Geomechanics and Engineering, *Vol. 18, No. 1 (2019) 59-69*
DOI: https://doi.org/10.12989/gae.2019.18.1.059

Groutability enhancement by oscillatory grout injection: Verification by field tests

Byung-Kyu Kim[a], In-Mo Lee[b], Tae-Hwan Kim[c] and Jee-Hee Jung*

School of Civil, Environmental and Architectural Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea

(Received January 15, 2019, Revised April 19, 2019, Accepted April 23, 2019)

Abstract. Grout injection is mainly used for permeability reduction and/or improvement of the ground by injecting grout material into pores, cracks, and joints in the ground. The oscillatory grout injection method was developed to enhance the grout penetration. In order to verify the level of enhancement of the grout, field grout injection tests, both static and oscillatory tests, were performed at three job sites. The enhancement in the permeability reduction and ground improvement effect was verified by performing a core boring, borehole image processing analysis, phenolphthalein test, scanning electron microscopy analysis, variable heat test, Lugeon test, standard penetration test, and an elastic wave test. The oscillatory grout injection increased the joint filling rate by 80% more and decreased the permeability coefficient by 33-68%, more compared to the static grout injection method. The constrained modulus of the jointed rock mass was increased by 50% more with oscillatory grout injection compared to the static grout injection, indicating that the oscillatory injection was more effective in enhancing the stiffness of the rock mass.

Keywords: oscillatory injection; rock joint grouting; artificial joint; field test

1. Introduction

The cement-based grouting method is most widely used for reducing permeability and/or improving the ground strength, which involves injecting grout material into pores and cracks of soils and joints of rock mass. The strength of the in-situ ground is improved and the permeability of the ground is reduced using this method.

In soil layers, as well as weathered or soft rock layers in which joints are well developed, permeation grouting is usually adopted among the possible grouting methods. However, as the cement-based permeation grouting uses cement-based suspension-type grout material, permeation through small pores and/or narrow joints is not feasible due to grout particle clogging phenomena.

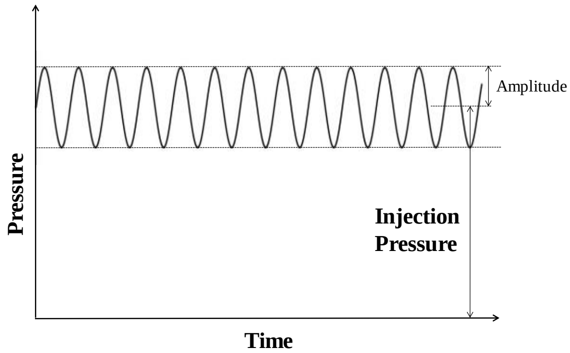
Many researchers have attempted to enhance the permeability of cement-based penetration grouting. Date *et al.* (2003) developed a dynamic grouting system, which used a pump to apply vibrations to grout materials to facilitate injection. