Geomechanics and Engineering, *Vol. 15, No. 3 (2018) 841-849*
DOI: https://doi.org/10.12989/gae.2018.15.3.841

Anchorage mechanism and pullout resistance of rock bolt in water-bearing rocks

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(Received May 20, 2017, Revised February 12, 2018, Accepted March 23, 2018)

Abstract. The purpose of a rock bolt is to improve the mechanical performance of a jointed-rock mass. The performance of a rock bolt is generally evaluated by conducting a field pullout test, as the analytical or numerical evaluation of the rock bolt behavior still remains difficult. In this study, wide range of field test was performed to investigate the pullout resistance of rock bolts considering influencing factors such as the rock type, water bearing conditions, rock bolt type and length. The test results showed that the fully grouted rock bolt (FGR) in water-bearing rocks can be inadequate to provide the required pullout resistance, meanwhile the inflated steel tube rock bolt (ISR) satisfied required pullout resistance, even immediately after installation in water-bearing conditions. The ISR was particularly effective when the water inflow into a drill hole is greater than 1.0 *l/min*. The effect of the rock bolt failure on the tunnel stability was investigated through numerical analysis. The results show that the contribution of the rock bolt to the overall stability of the tunnel was not significant. However, it is found that the rock bolt can effectively reinforce the jointed-rock mass and reduce the possibility of local collapses of rocks, thus the importance of the rock bolt should not be overlooked, regardless of the overall stability.

Keywords: pullout resistance; rock bolt; tunnel; water inflow

1. Introduction

A rock bolt prevents blocks of rock from loosening around tunnels and enhances rock arches (Osgoui and Ünal 2009). Various types of rock bolts can be applied, with typical examples including the fully grouted rock bolt (FGR) (in which pullout resistance is achieved by bonding disconnected rocks with rebar and grout material) and the inflated steel tube rock bolt (ISR) (in which a folded steel pipe is expanded in order to induce vertical stresses between the steel pipe and the rock which introduces a frictional force). The FGR is generally applied in both soil and rock ground, whereas the ISR is mainly applied in the rock slope due to its poor applicability to soft ground.

As shown in Fig. 1(a), the FGR consists of a rebar inserted in a borehole with a cementitious or resin anchoring agent inserted to exert the required anchoring force through adhesion with the rock. Several studies have been conducted to identify the anchoring behavior and the pullout resistance of the FGR (Farmer 1975, Oreste 1994, Hyett *et al.* 1996, Li and Stillborg 1999, Carranza-Torres and Fairhurst 2000, Oreste 2003, Cai *et al.* 2004). However, many uncertainties still remain in evaluating pullout resistance due to the various influencing factors involved in rock bolt installation. The rock bolt using grout requires curing time of the fixer until its strength is exhibited after installation, and it may not meet design strength according to the ground conditions. Previous studies have focused on the rock bolt pullout behavior, and the applicability to the water section and the experimental verification of the pullout load are insufficient. Therefore, it is necessary to study the behavior of FGR in the water section.

While the ISR was first developed in the early 1980s by Wijk and Skogberg (1982), studies on its anchoring behavior have only been carried out relatively recently (Li 2016). The ISR consists of a folded steel tube inserted into the borehole, with water pressure applied in the steel tube to develop normal stress through the expansion of the steel tube. The anchoring resistance is thus introduced through mechanical interlocking and frictional forces. As shown in Fig. 1(b) and as reported by Li and Håkansson (1999), the anchoring mechanism of the ISR consists of friction due to contact stress and the mechanical interlocking between the steel pipe and borehole.

The ISR has been preferred in water-bearing rock, because its pullout resistance is introduced immediately after installation. However, it has been reported that the FGR is less effective in terms of pullout resistance in some conditions, such as in the presence of water (KTA 2014a, 2014b). The lack of anchoring force of the FGR is generally caused by the incomplete filling of grout, and the lack of contact with the ground (Cai *et al.* 2004, Jia and Tang 2008). In particular, the water-cement ratio is an important factor to determine the anchoring force of the FGR (Vu and Stewart 2000, Jiang *et al.* 2014, Huang *et al.* 2017). In water-bearing rock, grout washing occurs, which increases

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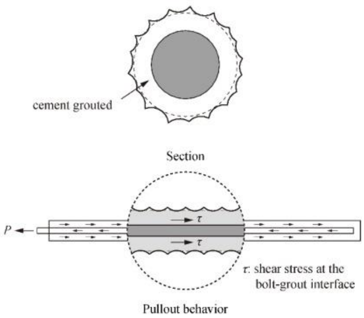
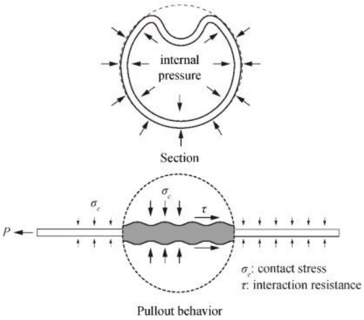
http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)



(a) Fully grouted rock bolt (FGR)



(b) Inflated steel tube rock bolt (ISR)

Fig. 1 Anchoring mechanism of rock bolts

the water-cement ratio, causing a lack of anchoring strength. Water-cement ratio is difficult to present in a universal ratio because the water content in the tunnel is different according to site conditions. One way to solve this problem is to apply a rock bolt, which can be used immediately after installation.

