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Numerical and experimental investigation of pillar reinforcement with pressurized grouting and pre-stress

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ABSTRACT

To prevent and/or minimize flood-induced damage in metropolitan cities like Seoul, South Korea, construction of an underground rainwater storage cavern becomes an alternative to other conventional countermeasures. In this paper, a new pillar-reinforcement method was developed to improve pillar stability that is crucial for the successful construction of the rainwater storage cavern. Three pillar-reinforcing scenarios were compared numerically: (1) shotcrete installation only, (2) shotcrete installation and pillar-reinforcement with radially pressurized grouting and pre-stress, and (3) shotcrete installation and pillar-reinforcement with vertical upward pressurized grouting and pre-stress. The third pillar-reinforcement readily made the stress condition return to an elastic state showing superior performance to the other methods. In addition, two pillar widths of 800 mm and 1200 mm were considered to investigate the effects of pillar width on pillar reinforcement by carrying out a small-scale model test, in which the three pillar-reinforcement scenarios can be modeled step-by-step. The pillar width of 1200 mm resulted in smaller major principal stresses, representing better reinforcing performance than that of 800 mm. Moreover, it was shown that the pressurized grouting enhances the ground strength and more importantly lessened stress concentration in the pillar. However, applying pre-stress further increased ground strength because of the increase in internal pressure.

1. Introduction

Underground spaces in metropolitan cities are significantly vulnerable to flood-induced damage. To minimize such unavoidable damage caused by natural disasters, it is necessary to construct underground rainwater storage caverns beneath existing structures. It is of importance to reinforce pillars efficiently for pillar stability that is crucial for the successful construction of the rainwater storage cavern (Seo et al., 2012a,b).

There have been many studies on reinforcing the pillar structure as well, but mostly focusing on the installation of concrete structures in twin tunnels. Kamimura (2002) suggested pillar-reinforcement methods constructing concrete walls, increasing lining thickness, and using ground strength. Kobayashi (1994) proposed various reinforcing methods in the design and construction of twin tunnels. Seo et al. (2012a,b) introduced a new pillar-reinforcement method applicable to an underground rainwater detention cavern constructed underneath existing structures. In this method, a steel bar and PC strands are used to mobilize the full strength of a pillar mass with application of pressurized grouting and pre-stress instead of installation of heavy concrete walls. The applicability of the pillar-reinforcement method was examined by performing a series of small-scale model tests (Seo et al., 2014).

In this paper, the effects of the pillar-reinforcement method proposed by Seo et al. (2012a,b) were examined numerically and experimentally for three pillar-reinforcing scenarios as follows: (1) shotcrete installation only, (2) shotcrete installation and pillar-reinforcement with radially pressurized grouting and pre-stress, and (3) shotcrete installation and pillar-reinforcement with vertical upward pressurized grouting and pre-stress. Small-scale model tests were also carried out to evaluate the effect of pillar width on pillar reinforcement for two different pillar widths, 400 mm and 600 mm. The stress conditions obtained from the numerical and experimental results were compared in the p–q diagram to identify the effect of pillar-reinforcement.

2. Overview of pillar-reinforcing method

When an underground rainwater detention cavern is constructed beneath existing structures, a pillar structure stands between two adjacent caverns. The mechanism of

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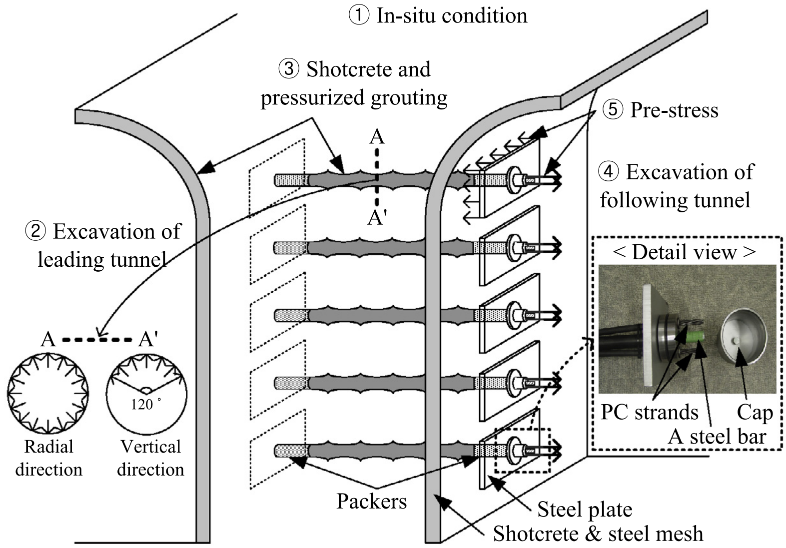

Fig. 1. Overview of new pillar-reinforcing method.

