	0.30	5.00e-3
Layer 2	WS	4.0	1,900	20	30	44	0.32	0.25	4.65e-4
Layer 3	WR	4.0	2,100	30	33	100	0.30	0.10	3.00e-4
Layer 4	SR	16.0	2,500	140	37	2,000	0.28	0.05	1.03e-4
Layer 5	HR	32.0	2,800	1,000	45	8,000	0.25	0.01	2.24e-5

The case of WR is constructed by exchanging the layer 4 to the weathered rock (WR). The quantity of groundwater inflow was determined by solving the problem with allowing whole drainage at the tunnel section (fix the pore pressure). Then, based on that quantity, the inflow was simulated until they converged. The results showed that lower groundwater level induced more settlements because the effective stress increment due to the drawdown cannot hold the overburden. Also, the weathered rock showed more settlements than soft rock, because its modulus was lower than that of soft rock. The extensive amount of groundwater inflow on weathered rock made a faster convergence with larger deformation.

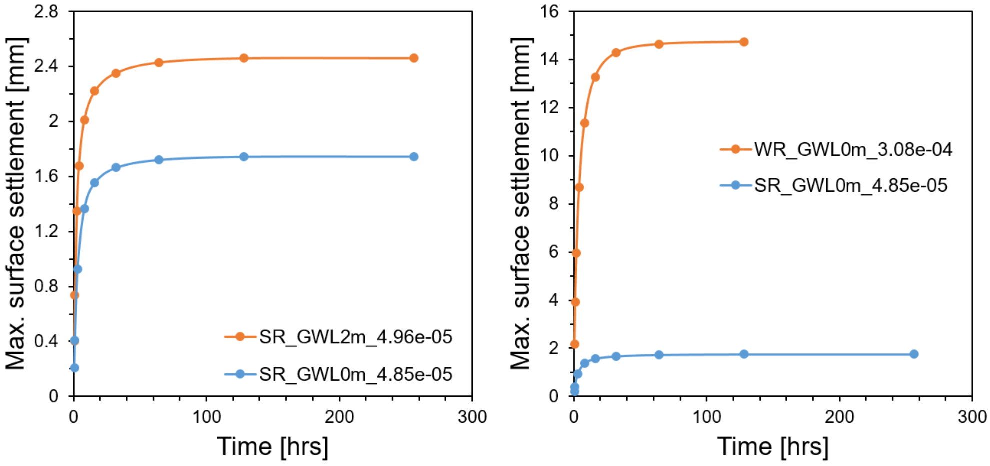

Fig. 1 Numerical experimental results

4. CONCLUSIONS

The groundwater inflow to the excavated tunnel can bring out enormous surface settlement. In this study, the contribution of the groundwater inflow was evaluated through the numerical experiments. The weaker ground requires more caution for the inflow quantity, especially detailed testing of groundwater table required.

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