Numerical Analysis of the Change in Groundwater System with Tunnel Excavation in Discontinuous Rock Mass

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ABSTRACT

In this study, a 2D finite-element analysis, using the SEEP/W program, was carried out to estimate the amount of groundwater flowing into a tunnel, as well as the groundwater tables around wetland areas during and after tunnel excavation through rock mass. Four sites along the Wonhyo-tunnel in Cheonseong Mountain (Gyeongsangnam-do, Korea) were analysed, where the model domain of the tunnel included both wetland and fault zones. The anisotropy of the hydraulic conductivities of the rock mass was calculated using the DFN model, which was then used as an input parameter into the continuum model. Parametric studies were performed on the influencing factors to minimize uncertainties in the hydraulic properties. Moreover, the volumetric water content and hydraulic conductivity functions were applied to the model to reflect the ability of a medium to store and transport water under both saturated and unsaturated conditions.

1. INTRODUCTION

Groundwater condition is one of the key elements in most construction projects. Proper evaluation of the groundwater table and groundwater inflow into a tunnel during and after tunnelling is very important at the design stage. Groundwater inflow during tunnelling gets in the way of construction works and it may be harmful to tunnel stability. A drawdown of groundwater level resulting from the groundwater inflow can affect the ecosystem around the tunnel.

The recent numerical methods used to analyze groundwater flow can be classified into 3 categories, based on modelling of the medium into which the groundwater flows; the equivalent porous medium, dual porous medium and the discrete fracture network models (Long et al, 1982; Priest, 1993). Conventional modelling of the groundwater flow in porous media has been preferred for design purposes. However, the flow characteristics described by such continuum models are quite different from those in a rock mass, as groundwater mainly flows through discontinuities, such as faults, joints and cracks. The discrete fracture network (DFN) model is frequently adopted for simulating groundwater flow in discontinuous rock mass. Zhang & Sanderson (2002) and Min et al. (2004) estimated the representative element volume (REV) and calculated the anisotropic hydraulic conductivities of a rock mass using the DFN model. With large-scale groundwater problems, however, the explicit representation of large number of fractures is inefficient.

In this study, a 2D finite-element model, using the SEEP/W program, was used to evaluate the amount of groundwater flowing into a tunnel, as well as the drawdown of groundwater around a wetland near the top of the mountain site. The anisotropic hydraulic conductivities of the rock mass were calculated using the DFN model, which were then used as input parameters for the FEM modelling. To minimize the uncertainties in the hydraulic properties, parametric study on the influencing factors, such as hydraulic conductivities of the fault and grouting zones, was performed.

2. SITE DESCRIPTION

2.1 Background

The study site was the Wonhyo tunnel around Cheonseong Mountain in Gyeongsangnam-do, Korea, which was designed for the high speed train, Korea Train Express (KTX). Initially, the construction of a 13.28km-long tunnel, part of a high-speed railway from Seoul to Busan, was scheduled to begin in June of 2002 and be completed in 2010. This project, however, became a social issue by environmental activists and citizen's groups for the conservation of highland swamps which had been designated as Natural Ecosystem and Wetland Conservation Areas.
As a matter of fact an Environment Impact Assessment (EIA) of the construction of the Wonhyo tunnel through Cheonseong Mountain was undertaken by Korea Rail Network Authority (KRNA) in October 1994. However, the environmental activists and citizens filed a lawsuit seeking to halt the construction of the tunnel, the so-called 'salamander lawsuit', in October 2003. They also demanded a re-examination of the EIA, as there had been no investigation about the effect of tunnel excavation on 22 natural highland swamps designated as protected areas, as well as 12 valleys, and the associated protected plants and animals including the 'Korean clawed salamander' living in the area. Ulsan district court and Pusan high court consecutively dismissed the suit in 2004; therefore, the KRNA launched the tunnel construction project. However, Jiyul, a Buddhist nun from a temple in Cheonseong Mountain, began a hunger strike against the court judgement.
In response to citizen pressure including Jiyul's hunger strike, Korea Environment Ministry accepted the demand of the environmental activists and citizen's groups and organized a research group, consisting of experts designated by both KRNA and citizen's groups to re-examine the EIA. Both sides agreed to file the report to the Supreme Court and follow the final judgement. A Joint-Environment Impact Assessment, covering the groundwater flow, structural geology, rock mechanics, ecosystem and geophysics, was conducted from September to December of 2004. This study is a part of the assessment work. In June 2006, the Supreme Court dismissed the suit by the environmental activists and citizens, and the construction finally restarted.

