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Shear strength behaviors of grouts under the blasting induced vibrations

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Abstract. Umbrella Arch Method (UAM) often employed in the tunnel construction under poor rock mass conditions in Korea. Insertion of steel pipes at the periphery of the tunnel and infiltration of grouts along the pipes into the rock masses increases tunnel stability. There are two major effects of grouts expected at the tunnel face: 1) increase of face stability by enhancing the frictional resistance of discontinuities and 2) decrease of permeability along the rock masses. Increase of resistance and decrease of permeability requires a certain curing time for the grout. In Korea, we require 24 hours for curing of grout, which means no progress of excavation for 24 hours after infiltration of grouts. This step delays the tunnel construction sequences. To eliminate such inefficiency, we propose MTG (Method for Tunnel construction using Grouting technology), which uses extended length of steel pipes (14 m) compared to conventional pipe roof method (12 m). The merit of MTG is the reduction of curing time. Because of the approximately 2 m extension of the length of steel pipe, blasting can be done after infiltration of grouting. For this paper, we conducted experiments on the shear strength behaviors of grout infilled rock joint with elapsing of curing time and blasting induced vibration. The results show that blasting induced vibration under MTG does not influence the mechanical features of grout material, which indicates no influence on the mechanical behaviors of grout, contributing to the stability of tunnels during excavation. This result indicates that MTG is a cost effective and fast construction method for tunneling in Korea.

Keywords: umbrella arch method (UAM); method for tunnel construction using grouting technology (MTG); grouting; tunnel reinforcement

1. Introduction

The umbrella arch method (UAM) often employed in tunnel construction in Korea under poor rock mass or soil conditions. UAM is a supplementary reinforcement method for the drilling and blasting. The purpose of UAM is to increase the stiffness of the ground and decrease the permeability of the rock and soil masses. According to Korea Construction Specification (KCS 27 50 15 : 2016), ground conditions for application of UAM are 1) where rock cover at the crown is shallow or soft, such that wide reinforcement of the rock cover is required, and 2) where deterioration of structures near the excavation is expected. Selected UAM is based not only on ground conditions but also on the following factors: cost, allowable deformation, rock and soil qualities, etc. (Ocak and Selcuk 2017).

Korea practice of UAM employs two different diameters of steel pipes The features of UMA in Korea can be found in Table 1. The features of large diameter UAM are as follows: diameter of the steel 125~150 mm, length of steel 12 m, overlapped interval of steel pipes 6 m, and cross-sectional interval of steel pipes 0.5 m, and inclination angle of steel pipes about 10° at tunnel. Conventional design practice can be found in Fig. 1. According to the Korea Construction Standard (KCS 27 50 15 : 2016), several requirements are specified: 1) one end of steel pipe must be supported by steel set, 2) longitudinal insertion angle of the steel pipe is less than 20°, 3) the overlapped length of the steel pipe is less than 6 m, 4) grout can be injected one or several times, 5) construction details such as type of grout, mixing ratio, injection pressure, volume and injection speed must be recorded

Likewise, UAM, with use of steel pipe and grout, is an

Table 1 Features of UAM in Korea

	Classification	Small diameter UAM	Large diameter UAM
Drilling	Diameter (mm)	100	125~150
	Length (m)	12~16	12
	Inclination angle (°)	at portal, 2~3° at tunnel, 10~15°	at portal, below 5° at tunnel, below 5~15°
	Drilling interval (m)	0.5	0.4~0.5
Steel pipes	Outer diameter (mm)	60.4	114
	Thickness (mm)	4	6.0~8.5
	Length (m)	6	6
	Injection hole interval (m)	0.5~0.75	0.5~1.0
	Injection hole diameter (m)	5	10~12
	Number of injection hole per steel pipe	4	4

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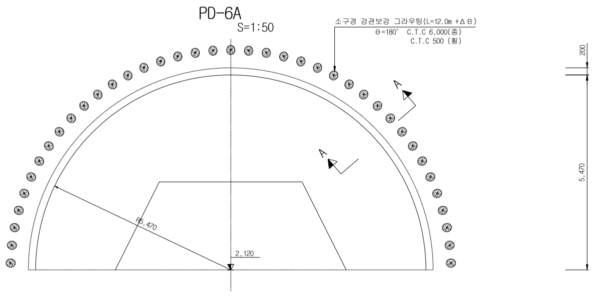