In this study, field tests were performed to investigate the characteristics of the rock bolt behavior and pullout resistance. Influencing factors such as the rock condition, rock bolt type, rock bolt length, and curing time are considered. Particular attention was given to investigate the effect of the presence of ground water. In addition, a numerical analysis was conducted to investigate the effect of the rock bolt on the structural stability of a tunnel.

2. Field pullout test

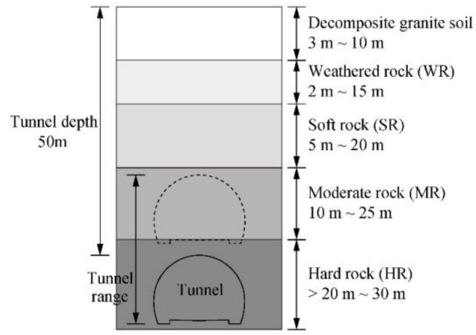
2.1 Numerical simulation procedure

To investigate the anchoring and pullout behavior of a rock bolt, several field tests were conducted at the tunnel site of the Seoul Metropolitan High Speed Railway Line (Suseo-Pyeongtaek) in South Korea. The project includes a total of 61.1 km of railway tunnel with a tunnel depth of 50 m. The RMR of the area was initially evaluated as 20 or more before excavation, however the value was reevaluated as 15-20 through face mapping during excavation. The main rock component is gneiss, and joint spacing is classified as dense and filling materials are soft.

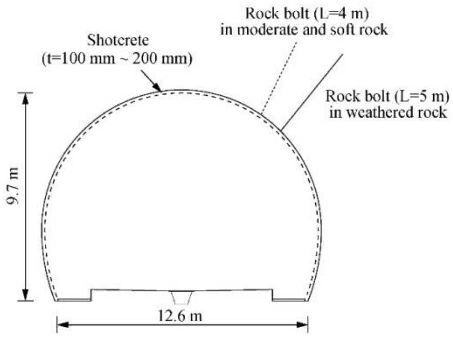
Typical rock conditions for the tunnel test are shown in Fig. 2(a). Table 1 shows the characteristics of the rock. The tunnel has a width of 12.6 m and a height of 9.7 m. The tunnel was excavated using the drill & blast method (New Austrian Tunneling Method, NATM). The tunnel supports

Table 1 Ground profiles

Parameter	Classification		
	Moderate rock	Soft rock	Weathered rock
RMR	41-60	21-40	< 20
RQD	50-75	25-50	< 25
Q-value	1-10	0.1-1	< 0.1



(a) Ground condition



(b) Tunnel section

Fig. 2 Test site and tunnel profile

Fig. 3 Inflow of ground water through drilling holes in water-bearing rock

were designed using shotcrete and rock bolts. The shotcrete for each cross section of the tunnel was designed to have thicknesses of 100 mm, 150 mm, and 200 mm for moderate rock, soft rock, and weathered rock, respectively, and the lengths of the rock bolts were planned to be 4 m in moderate rock and soft rock, and 5 m in weathered rock (Fig. 2(b)).

To identify the rock bolt behavior according to the rock types, moderate rock, soft rock, and weathered rock conditions were considered. To investigate the effect of water inflow into the drill hole, test sections were classified into a dry section and a water-bearing section according to the presence of water inflow. The dry section of the tunnel appeared at the moderate rock, soft rock, and weathered rock, while the water-bearing section consisted of soft rock and weathered rock. Fig. 3 shows the current situation of the ground water inflow through the drill hole. In the field, a borehole was installed for rock bolt installation, and water drained from the borehole was checked. The amount of water discharged per minute was checked using a plastic beaker of 5*l* capacity. The inflow rate was 0~3.78 *l/min* at the left side (0~60˚), the crown (60~120˚), and the right side (120 ~180˚) of the tunnel.

2.2 Test method

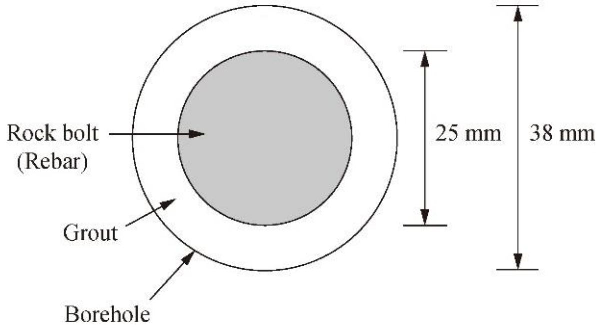
The anchoring force of the rock bolt is generally evaluated using a pullout test (Kilic *et al.* 2002, Jalalifar 2006, Merifield and Smith 2010, Kristjánsson 2014, Zhu *et al.* 2015), and the anchoring behavior of the rock bolt was investigated from the load-displacement curves of the pullout test. A pullout load is applied at the outer end of the rock bolt and the displacement of the rock bolt is then measured (Malhotra and Carino 2003). The borehole for a rock bolt is generally drilled perpendicular to the tunnel excavation surface.

The borehole of the FGR was drilled to a size of 38 mm. A D25 rebar was used for the FGR, with an yield strength of 350 MPa and an elongation of 18. The grout was a cement mortar mixed with normal Portland cement and sand at a ratio of 1:1. Sand with a maximum particle size of 2 mm was used. The water-cement ratio (W/C) was kept at 40~50%. A flat plate with a thickness of 6 mm was used for the pullout test. The pullout test for the FGR was conducted 24 hr after inserting the rebar and grout into the borehole to develop the required material strength.