2.2 Geology

The construction site was classified into 2 domains based on the rock mass characteristics: granite (domain 1) and volcanic rocks complex (domain 2). The main concern in domain 1 was the drawdown of groundwater caused by the tunnelling, as this could affect many wetland and wildlife conservations at the top or ridge of the mountain. Groundwater simulations were then required to estimate the inflows into the tunnel and evaluate the changes in the groundwater level around the wetlands due to the tunnelling. In domain 2, the least overburden was 20.4m around the Gancheon Valley; therefore, the groundwater inflow into tunnel was estimated for a tunnel safety analysis. Three sites in domain 1 and one site in domain 2 were selected for analyses, which considered the scale of the wetlands, the distance from the wetlands to the tunnel and the existence of the fault zone: Mujechi 3rd swamp, Daeseongdwit swamp, Daeseongkeun swamp (domain 1) and Gancheon valley (domain 2). Tables 1 and 2 contain information on the wetlands and faults that were included in the model domains.

Table 1. Summary of the wetlands information.

Swamp	Station	Scale	Horizonal distance	Vertical distance	The least distance
Mujechi 3rd	369 km 820	50 m × 50 m	130 m	50 m	280 m
Daeseongdwit	370 km 400	150 m × 50 m	400 m	270 m	260 m
Daeseongkeun	370 km 780	120 m × 300 m	420 m	275 m	380 m

Table 2. Summary of faults information.

Fault	Station	Strike/Dip	Length	Gouge	Fault	Influence zone
F2	368 km 690	N35°E / 75°SE	>1.5 km	10-15 cm	10 m	20 m
F3	370 km 630	N14°E / 80°SE	>8.0 km	10 cm	10 m	30 m
F4	370 km 770	N35°W / 80°SW	>2.0 km	3-5 cm	5 m	15 m

3. 2-DIMENSIONAL FINITE ANALYSIS

3.1 Input data and approach

Various in-situ tests and laboratory tests were carried out to investigate the hydraulic conductivities of each layer in the model domains. Putting these data together, hydraulic conductivities were determined and applied to the analyses. The maximum hydraulic conductivity of fault zone was measured to be 5.86×10^{-7} m/sec, but this value was applied to the influenced zone of the fault and 1.00×10^{-5} m /sec and 1.00×10^{-6} m/sec were applied to the faults in the simulations, respectively as shown in Table 3.
A total of 6~8 cases of transient flow simulation was performed at each site for parametric studies of the hydraulic conductivities of the fault zone, grouting zone and excavation damaged zone to overcome limitations of deterministic flow analysis with only a single hydraulic conductivity value. Table 4 and Table 5 show the simulation cases. The hydraulic conductivity of grouting zone was assumed to be 1/10, 1/50 and 1/100 of the conductivity of rock mass. For the analyses at Gancheon Valley, the increase of the hydraulic conductivity of the excavation damaged zone (EDZ) was considered. The excavation damaged zone was formed up to 1.5m thick with about 3 orders higher hydraulic conductivity than the undisturbed rock (Bäckblom & Martin, 1999).
DFN models in 2-dimension were constructed by using UDEC (Universal Distinct Element Code) to reflect these features in a continuum model. In order to evaluate the existence and magnitude of REV, 50 m×50 m parent DFN models were generated 10 times and were divided into a series of sub-areas; 4 m×4 m, 10 m×10 m, 20 m×20 m, 30 m×30 m and 40 m×40 m. The K-anisotropy ratios (K_x/ K_y) were 0.65 in domain 1 and 0.91 in domain 2 and were used as input parameters of the continuum model.
The volumetric water content function describes the capability of the medium to store water according to the negative pore-water pressure (suction), and the hydraulic conductivity function represents the ability of the medium to transport water according to the negative pore-water pressure. As pore water pressure becomes increasingly negative, more pores become air-filled and the volumetric water content and the hydraulic conductivity decrease further. Actual measurement of the hydraulic conductivity function is a time-consuming and expensive procedure, but the function can be readily developed using a grain-size curve. In this study, the functions of the sedimentary layer in the wetland and the outer weathered soil layer were estimated because the drainage was expected to begin these layers. To estimate the volumetric water content functions, the methods suggested by Kovacs (1981) and Arya & Paris (1981) were used, respectively. And the hydraulic conductivity functions were estimated by the method suggested by Fredlund et al. (1994). Figure 1 and Figure 2 show the estimated functions of the sedimentary layer in the wetland and the weathered outer layer, respectively. The average annual rainfall during the last 10 years was 1,219 mm, and the infiltration rate was calculated to be 14.5% in this region. Based on these data, 5.6×10^{-9} m/sec was applied to the simulation as the flux boundary at the surface. The groundwater table measurement provided that most of the sites around wetlands were near or above the ground surface. Initial conditions were established by running the steady state analyses at each site, and transient analyses were performed 10 years after excavation. The time step applied to transient analysis is shown in Table 6.