Fig. 1 Design practice of UAM

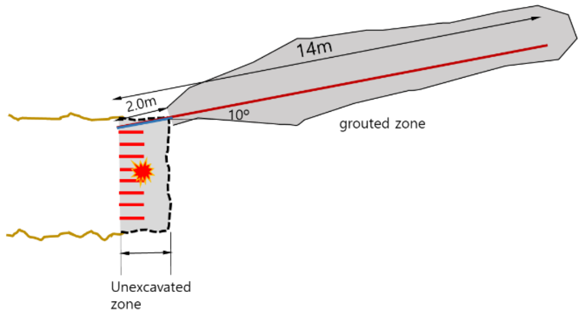


Fig. 2 Cross-sectional view of MTG

Table 2 Features of UAM in Korea

	MTG	UAM
Drilling length (m)	14	12
Grout curing time after blasting (h)	6, 18	24
Construction sequence	Insertion of steel pipes → grout → drilling → blasting (6 hours after grout) → removal of blasted rocks→ drilling → blasting (18 hours after grout)	Insertion of steel pipes → grout → drilling → blasting (24 hours after grout)

effective reinforcement method for tunnel face. The merits of two different materials can be utilized. However, one demerit is required curing time for the grout. According to Expressway Construction Specification EXCS 27 50 15 (2016), after injection of the grout, 24 hours of curing time is required. Therefore, sequential blasting is prohibited for 24 hours for the curing purpose of grout. To eliminate such demerit, MTG (Method for Tunnel construction using Grouting technology) is proposed.

MTG uses 14 m long hybrid steel pipe, instead of the normal 12 m long steel pipe that has been used in conventional UAM (See Fig. 2). Hybrid steel pipe consists of 12 m long steel pipe and 2 m long plastic pipe. Since there exists a 2 m length unexcavated zone, the zone functions as large reinforcement against tunnel instability.

The difference between MTG and UAM can be found in Table 2. The construction sequence of UAM is 1) insertion of steel pipes, 2) grouting, 3) drilling for blasting 4) blasting (can be done 24 hours after grouting). The sequence of MTG is 1) insertion of steel pipes, 2) grouting, 3) drilling, 4) blasting (can be done 6 hours after grouting). As mentioned previously, since in MTG it is possible to conduct blasting 6 hours after grouting, this technology is cost effective compared to UAM. However, questions must be raised about the influence of blasting on the mechanical properties of grout, such as the frictional resistance of grout infilled rock joint and unconfined compressive strength. Therefore, this paper focuses on the effects of blasting on the grout material in aspects of joint frictional resistance with time and blasting induced vibration.

2. Features of grouting in previous studies

Effects of grouting against soil ground or rock fracture has been extensively conducted (Aflaki and Moodi 2017, Lee *et al.* 2017, Zhang *et al.* 2017, Jin *et al.* 2018, Celik 2019, Li *et al.* 2019) and special grouting technologies such as bio grouting (Kim and Park 2017). However, effects of grouting on shear behaviors of rock joint and tunnel reinforcement have been seldomly studied (Salimian *et al.* 2017). The laboratory study shows that grouting shows positive effects on the shear strength, compressive strength, friction angle and cohesion. Increase of rock mass properties including reduction of permeability can be also found in field experiments (Zolfaghari *et al.* 2015, Paulatto and Carstensen 2017). Especially at the underground construction site, grouting is often adapted with reinforcement such as rock bolt. Therefore bolt-grouting is an effective way of securing a tunnel face stability. Wang *et al.* (2020) shows a theoretical approach to evaluate the interface shear strength before and after grouting. Stjern and Myrvang (1998) shows influence of blasting on grouted rock bolt. They conducted field and laboratory experiments to evaluate the performance of grouted rock bolt near the blasting. The range of the vibration was from 1,000 mm/sec to 100mm/sec and the blast impact did not effectively influence on the anchorage capacity of rock bolts. In addition, increase of the capacity was found with the elapse of curing time.