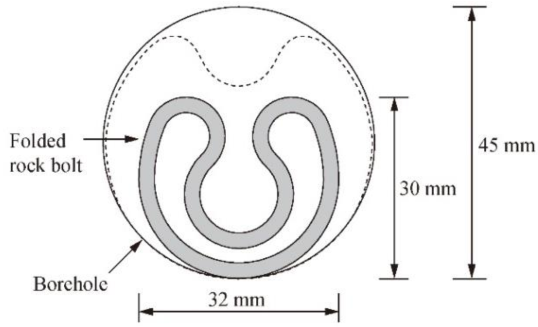
A cementing agent is not needed for the ISR because the anchoring contact stress is introduced by inflating the steel tube in the borehole. Yield strength of the steel pipe is 430 MPa, elongation rate is 18, and original diameter before rock bolt processing (bending) is 48 mm with a thickness of 2.3 mm. The borehole for the ISR is drilled to a size of 45 mm considering the diameter of the steel tube. Fig. 4 shows the details of the FGR and ISR used in the test.

Fig. 5 shows the pullout test setup consisting of a load cell, dial gauge, hydraulic ram, hand pump, pressure transducer, and reaction frame. In the pullout test, an incremental force of 10 kN per minute is applied in steps, and the load-displacement is measured at each step to obtain the load-displacement relationship. For the ISR, a steel tube was inserted into the borehole immediately after drilling to expand the steel pipe using the water pressure in the pipe, and the load-displacement curve was obtained by applying the pullout load stepwise. The water pressure in the ISR during expansion increased up to 25~30 MPa.

The pullout resistance was evaluated based on the load-displacement curves according to ASTM D4435-13e1 (2013). In this case, the pullout failure was defined when the maximum load remained constant or the total displacement reached 12.7 mm. Ultimate capacity and working capacity can be determined from the relationship between the displacement and the load shown in Fig. 6(a).

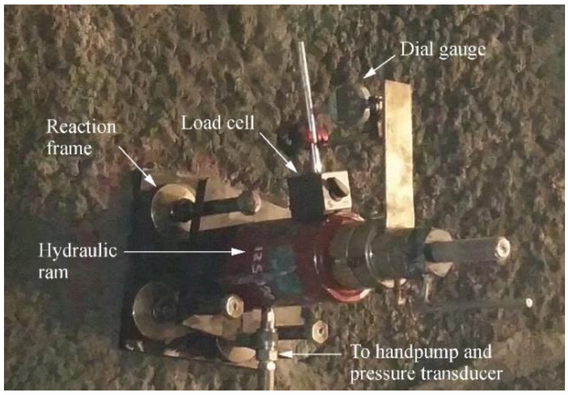


(a) Fully grouted rock bolt (FGR)



(b) Inflated steel tube rock bolt (ISR)

Fig. 4 Cross sections of the FGR and ISR

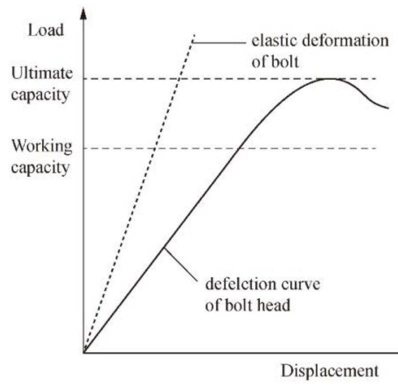


(a) Attaching the pullout test machine

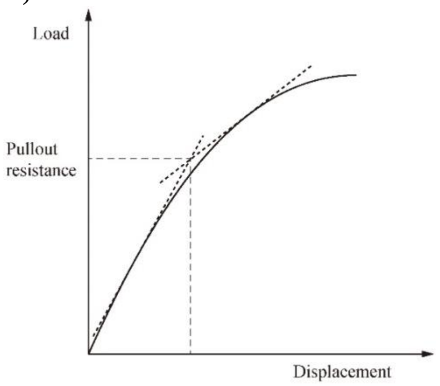

(b) Pullout test measurement

Fig. 5 Rock bolt pullout test

In this study, intersections of two tangential lines of the load-displacement representative curves are defined as the pullout resistance as shown in Fig. 6(b) (Zhang *et al.* 2014, Huang *et al.* 2017, Khan *et al.* 2017, Li *et al.* 2017).



(a) Typical load versus deflection curve (ASTM D4435-13e1 2013)



(b) Determination of pullout resistance

Fig. 6 Pullout load-displacement curve

Table 2 Field test cases: Conditions and parameters

Parameter		Ground	Rock bolt type	Length (m)	Adhesives material	Water inflow (l/min)	Number of test
Dry section test	Rock type	moderate rock, soft rock, weathered rock	FGR	4	cement mortar	-	10 / rock Type
	Rock bolt length	Moderate rock, soft rock	FGR	3, 4, 5	resin	-	3 / rock type
	Curing time	moderate rock, weathered rock	FGR	4	cement mortar	-	MR: 3 WR: 5
Water-bearing section test	Water inflow	soft rock	FGR, ISR	4	cement mortar, inflation	0.0-1.00	FGR: 4 ISR: 7
		weathered rock	FGR, ISR	4	cement mortar, inflation	1.2-3.78	FGR: 5 ISR: 5

2.3 Test case

To compare the behavior of the rock bolt in dry conditions with that when applied in a water-bearing rock, the test types were classified into a dry section test and a water-bearing section test. The rock bolt behavior in the dry section only using the FGR was investigated. The factors that were considered to influence the pullout test included rock type, rock bolt length, anchoring agent curing time, and inflow of ground water. The pullout tests of both the FGR and ISR in the water-bearing section were performed. The purpose of this study is to evaluate the applicability of rock bolts in dry and watering conditions. We found that the applicability of rock bolt varies depending on the amount of water in the watering section. The water-bearing section was again divided into a small inflow section and a large inflow section based on a water flow of 1.0 l/min, and at least 3 test locations were tested for each influencing factor. The test cases are summarized in Table 2.