Table 3. Hydraulic conductivity of layers at study site.

Layer	Domain 1 (m/sec)	Domain 2(m/sec)
Sedimentary layer in wetlands	7.56×10^{-9}	-
Weathered soil	3.24×10^{-6}	3.24×10^{-6}
Weathered rock	3.24×10^{-7}	3.24×10^{-7}
Soft rock	3.86×10^{-7}	3.86×10^{-7}
Hard rock	2.01×10^{-7}	1.49×10^{-7}

Table 4. Simulation cases in domain 1(around wetlands).

Grouting zone / Fault zone	No grouting considered	1/10 of the original	1/50 of the original	1/100 of the original
10^{-5} m/sec	Case 1	Case 2	Case 3	Case 4
10^{-6} m/sec	Case 5	Case 6	Case 7	Case 8

Table 5. Simulation cases in domain 2(around Gancheon Valley).

Grouting zone / EDZ	No grouting considered	1/10 of the original	1/100 of the original
100 times higher	Case 1	Case 2	Case 3
10 times higher	Case 4	Case 5	Case 6

Table 6. Time step applied to the transient analysis.

Time step	1	2	3	4	5	6	7	8
Time after excavatio	15 days	1 month	6 months	1 year	2 years	3 years	5 years	10 years

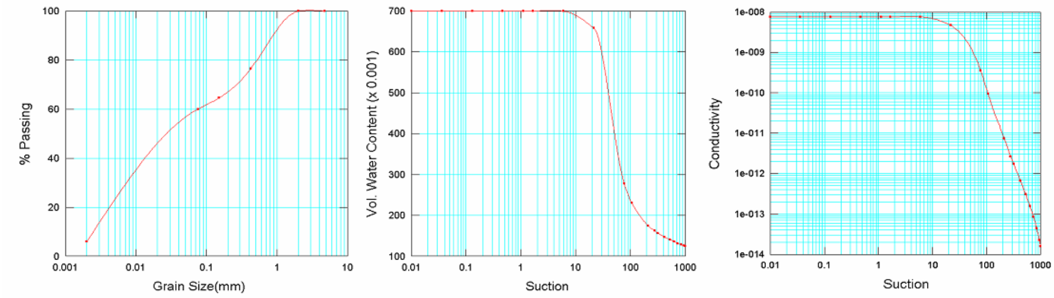

Fig. 1. Estimation of vol. water content function and hydraulic conductivity function of the sedimentary layer in wetlands.

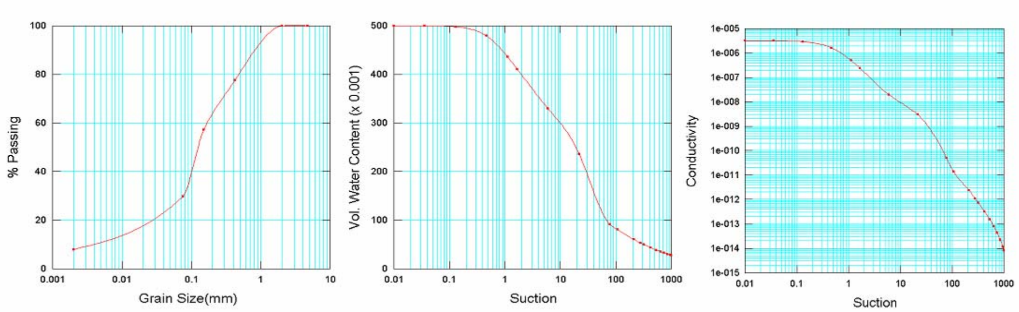

Fig. 2. Estimation of vol. water content function and hydraulic conductivity function of the outer weathered soil.