Grouting process is quite complicated and complex in the aspect of phase change of the grout mixture and separation of the ingredients. Water/cement ratio, chemical characteristics of the ingredients, gel time, grouting pressure and volume can influence on the mechanical and hydraulic features of grout infilled rock masses. Some features of grout and cement-based sealant properties can be found from Sagong *et al.* (2018), Zhang *et al.* (2017). They showed the numerical and experimental approaches on the grouting mechanism with variation of viscosity and space. Again grouting is complex process which undergoes hydro-mechanical variation of grout material. Therefore, there is few study on the features of grout in consideration of construction sequence, especially for a tunnel construction. In this study we will consider the distance and amount of charge to calculate the blasting induced vibration and reproduce the calculated vibration on the rock specimens to evaluated the effects of vibration on the shear strength of grout infilled rock specimens.

3. Structural reliability analysis

In this paper, a comparison of the mechanical properties

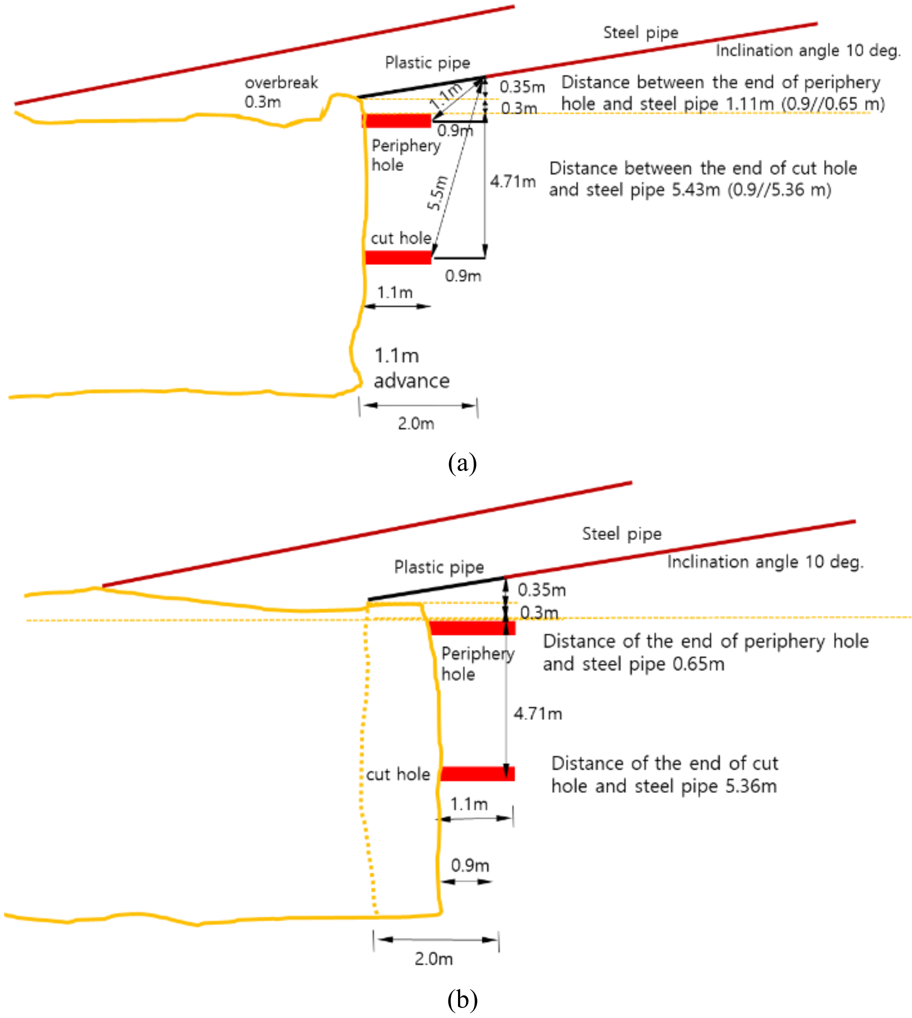


Fig. 3 Excavation sequence of MTG applied tunnel (a)1st step and (b) 2nd step for 2.2 m advancement