3. Test result

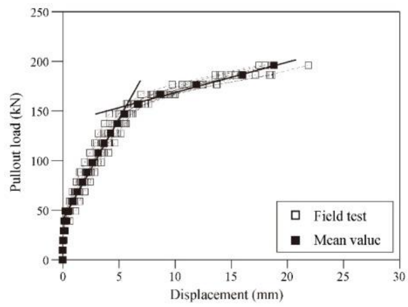
3.1 Behavior of rock bolts in dry rock

The rock bolt behavior was investigated by analyzing the load-displacement relationship from the pullout test. The effect of each parameter on the behavior of the rock bolt was examined by comparing the pullout resistance and the displacement at yielding.

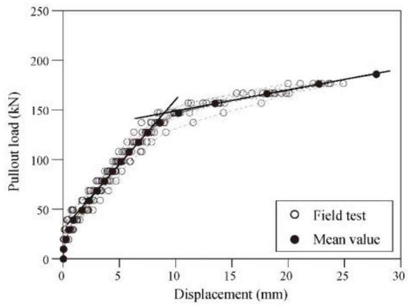
3.1.1 Effect of rock types (FGR)

The effect of the rock type on the rock bolt behavior was investigated by performing pullout tests with the FGR placed 4 m under moderate rock, soft rock, and weathered rock. Ten cases of tests were performed for each rock condition. The ISR is not tested, as the pullout resistance of the ISR is independent on the ground water condition.

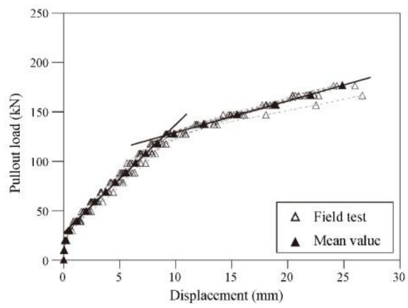
Fig. 7 shows the relationship between the pullout load and displacement for each rock conditions. The pullout resistance was determined according to ASTM D4435-13e1 (2013). The results of the test show that the slope of the load-displacement curve increased with an increase in rock stiffness, and consequently pullout resistance also increased. This tendency was more pronounced as the rock became harder (stiffer).



(a) Moderate rock



(b) Soft rock



(c) Weathered rock

Fig. 7 Pullout load-displacement curves for rock types

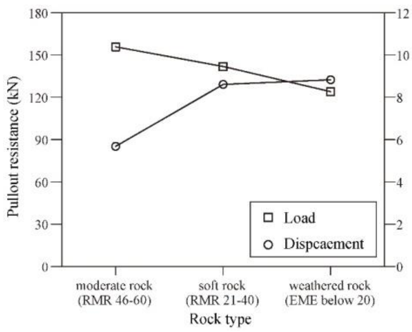
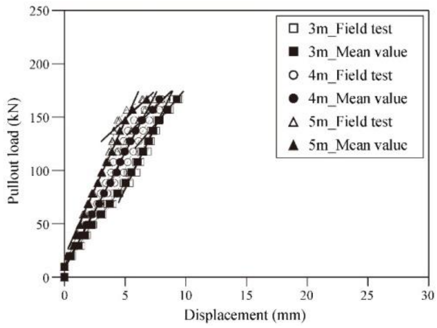
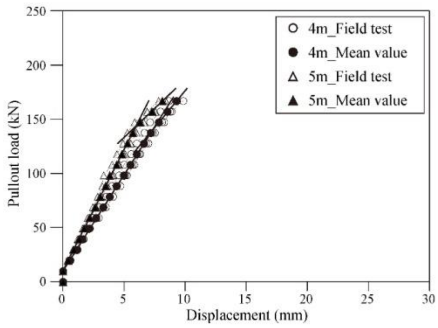


Fig. 8 Effect of rock types



(a) Moderate rock



(b) Soft rock

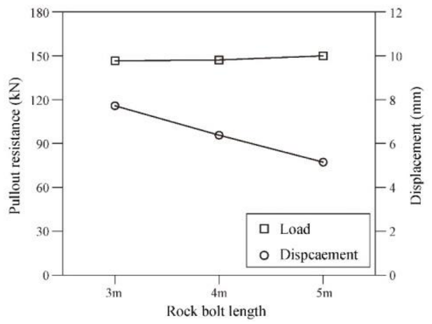
Fig. 9 Pullout load-displacement curves for rock bolt length

The average pullout resistance and displacement at yielding for each rock type are presented in Fig. 8. The average pullout resistance increased up to 155.81 kN for moderate rock. The rock bolt pullout resistance increased as the rock stiffness increased. This is because, the borehole formation in strong rock contributes the increase in the bond strength of the grout.

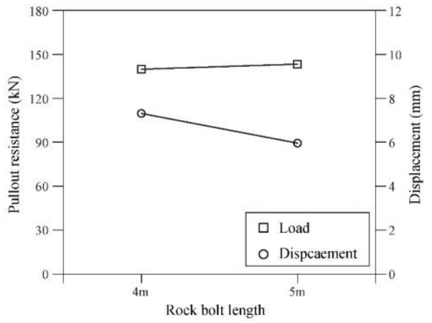
3.1.2 Effect of rock bolt length (FGR)

The effect of the rock bolt length on the pullout behavior was investigated with the FGR with a length of 3~5 m in moderate rock and soft rock. Fig. 9 shows the relationship between the pullout load and the displacement for different rock bolt lengths. In moderate and soft rock, the slope of the load-displacement curve increased with a decrease in the rock bolt length; however, the pullout resistance decreased. That is, an increase in rock bolt length resulted in a slight increase in yield load and an increase in the pullout resistance.