3.2 Results and discussion

3.2.1 Site around Mujechi 3rd swamp

When the hydraulic conductivity of the fault was 10^{-6} m/sec, the inflows into tunnel decreased by 0.43~4.4% in comparison with those in case of 10^{-5} m/sec. Even though there were four adjacent fault zones in the modelling domain, the inflows into tunnel were not influenced significantly by the change in the hydraulic conductivity of the fault zone. It was because the fault zone did not intersect the tunnel. As the hydraulic conductivities of grouting zone were reduced to 1/10, 1/50 and 1/100 of the original rock mass, inflow into tunnel were decreased linearly. The maximum inflows were examined to be 1.67 m^3 /km/min in Case 1. Figure 3 shows the inflows into the tunnel during 10 years around Mujechi 3rd swamp. The influence of tunnelling on groundwater table around Mujechi 3rd swamp was evaluated based on the change in the drawdown around the swamp 10 years passed after excavation. When the hydraulic conductivity of the fault zone was 10^{-5} m/sec, the drawdowns of the groundwater table were predicted to be 6.6 m (Case 1), 3.5m (Case 2) and 1.9 m (Case 3) and when the hydraulic conductivity of the fragmental zone was 10^{-6} m/sec, they were 3.7 m (Case 5) and 2 m (Case 6). In the rest of the cases, drawdown did not occur. The values of the drawdown were examined to be relatively large because Mujechi 3rd swamp was located at the top of the fault zone (F-3). Figure 4 shows the drawdown of groundwater around Mujechi 3rd swamp due to the tunnel excavation with the condition of Case 1(a) and Case 3 (b). Note that the lines marked with time steps 2, 4 and 8 correspond to the groundwater tables for 1 month, 1 year and 10 years after excavation, relatively.

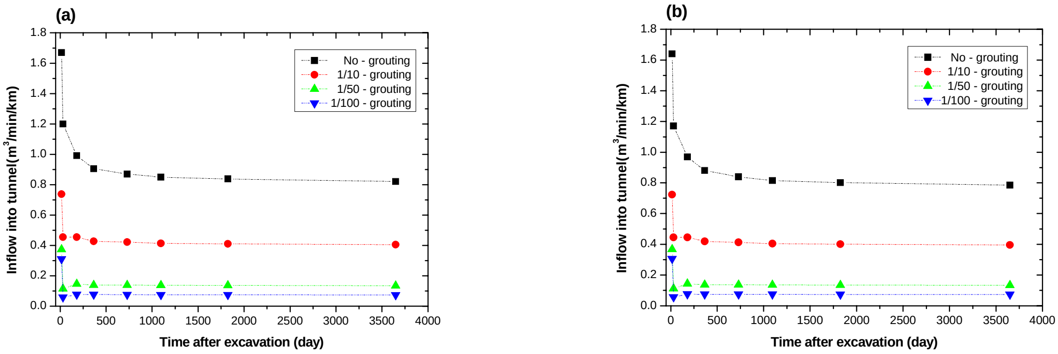

Fig. 3. Inflows into tunnel at the site around Mujechi 3rd swamp in case that the hydraulic conductivity of fault zone is (a) 10^{-5} m/sec and (b) 10^{-6} m/sec.

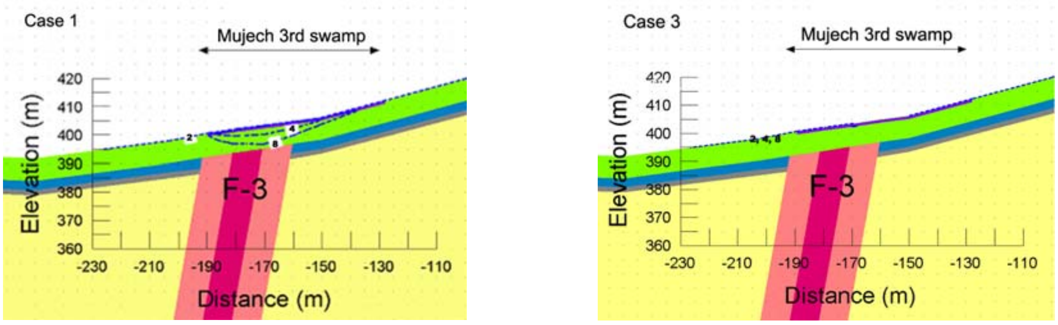

Fig. 4. Drawdown of groundwater around Mujechi 3rd swamp.

