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Excessive groundwater inflow during TBM tunneling in limestone formation

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ABSTRACT

A sudden increase of groundwater inflow of 670 tons a day was experienced during tunneling in a limestone formation at around 53 m below the ground surface. The limestone cavities were expected to be located at 5–10 m or more above the tunnel crown in geotechnical exploration. However, limestone cavity network was encountered at the tunnel depth, and large groundwater inflow was experienced. Because of the excessive groundwater inflow into the tunnel, the groundwater level dropped to GL-32 m from the original level of GL-16 m, and consequently maximum of 23 mm of ground settlement and damage of adjacent structures took place. In this study the change of groundwater regime during tunneling in limestone area containing cavity network was analyzed through 3-dimensional numerical analysis, and the mechanism of groundwater level drawdown followed by ground subsidence was analyzed by comparing measurements and numerical analysis results. And also the analytical solution for determining the range of cutoff grouting was proposed to minimize groundwater inflow during excavation in a fractured zone.

1. Introduction

Limestone cavity zone causes various stability problems during tunneling and foundation problems (Marinos, 2001; Fookes and Hawkins, 1988; Statham and Baker, 1986; Barla, 2016; Tosevski et al., 2010). Jin et al. (2002) studied about the influence of a large-scale cavity on tunnel stability by performing numerical parametric study. Chung et al. (2013) performed small-scale model tests to investigate the behavior characteristics of a tunnel in limestone formation containing cavities. Fookes and Hawkins (1988) proposed a simple engineering classification of the solution features characteristics of limestones.

Limestone cavity zone often contains large amount of water and groundwater flows fast in a cavity network zone. Many researchers discussed about water-related troubles and case histories (Calembert, 1975; Kavvadas and Marinos, 1994). Hwang and Lu (2007) and Schwarz et al (2006) performed hydrogeological modelling to assess the water inflow and the risks during tunnel construction. Gisbert et al (2009) and Day (2004) performed hydrological model test to investigate the hydrological impact of tunneling in karstic terrains.

Because of the possibility of rapid increase of groundwater inflow and consequent ground settlement when limestone cavities are encountered during tunneling in limestone formation, it is necessary to examine closely the geological structure of the limestone cavities and the possibility of encounters during geological investigation. Zarei et al (2012) studied the reducing of risk related to tunnel construction in Karstic rocks through geological investigation. Alija et al (2013) performed geological analysis to improve the design and stability of tunnel construction in Karst rock mass.

In this study, the behavior of groundwater flow and surrounding ground were discussed from the case study in which as large as 670 tons/day of groundwater inflow during tunneling using a dual-mode earth pressure balanced machine (EPBM) in a fractured zone connected to limestone cavity network. The contractor expected large water inflow to be continued only for at most one or two days and reduced with time. However, the large groundwater inflow continued for more than a month while tunneling because large amount of water was supplied continuously through the limestone cavity network. The groundwater level dropped to GL-32 m from the original groundwater level of GL-16 m, and the ground settlement up to 23 mm and damages of neighboring buildings were reported. It was impossible to block the high-pressure groundwater inflow with the close-mode EPBM due to the water pressure (around 4 bars) exceeding the screw conveyor capacity (around 2–3 bars), and the high-elasticity urethane grout was injected twice into the extraction chamber. Fortunately, the large groundwater inflow was stopped after injection of grout, and the groundwater level recovered to GL-17m in about two weeks.

In this study, the mechanism of excessive groundwater inflow was analyzed through additional ground survey and field measurement. The

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back-analysis using 3-dimensional numerical analysis was also performed from groundwater level and inflow rate measurements, and the behavior of groundwater flow and ground settlement with time were analyzed.

Ground settlement is expected in the deep valley region filled the weathered soil (silty sand) if similar event of high groundwater inflow occurs again, the soft ground area was planned to be grouted to decrease the permeability. The quality control of grouting is the most important for ground improvement (Tseng et al., 2001), but it is also important to determine the area of grouting and volume of grout injection to achieve the desired level of water tightness. This study proposed the analytical solution for determining the range of cutoff grouting to minimize groundwater inflow during excavation in a fractured zone.

2. General conditions

In this case study, excess groundwater inflow was drained through the tunnel face in fractured limestone formation with cavities during the 1873 m–long cable tunnel excavation in at about GL-50 m depth. The initial groundwater level of GL-16 m was dropped to GL-32 m, and ground subsidence and damage of adjacent buildings were reported. Fig. 1 shows some pictures of building damages and subsidence of roads near NO.34 + 16 where EPBM experienced high water inflow rate.

The schematic drawing of the EPBM used in this site is shown in Fig. 2. It is a refurbished single-type EPBM composed of an excavation face plate with a diameter of 3.55 m, 2-rows of tail seal, and a ribbon-type screw conveyor. A probe drilling equipment (4 holes for grouting upper 120° area with length of 20 m) was installed for drilling and grouting in the fracture zone and weathered soil area.

If the chamber pressure of close-mode shield TBM is sufficiently managed to correspond to the water pressure, there will be almost no problem with the ground settlement. However, the shield TBM used in the site could handle only 2–3 bars of water pressure, although the maximum expected water pressure could be 4 bars. Also, it is considered that the probe drilling facility for grouting the upper 120° above the tunnel will not be able to sufficiently cope with the high-pressure groundwater inflow from bottom and sides.

3. Geological condition

The limestone cavity zone generally appears as a narrow-width cavity network along the discontinuities, or as a large-scale cavity with a width of tens to hundreds of meters as shown in Fig. 3 (Lee and Sun, 2010). The narrow-width cavity network type is a structure in which the limestone is dissolved due to groundwater flow along the discontinuities. It was considered from the geological investigation that the limestone formation in this case history has a narrow-width cavity network developed mainly along the discontinuities.

The limestone cavities were found at GL-23 ~ 45 m depth and relatively good quality rock mass was encountered at the tunnel depth (GL-50 ~ 55 m) during Phase I geotechnical investigation as shown in Fig. 4. In the limestone formation, there are 2 joint sets dipping 10–30° and 60–80°, and narrow-width cavities are expected to distributed along joints. The limestone cavities were found at 5–10 m above the tunnel crown, and the possibility of encountering cavities during tunneling was overlooked in tunnel design. It was actually planned to grout the 30 m-long section above the tunnel before passing the narrow-width cavity network zone, but it was found during tunneling that the rock condition was better than expected and the planned grouting work was not carried out.

However, the development depth of the narrow-width cavity network is generally irregular according to the discontinuity structure and groundwater flow condition through the discontinuities. As shown in the Fig. 5, it could be thought that the boring investigation only met cavities few meters above the tunnel crown, but the tunnel suddenly encountered a deeply-developed high-dipping cavity at No. 34 + 04, and sudden large amount of water burst out through a small hole in the excavation face.

Large, continuous groundwater inflow took place when the tunnel reached the fractured zone. The inflow rate was expected to be tens of tones a day and to reduce with time. However, the inflow rate was as large as 670 tons a day and that large amount of water inflow continued for a month until the pressure chamber was filled with high-elasticity urethane grout.

Further drilling and electro-resistivity tomography were performed to better understand the geological conditions of fractured zone after

Fig. 1. Ground settlement due to excessive water inflow during tunneling.