Fig. 10 shows the average pullout resistance and displacement at yielding for the length of rock bolt. The



(a) Moderate rock



(b) Soft rock

Fig. 10 Effect of rock bolt length

pullout resistance increased by 2~2.5% when the rock bolt length increased from 4 m to 5 m. An increase in the rock bolt length caused a slight increase in the total anchoring force and consequently the pullout resistance. This tendency was observed in both moderate rock and soft rock.

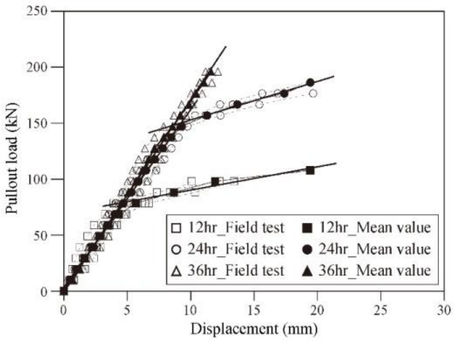
3.1.3 Effect of curing time (FGR)

The influence of the grout curing time on the pullout behavior of the rock bolt was investigated for moderate rock and weathered rock. A 4 m rock bolt was used for moderate rock and 5 m rock bolt was used for weathered rock. Cement mortar was used as a grout. The curing times for the pullout test were set at 12 hr, 24 hr, and 36 hr. The test was carried out at 3 and 5 locations for moderate rock and weathered rock, respectively.

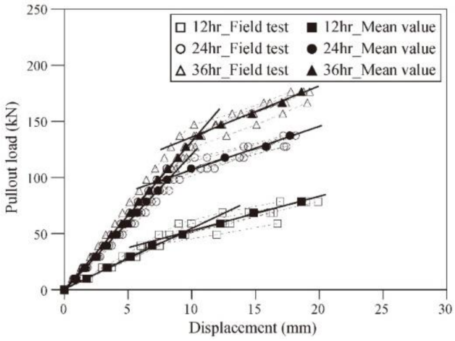
The pullout load-displacement relationships for different curing times are shown in Fig. 11. Although the pullout resistance considerably increased, the slopes of the load-displacement curves did not show any significant difference among the curing times. In the weathered rock condition, a shorter curing time resulted in a smaller gradient in the load-displacement curves.

The pullout resistance, as shown in Fig. 12, increased with an increase in curing time. The pullout resistance was 79.24 kN at 12 hr and 150.27 kN at 24 hr under moderate rock conditions. In the case of 36 hr, the pullout resistance was not determined due to high resistance, so the yield point of the rock bolt (173.4 kN) was taken as the pullout resistance according to ASTM D4435-13e1 (2013). When the curing time was increased from 12 hr to 36 hr, the pullout resistance increased by 218.39%. Under weathered rocks, the pullout resistance increased by 275.15%.

The results of the curing time test confirmed that the required pullout resistance can be obtained after at least 24 hr, regardless of the rock type. Therefore, using the FGR

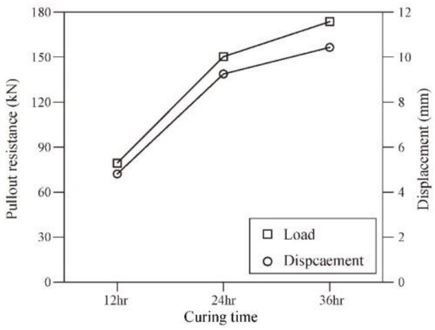


(a) Moderate rock

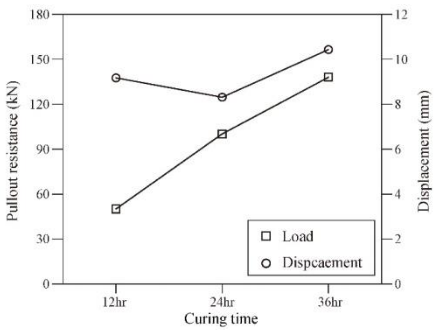


(b) Weathered rock

Fig. 11 Pullout load-displacement curves for curing time



(a) Moderate rock



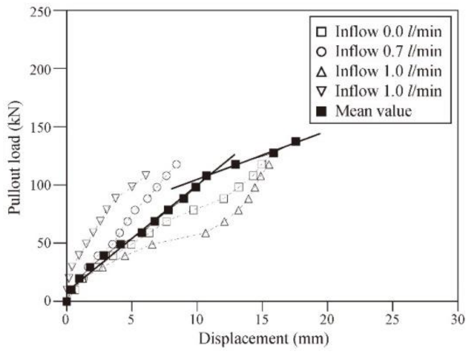
(b) Weathered rock

Fig. 12 Rock bolt pullout resistance according to curing time

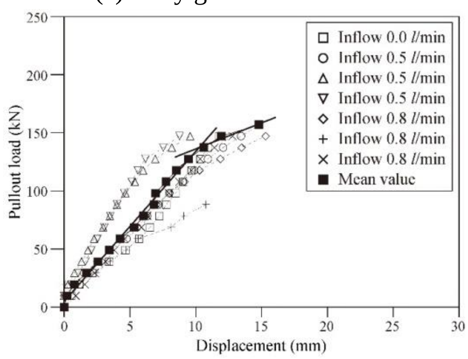
may be insufficient when a tunnel needs early stabilization after excavation.