3.2.2 Site around Daeseongdwit wetland

When the hydraulic conductivity of the fault was 10^{-6} m/sec, the inflows into tunnel decreased by 0.15~8.40% in comparison with those in case of 10^{-5} m/sec. The inflows into the tunnel were also not influenced significantly by the hydraulic conductivity of fault zone for the same reason as the site around Mujechi 3rd swamp. The maximum inflows were examined to be 1.45 m^3/km/min in Case 1. Figure 5 shows the inflows into the tunnel during 10 years at the site around Daeseongdwit swamp. In all of the cases, the groundwater tables around the swamp were not changed when 10 years passed after excavation.

3.2.3 Site around Daeseongkeun wetland

At this site, Yongyon fault (F3) with the 30m width influenced zone intersected the tunnel section and crossed Jokye fault (F4) with the 15m width influenced zone above the ceiling of the tunnel. The inflows into the tunnel were dependent directly on the hydraulic conductivity of the fault zone.

When the hydraulic conductivity of the fault was 10^{-6} m/sec, the inflows into tunnel decreased by up to 75.18% compared with those in case of 10^{-5} m/sec. When the hydraulic conductivity of the grouting zone was reduced to 1/10, 1/50 and 1/100 of the original rock mass, the inflows into tunnel were 7.21, 2.70 and 1.75 m^3/km/min. Figure 6 shows the inflows into tunnel during 10 years at the site around Daeseongkeun swamp. The influence of tunnelling on groundwater table around Daesongkeun swamp was examined 10 years after excavation. The drawdown occurred when grouting was not performed and the hydraulic conductivity of grouting zone was reduced to 1/10 (Case 1, 2, 5 and 6). Groundwater table around the wetland maintained when the hydraulic conductivity of grouting zone was reduced to be less than 1/50. The maximum drawdown was estimated to be 0.6m in the part of the swamp in Case 1. Figure7 shows the drawdown of groundwater around Daeseongkeun swamp due to the tunnel excavation with the condition of Case 1(a) and Case 3(b). Note that the line marked with time step 8 corresponds to the groundwater table for 10 years after excavation.

3.2.4 Site around Gancheon Valley

Figure 8 shows the inflows into the tunnel during 10 years at the site around Gancheon valley. When the EDZ's hydraulic conductivity was 10 times higher than the undisturbed rock, the inflows of tunnel showed a decrease by 39.6% compared with those in case of 100 times higher. As the hydraulic conductivity of grouting zone decreased, the inflows into tunnel decreased linearly and the maximum inflows into tunnel was expected to be 2.18 m^3/km/min in Case 1.

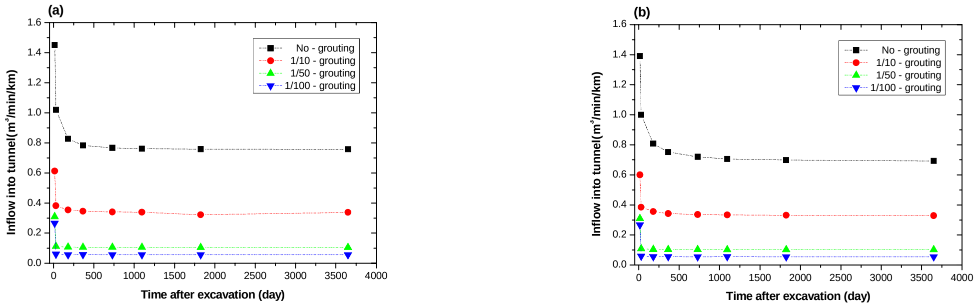

Fig. 5. Inflows into tunnel at the site around Daeseongdwit swamp in case that the hydraulic conductivity of fault zone (a) 10^{-5} m/sec and (b) 10^{-6} m/sec.