Table 3 Calculated distance and amount of charge

	1st blasting		2nd blasting	
	Periphery hole	Cut hole	Periphery hole	Cut hole
Minimum distance between borehole and steel pipe (m)	1.1	5.5	0.65	5.36
Borehole length (m)	1.1			
Amount of charge (kg)	0.35	0.5	0.35	0.5

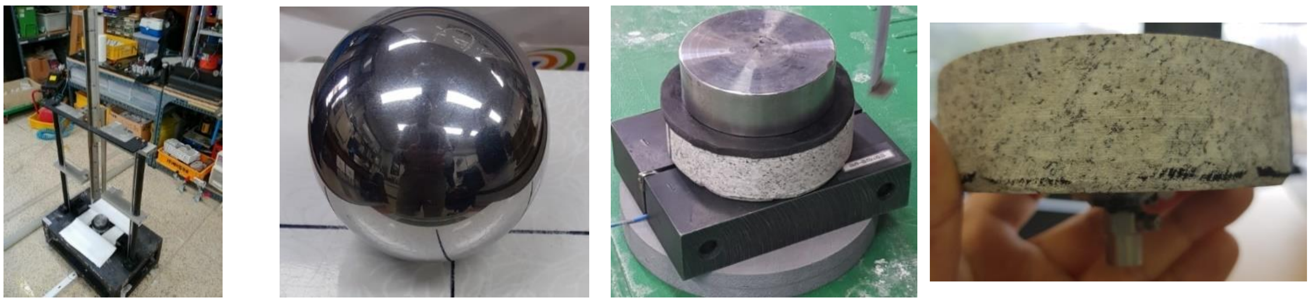
Table 4 Blasting induced vibration models

Models	Equations	Parameters
Langfors and Kihstrom (1968)	$v = K\dfrac{W^a}{D^b}$	W: maximum charge per delay, D: distance from the blast site, K, a, b are site specific parameters(K : 0.7m/s, a : 0.7, b: 1.4)
Persson (1994)	$v = K\left(\dfrac{W}{r_0}\right)\left[arctan\left(\dfrac{H + x_b - x_0}{r_0}\right) + arctan\left(\dfrac{x_0 - x_b}{r_0}\right)\right]^a$	W: linear charge concentration (kg/m), H: charge hole length, r_0, x_b, x0 : geometric parameters
Kumar *et al.* (2016)	$v = \dfrac{(0.59476RQD + 0.00893RQD^2)^{0.642}D^{-1.463}}{\gamma}$	When RQD<75, γ: unit weight, D: scaled distance (m/kg$^{0.5}$)

of grout is conducted between MTG and conventional UAM. In the MTG construction sequence, 1.1 m length of excavation is assumed per excavation cycle. Two steps of blasting are assumed; and the vibration is calculated at each step and at the nearest point of steel pipe. The blasting sequence and the points of interest are shown in Fig. 3.

Table 5 Blasting induced vibration under MTG

		1st vibration		2nd vibration		Remarks
		Periphery hole	Cut hole	Periphery hole	Cut hole	
Minimum distance between blasting point and steel pipe		1.1	5.5	0.65	5.36	
Drill length (m)		1.1				
Charge (kg)		0.35	0.5	0.35	0.5	
Peak particle velocity (mm/sec)	Langfors & Kihstrom (1968)	293.8	39.6	**613.6**	41.1	
	Persson (1994)	**297.6**	42.4	574.7	43.8	
	Kumar *et al.* (2016)	93.7	11.5	202.2	12.0	Assumed RQD = 20
Peak particle acceleration (g)	Langfors & Kihstrom (1968)	94.2	12.7	**196.7**	13.2	
	Persson (1994)	**95.4**	13.5	184.2	14.0	
	Kumar *et al.* (2016)	28.6	3.5	61.7	3.7	



(a) (b) (c) (d)

Fig. 4 Weight release system to reproduce the blasting induced vibration (a) Drop Table, (b) Steel ball, (c) Upper and bottom covers and (d) Accelerometer attached at the bottom of the rock specimen

During 2.2 m advancement, two steps of blasting are conducted. For each sequence, the gaps between blasting hole and the nearest points of steel pipe are calculated. The calculated distance and the amount of charge is summarized at Table 3.