3.2 Behavior of rock bolts in water-bearing rock

The effect of groundwater inflow into the borehole was



(a) Fully grouted rock bolt



(b) Inflated steel tube rock bolt

Fig. 13 Pullout load-displacement curves in a small water leaking section

investigated by carrying out the pullout tests on the FGR and ISR that do not require adhesives. For soft rock and weathered rock with a groundwater inflow of 0~3.78 l/min, rock bolts with a length of 4 m were tested. The test sections were divided into two groups, one section having slight leaking of groundwater and the other having significant leaking of groundwater, based on the inflow rate of 1.0 l/min.

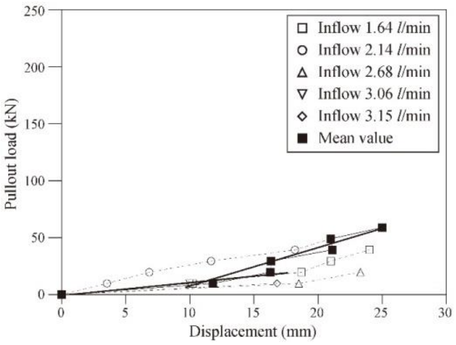
3.2.1 Pullout behavior of the rock bolt in a small water leaking rock

The test was carried out at 4 and 7 locations for the FGR and ISR, respectively. A rock bolt with a length of 4 m was tested in the soft rock conditions with an inflow rate of less than 1.0 l/min. The FGR was tested 24 hours after cement mortar injection to exert sufficient bond resistance between the rebar and the borehole.

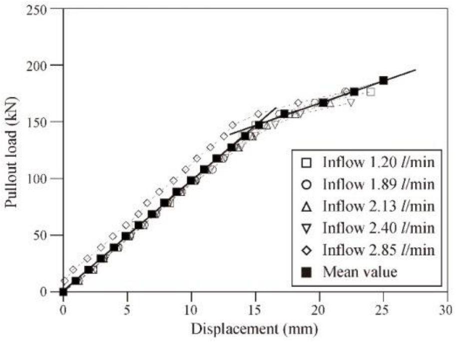
Similar to the test results shown in Fig. 13, the pullout load-displacement behavior of the FGR varies irregularly with leaking amount. In contrast, the results of the ISR showed that the inflection point of the pullout load-displacement curve was relatively obvious and constant in comparison with those of the FSR. The pullout resistance of the ISR was 125.96% higher than that of the FGR in the small leaking condition.

3.2.2 Pullout behavior of the rock bolt in a large water leaking rock

The pullout tests were performed at 5 locations. Both the FGR and the ISR with a length of 4 m were tested under weathered rock conditions, the leaking amount of which is over 1.0 l/min The FGR tests were performed at five sites

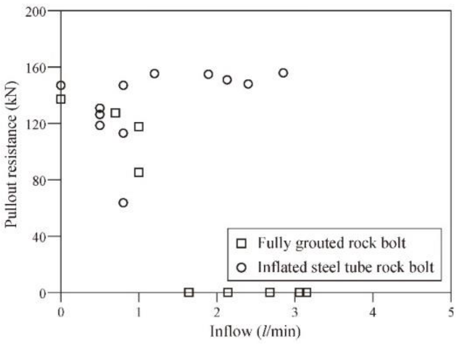


(a) Fully grouted rock bolt

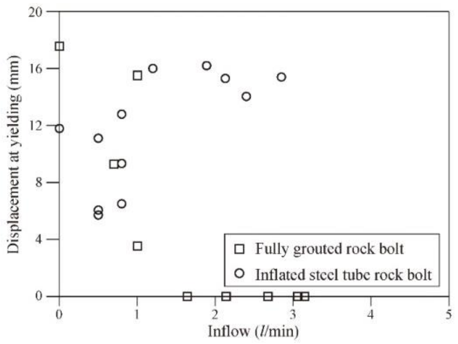


(b) Inflated steel tube rock bolt

Fig. 14 Pullout load-displacement curves in a large water leaking section



(a) Inflow-pullout resistance



(b) Inflow-displacement

Fig. 15 Rock bolt pullout test results according to amount of leaking groundwater

under conditions in which the leaking amount ranged from 1.64 to 3.15 *l/min* as shown in Fig. 14(a). In four of the five sites, rock bolts were pulled out before the yielding occurred, and consequently the pullout resistance could not be determined. Even in the case of the one successful test, the pullout resistance was only 12.01 kN, which is very low. On the other hand, as shown in Fig. 14(b), the pullout loads of the ISR tests were considerable pullout load, even with a leaking amount of 1.2~2.85 *l/min*. The average pullout resistance of the ISR in the large leaking condition was 146.63 kN, which is more than 100% of that of the FGR.

As shown in Fig. 15, the pullout resistance in water-bearing rock was greater than 80 kN for the FGR and more than 120 kN for the ISR. In the large leaking condition with water inflow greater than 1.0 *l/min*, the FGR was pulled out before yielding occurred, while the pullout resistance of the ISR showed no dependency on the leaking amount. Taking into account the rock bolt pullout behavior in the water-bearing condition, the FGR showed a decrease in the pullout resistance as the groundwater inflow increased. In particular, the adhesion of the FGR could be completely lost due to the large amount of leaking groundwater, whereas the ISR showed a negligible effect of groundwater leakage on pullout resistance.