Table 1
Mechanical property and dimension of PC strand and steel bar.

Type	Elastic modulus (GPa)	Yield stress (MPa)	Yield load (kN)	Diameter (mm)	Cross-sectional area (mm^2)
PC strand	200	161	159	12.7	98.7
Steel bar	204	400	203	25	506.7

pillar-reinforcement is analogous to the reinforcing process in the construction of twin tunnels.

Pillars are frequently used to support the weight of overlying ground and to reduce surface settlements in many underground structures, i.e. in mining, tunneling, and storage and/or utility caverns, or for quarrying (Yu et al., 2014; Ringwald and Brawner, 1989; Cording et al., 2015; Pelizza et al., 2000). Available techniques to reinforce the pillar include rock bolts, cable bolts and strands, shotcrete with wiremesh, etc. Ringwald and Brawner (1989) studied the utilization of grouted threaded rods (wire ropes) to reinforce the concrete model pillars. The stability of roadway with narrow coal pillar in fractured zone utilizing the polymer grouting technique was studied by Yu et al. (2014). The yield pillar theory was intensively discussed by Tadolini and Zhang (2007). The tangential stress concentration that occurred in the pillar was found to be a major factor inducing yielding zones. In order to reduce yielding zones in the pillar, firstly, the primary shotcrete was applied to increase the confinement, and then the rock bolt was installed as well. The paramount thing was to apply the pre-stress to switch yield zones back to elastic state.

The pillar reinforcement system we propose in this paper also belongs to the yielded pillar mentioned above. The tunnel excavation stages as well as overview of the proposed pillar reinforcement system are as follows. After a leading tunnel is excavated, as shown in Fig. 1 (see ② Excavation of leading tunnel), reinforcement is applied to the excavated tunnel surface with a steel bar and two PC strands. The mechanical properties of the reinforcement components are summarized in Table 1. The PC strands are adopted for applying pre-stress. A cap encloses the tip of reinforcing bundles to protect the PC strands during the excavation of the following tunnel (see 'detail view' in Fig. 1). Pressurized grouting can be applied by a packer system in either a radial direction or a vertical upwards direction exclusively (see ③ Shotcrete and pressurized grouting and cross section A–A′ in Fig. 1). The pressure level is usually between 500 and 1000 kPa. Seo et al. (2012a,b) presented the detail construction procedures.

The following tunnel succeeds the leading tunnel, while maintaining a specified distance between the two (see ④ Excavation of following tunnel in Fig. 1). This construction stage is most dangerous because of stress concentration in the pillar with considerable reduction in horizontal stress (or minor principal stress) to the sidewall. To recover the horizontal stress at sidewall, pre-stress is applied through the PC strands (see ⑤ pre-stress in Fig. 1), which enhances confinement with an increase in internal pressure compared with sole application of shotcrete. In this paper, the effects of pillar-reinforcement were examined numerically and experimentally.

3. Numerical analyses

3.1. Numerical modeling of pillar reinforcement

A series of numerical analyses was performed to identify the ground behavior corresponding to each construction stage of pillar reinforcement for underground rainwater detention caverns underneath existing structures. In the numerical analysis, three pillar-reinforcing scenarios were compared: (1) shotcrete installation alone, (2) shotcrete installation and pillar-reinforcement with radially pressurized grouting and pre-stress, and (3) shotcrete installation and pillar-reinforcement with vertical upward pressurized grouting and pre-stress. The three reinforcement scenarios are compared in Table 2. Because application of the pressurized grouting is intended mainly to mitigate stress concentration in the pillar during excavation, the direction and amount of pressurized grouting should be of paramount importance in controlling pillar reinforcement with varying maximum principal stresses.

The construction stages and pillar reinforcement in an underground rainwater detention cavern are simulated by the FE