With the amount of charge and the charge distance, blasting induced vibration was calculated using the three models of Langfors and Kihstrom (1968), Persson (1994), Kumar *et al.* (2016) (see Table 4). From the models, maximum amounts of vibration are calculated as shown in Table 5. From the calculation, the peak particle accelerations under MTG at the 1st and 2nd blasting are 95.4 g and 196.7 g and the peak particle acceleration under conventional UAM is about 580.6 g. The curing times of the grout of the 1st and 2nd blastings of MTG is about 6 and 18 hours and for UAM is 24 hours. To convert measured velocity to acceleration, we used following relation: $PPA = 2\pi f PPV$, where PPA : peak particle acceleration, PPV : peak particle velocity, f : frequency (adopted 500Hz in this study, as has been adopted in Bäuml and Sundqvist (2013)).

4. Direct shear test for grout infilled rock joints

4.1 Reproduction of blasting induced vibration using weight release system

The calculated blasting induced acceleration values are about 95.4 g and 196.7 g during the construction of MTG and maximum acceleration is 580.6 g for conventional UAM. Reproduction of these acceleration value is conducted using a weight release system as shown in Fig. 4(a). The 2.08 kg steel ball is dropped from a certain height to reproduce the accelerations (Fig. 4(b)). The ball hits the rock specimen and the induced vibration is measured at the other side of the rock specimen like in Fig. 4(c). To avoid the damage of the rock specimen and spread of impact energy of the steel ball, soft and hard covers are used as shown in Fig. 4(c). At the bottom of the specimen, 20.2 mm elastic rubber pad is used; a 31 mm steel pad and thin and soft rubber pad are used at the top of the specimen. The acceleration is measured using an accelerometer attached to the bottom of the specimen (see Fig. 4(d))

Several drops at the different height were conducted and the accelerations are measured. The correlation is made to decide the required accelerations at the specific height. The measured acceleration wave profiles at different height can be found in Fig. 6; a summary of details can be found in Table 6. From the results, the derived correlation between the height and the acceleration is as follows: $y = 22.1x - 61.4$, where x is the height and y is the measured acceleration. From the correlation, the required height for accelerations of 95.4 g, 196.7 g, and 580.6 g are 7.1 cm,

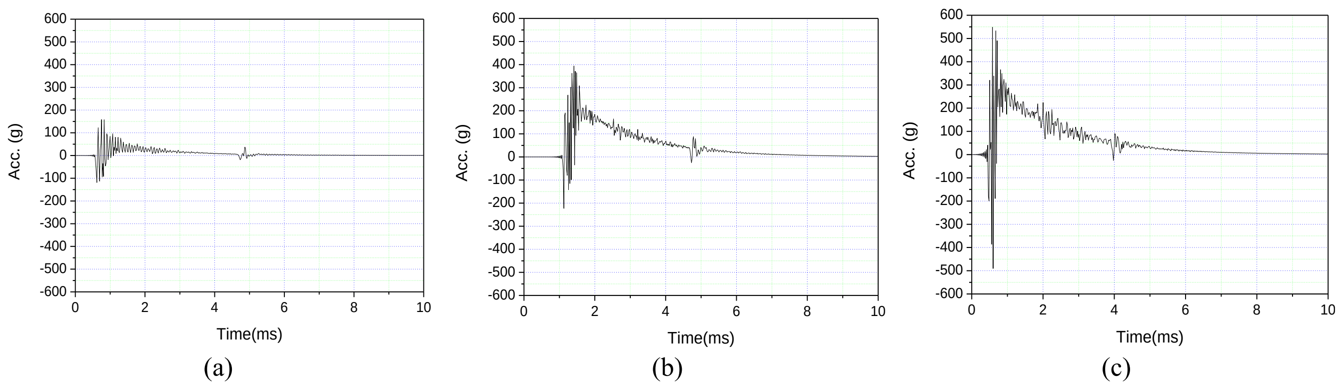


Fig. 6 Acceleration wave profile at the different heights (a) height of 10 cm, (b) height of 20 cm and (c) height of 30 cm