Field test results showed that both grouted rock bolts and inflated rock bolts exert pullout load under low water flow rate. However, grouted rock bolt was not able to exert a pullout load under high water inflow rate. On the other hand, the inflated rock bolt showed high pullout load and high applicability in the water section.

4. Effect of rock bolt failure on tunnel stability

The lack of anchoring capacity of a rock bolt can threaten the stability of a tunnel. A numerical analysis was performed to investigate the effect of the rock bolt pullout resistance on the tunnel stability.

Fig. 16 shows the most common type of tunnel cross section in the test section. A system of rock bolts was adopted. In the FGRs shown in the area marked ‘A’ (between the shoulder and the side wall), it is assumed that the anchoring capacity was depleted in the water-bearing condition, and their function was thus lost. The failure of the FGR in the water-bearing section means that pullout resistance cannot be mobilized appropriately. Therefore, the FGRs in the area ‘A’ were replaced with the ISRs. These two cases are thus analyzed and the results are compared.

Tunnel stability is evaluated in terms of the shotcrete stress and axial force of the rock bolt. They are presented and compared in Fig. 17. The shotcrete bending stress was 2.93 MPa and 2.95 MPa in the case where the rock bolt no longer functioned (FGR) (therefore, its axial force is almost zero), and in the case where the rock bolt functioned properly (ISR), respectively. The shotcrete stress was considerably less than the allowable stress of 8.4 MPa, and no significant difference was shown between the two cases. This indicates that the effect of the rock bolt imperfection on the overall tunnel stability was not significant. Although the results reflect the limits of the numerical modeling method, they support the general understanding that the role of the rock bolt as a tunnel support is relatively small.

However, the axial force of the FGR and ISR was about 0.0 and 11.45 kN, respectively. The difference in the axial force is considerable, which means that, although the

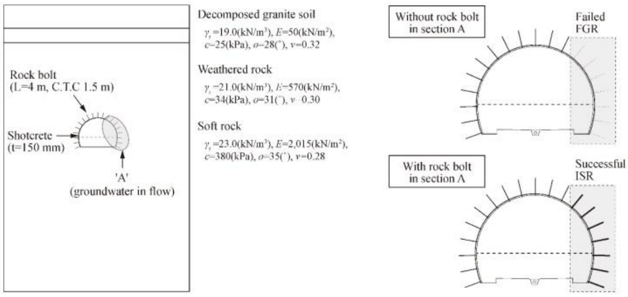


Fig. 16 Modeling of rock bolt failure case

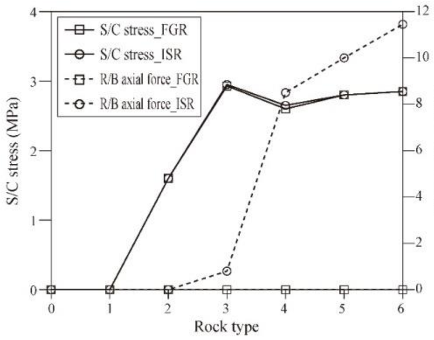


Fig. 17 Rock bolt partial loss of effect

contribution of the rock bolt to the tunnel stability is not significant, the local reinforcement of the jointed-rock mass is still effective. In other words, the pullout resistance of the rock bolt reduces the possibility of local collapses of rocks by combining the rock joints, thus the importance of the rock bolt cannot be overlooked, regardless of the overall stability.

In the case of the FGR in the water-bearing rock, obtaining the sufficient pullout resistance is difficult because the grout adhesion cannot be effectively obtained. Therefore, it is necessary to adopt the appropriate type of rock bolt and manage the construction to introduce the proper pullout resistance in the water-bearing condition. In particular, it might be possible to select a method that does not result in a decrease in the anchoring force due to water leaking. If the FGR is used in a section with a flow rate of more than 1.0 *l*/*min*, a separate water drain pipe would need to be installed.

5. Conclusions

In this study, a field rock bolt pullout test was performed at a tunnel and the anchoring characteristics of rock bolts were investigated. Pullout resistance was evaluated by considering the rock type, rock bolt length, curing time, and presence of water-leaking.

In dry rock condition, a sufficient pullout resistance could be obtained using the adhesive such as cement mortar. Pullout resistance increases as the rock stiffness increases and as the rock bolt length increases. The curing time of the grout was more than 24 hr to mobilize the required pullout resistance. The FGR was found to have increased the rock stiffness with an increase in the rock bolt length and with a curing time of 24 hours or more.

In the water-bearing rock condition, the pullout resistance was dependent on the rate of grout water inflow. Both the FGR and the ISR showed sufficient pullout resistance under the water inflow rate of less than 1.0 *l*/*min*. Under the water-bearing rock, of which the inflow rate is 1.0 *l*/*min* or more, the FGR failed to provide adequate anchoring force. On the other hand, the ISR exhibited the required pullout resistance. Therefore, a specified construction management of the rock bolt is required to obtain required rock bolt resistance in water-bearing rocks.

The result of numerical analysis showed that the effect of rock bolt imperfection on the tunnel stability was not significant. However as the local reinforcement of the jointed-rock mass is still effective, the pullout resistance of the rock bolt reduces the possibility of local collapses of rocks by combining the rock joints. Thus the importance of the rock bolt cannot be overlooked, regardless of the overall stability.

Acknowledgements

This preparation of this paper was supported by Konkuk University in 2017.