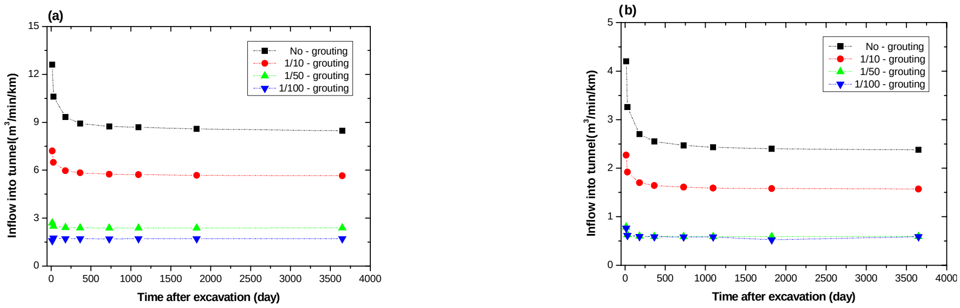

Fig. 6. Inflows into tunnel at the site around Daeseongkeun swamp in case that the hydraulic conductivity of fault zone is (a) 10^{-5}m/sec and (b) 10^{-6} m/sec.

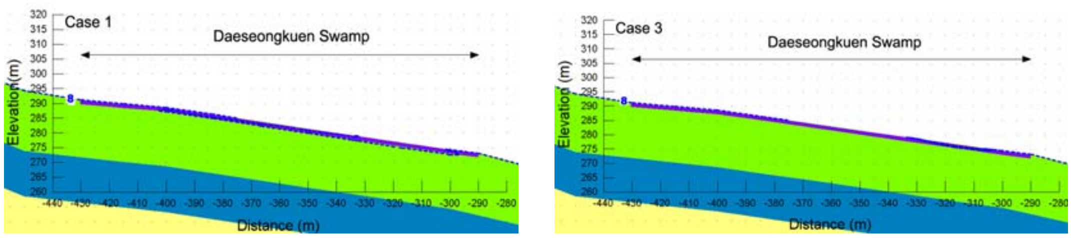

Fig. 7. Drawdown of groundwater around Daeseongkeun swamp.

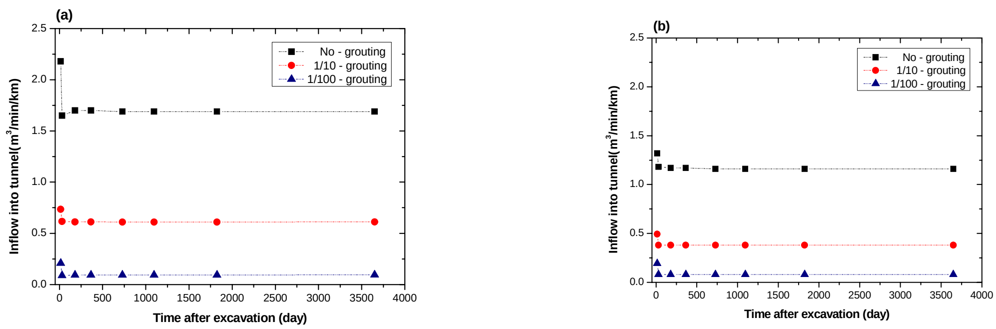

Fig. 8 Inflows into tunnel at the site around Gancheon valley in case that the hydraulic conductivity of EDZ is (a) 100 times higher and (b) 10 times higher than the original

4. CONCLUSIONS

In this study, 2D finite-element model was simulated to estimate the amount of groundwater flowing into a tunnel and ground water table around wetlands when the tunnel is excavated in jointed mass. Many cases of transient flow simulation were established at four sites. The results of this study can be summarized as follows:

1. The comparison of the results of Mujechi 3rd swamp and Daeseongkuen swamp showed that the hydraulic conductivities of fault zone significantly influenced groundwater inflow only when the fault zone crossed through the tunnel.
2. Groundwater table around wetlands maintained if the hydraulic conductivity of grouting zone was reduced to less than 1/50 of the conductivity of rock mass at all analysis sites.
3. When the conductivity of EDZ was 10 times higher than the conductivity of undisturbed rock, the inflows into tunnel decreased by 40%, compared with those in case of 100 times higher.
4. Unless the fault zone and the surface of tunnel were in contact, the fault adjacent to the tunnel did not influence significantly on the inflows into tunnel.

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