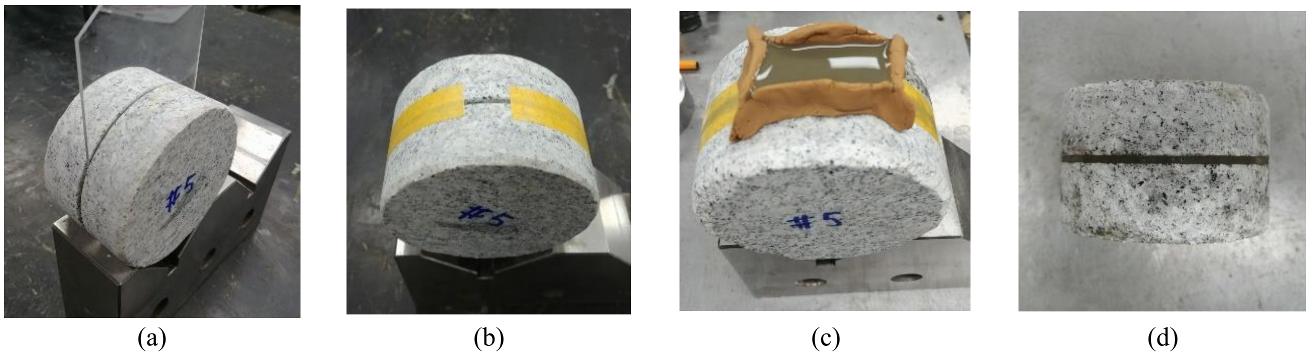


Fig. 7 Preparation of rock specimen with grout infilled (a) securing a space for grout, (b) wrapping the perimeter of the specimens, (c) building the clay inlet for allowing grout mixture infiltration and (d) removal of clay inlet and curing

11.6 cm, and 29.0 cm, respectively.

4.2 Preparation of the specimens for grout infilled direct shear tests

One of the purposes of this study is to identify the effects of blasting induced vibration on rock joint with grout infilled. To evaluate the influence on the grout infilled rock joint, rock joint shear behaviors were tested with different level of vibration on the specimens. We prepared specimens for direct shear tests with grout infilled rock specimen. The process of the preparation of the specimen is as follows.

Disc type cored rock specimens were prepared. The thickness of the specimen was about 30 mm and the diameter of the specimen is about 100 mm. The surface was ground with #100 grit. A pair of rock disc is used for the test.

Grout was carefully infiltrated. The composition of the grout is shown in Table 7. We use sodium silicate as an accelerating agent for the test. Typically, in the field, mixtures of cement and water are often used. However, near the end of the grout, grout with accelerating agent is often used in Korea for rapid solidification of the borehole. During the time of interest in this paper, the cement and water mixture would not normally show any cementation. Therefore, considering the field condition, a mixture of water, cement and sodium silicate was used.

The preparation of rock specimen with grout infilled followed several steps. 1) a pair of rock specimens was prepared and 2 mm thickness of acrylic plate was inserted to leave the space for grout, 2) paper tape was used to wrap the perimeter of the rock specimen to contain the liquid grout mixtures, 3) a temporary clay inlet is built to host grout mixture overflow, 4) curing of grout and removal of clay inlet, 5) drop of steel balls to induced the vibrations. This process can be seen in Fig. 7