References

ASTM D4435-13e1. (2013), *Standard Test Method for Rock Bolt Anchor Pull Test*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Cai, Y., Esaki, T. and Jiang, Y. (2004), “An analytical model to predict axial load in grouted rock bolt for soft rock tunneling”, *Tunn. Undergr. Sp. Technol.*, **19**(6), 607-618.

Carranza-Torres, C. and Fairhurst, C. (2000), “Application of the convergence-confinement method of tunnel design to rock masses that satisfy the Hoek-Brown failure criterion”, *Tunn. Undergr. Sp. Technol.*, **15**(2), 187-213.

Farmer, I.W. (1975), “Stress distribution along a resin grouted rock anchor”, *J. Rock Mech. Min. Sci. Geomech. Abstr.*, **12**(11), 347-351.

Huang, M., Xu, C.S., Zhan, J.W. and Wang, J.B. (2017), “Comparative study on dynamic properties of argillaceous siltstone and its grouting-reinforced body”, *Geomech. Eng.*, **13**(2), 333-352.

Hyett, A.J., Moosavi, M. and Bawden, W.F. (1996), “Load distribution along fully grouted bolts, with emphasis on cable bolt reinforcement”, *J. Numer. Anal. Meth. Geomech.*, **20**(7), 517-544.

Jalalifar, H. (2006), “A new approach in determining the load transfer mechanism in fully grouted bolts”, Ph.D Dissertation, University of Wollongong, New South Wales, Australia.

Jia, P. and Tang, C.A. (2008), “Numerical study on failure mechanism of tunnel in jointed rock mass”, *Tunn. Undergr. Sp. Technol.*, **23**(5), 500-507.

Jiang, S.H., Li, D.Q., Zhang, L.M. and Zhou, C.B. (2014), “Time-dependent system reliability of anchored rock slopes considering rock bolt corrosion effect”, *Eng. Geol.*, **175**, 1-8.

Khan, A.J., Mostofa, G. and Jadid, R. (2017), “Pullout resistance of concrete anchor block embedded in cohesionless soil”, *Geomech. Eng.*, **12**(4), 675-688.

Kilic, A., Yasar, E. and Celik, A.G. (2002), “Effect of grout properties on the pull-out load capacity of fully grouted rock bolt”, *Tunn. Undergr. Sp. Technol.*, **17**(4): 355-362.

Kristjánsson, G. (2014), "Rock bolting and pull out test on rebar bolts," Master Dissertation, Institutt for Geologi og Bergteknikk, Trondheim, Norway.

KTA. (2014a), *A Study on the Rock Bolt Installation and its Effect on the Tunnel Stability in Water-Bearing Rock*, Korean Tunnelling and Underground Space Association (KTA), Seoul, Korea.

KTA. (2014b), *A Study on Proper Rock Bolt Installation Method in the High Speed Railway Tunnel*, Korean Tunnelling and Underground Space Association (KTA), Seoul, Korea.

Li, C. and Håkansson, U. (1999), "Performance of the Swellex bolt in hard and soft rocks", *Proceedings of the International Conference on Rock Support and Reinforcement Practice in Mining*, Kalgoorlie, Australia, March

Li, C. and Stillborg, B. (1999), "Analytical models for rock bolts", *J. Rock Mech. Min. Sci.*, **36**(8), 1013-1029.

Li, C.C. (2016), "Analysis of inflatable rock bolts", *Rock Mech. Rock Eng.*, **49**(1), 273-289.

Li, Y., Luo, R., Zhang, Q., Xiao, G., Zhou, L. and Zhang, Y. (2017), "Model test and numerical simulation on the bearing mechanism of tunnel-type anchorage", *Geomech. Eng.*, **12**(1), 139-160.

Malhotra, V.M., and Carino, N.J. (2003), *Handbook on Nondestructive Testing of Concrete Second Edition*, CRC Press, Boca Raton, Florida, USA.

Merifield, R.S. and Smith, C.C. (2010), "The ultimate uplift capacity of multi-plate strip anchors in undrained clay", *Comput. Geotech.*, **37**(4), 504-514.

Oreste, P. (1994), "Comportamento di bulloni passivi in galleria: Un nuovo modello di simulazione", *Gallerie e Grandi Opere Sotterranee*, 32-41.

Oreste, P.P. (2003), "Analysis of structural interaction in tunnels using the covergence-confinement approach", *Tunn. Undergr. Sp. Technol.*, **18**(4), 347-363.

Osgoui, R.R. and Ünal, E. (2009), "An empirical method for design of grouted bolts in rock tunnels based on the Geological Strength Index (GSI)", *Eng. Geol.*, **107**(3), 154-166.

Vu, K.A.T. and Stewart, M.G. (2000), "Structural reliability of concrete bridges including improved chloride-induced corrosion models", *Struct. Saf.*, **22**(4), 313-333.

Wijk, G. and Skogberg, B. (1982), "The inflatable rock bolting system", *Proceedings of the 14th Canadian Rock Mechanics Symposium. Canadian Institute of Mining and Metallurgy*, Vancouver, British Columbia, Canada, May.

Zhang, C.C., Xu, Q., Zhu, H.H., Shi, B. and Yin, J.H. (2014), "Evaluations of load-deformation behavior of soil nail using hyperbolic pullout model", *Geomech. Eng.*, **6**(3), 277-292.

Zhu, C., Chang, X., Men, Y. and Luo, X. (2015), "Modeling of grout crack of rockbolt grouted system", *J. Min. Sci. Tech.*, **25**(1), 73-77.

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