Table 7 Composition of grout per batch

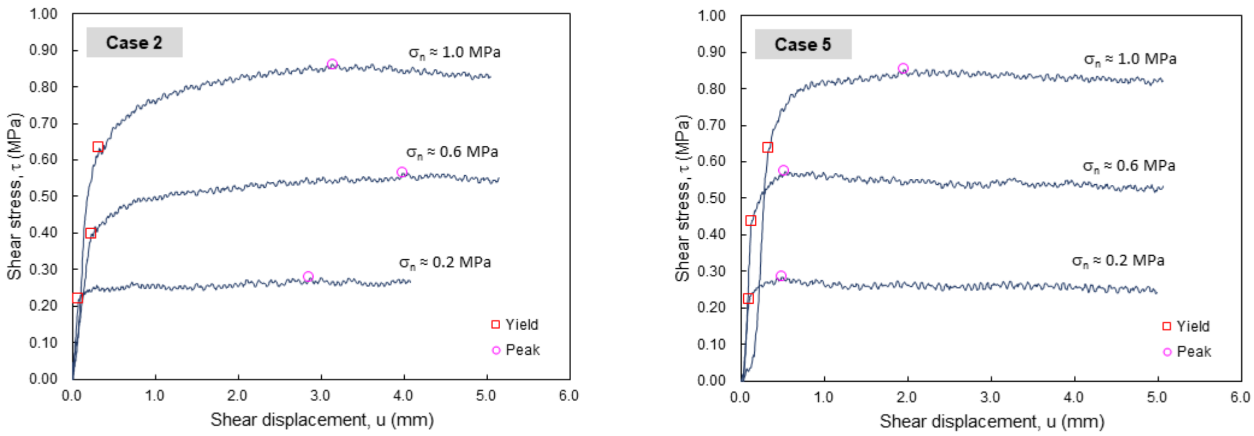
1 Batch Volume (ℓ)	A Liquid		B Liquid	
	Sodium Silicate (ℓ)	Water (ℓ)	Cement (kg)	Water (ℓ)
400ℓ	100	100	100	168

Table 8 Rock joint shear test conditions

Test cases	Conditions
Case 1	Rock joint without grout
Case 2	Rock joint with grout of 24 hours of curing after vibration of 580.6 g
Case 3	Rock joint with grout of 6 hours of curing without vibration
Case 4	Rock joint with grout of 6 hours of curing after vibration of 95.4 g
Case 5	Rock joint with grout of 18 hours of curing after vibration of 95.4 g at 6 hours and 196.7 g at 18 hours

4.3 Shear resistance behaviors of rock joint with grout infilled

In this paper 5 different cases of rock joint shear tests were conducted. The conditions for the test are summarized



(a) (b)

Fig. 8 Shear displacement and stress curves for cases 2 and 5 (a) case 2 and (b) case 5

Table 9 Summary of the shear behaviors of grout infilled rock joint with different curing and vibration conditions

Cases	Yield values		Peak values	
Cases	Cohesion (MPa)	Internal friction angle (°)	Cohesion (MPa)	Internal friction angle (°)
Case 1			0.097	25.5
Case 2	0.107	27.1	0.132	35.0
Case 3	0.061	18.7	0.114	29.3
Case 4	0.062	20.6	0.115	30.7
Case 5	0.129	27.2	0.155	34.2

in Table 8. From the test shear displacement and shear stress are measured.

The measured shear displacement and stress of cases 2 and 5 are shown in Fig. 8, and summarized results are shown in Table 9.

A comparison needs to be made between MTG and conventional UAM, which are cases 4 and 5 (MTG) and case 2 (UAM). After a short period of curing (6 hours), the shear strength parameters are lower than the parameters from MTG. Approximately 13.6~16.3% drop of cohesion and internal friction angle can be found. This result shows the influence of vibration of the shear strength of rock joints. However, with increase of curing time (18 hours), cohesion increases about 17% and internal friction angle decreases about 2.3% compared to case 2 (UAM). No reduction of shear strength parameters is found. Therefore, compared to conventional UAM, blasting-induced vibration during MTG does not reduce the shear strength behavior of grout infilled rock joint.

5. Conclusions

In this paper, the effects of blasting induced vibration are evaluated from the aspects of shear strength under the condition of MTG and conventional UAM. MTG is a new approach to use extended hybrid reinforcing steel pipe. We tested grout infilled rock joint shear behaviors with blasting-induced vibration with 5 different cases. From the test, the blasting induced vibrations were found not to affect the shear strength of grout infilled rock joints. Interfacial shear strength of rock joint strongly depends upon the material features of grout material. Viscosity features of grout can sustain the vibration and maintain and develop the shear strength of grout. Apparently mobilized shear strength is function of the magnitude of vibration and the developed strength with curing time. We evaluated quite approximate blasting condition which often encounters at the tunnel construction site. Under such condition, no apparent deterioration of the shear strength can be found from rock joint shear tests. Furthermore, MTG has 2 m length of unexcavated zone, function as a core zone, compared to conventional UAM. Therefore, MTG has higher level of stability compared to conventional UAM.

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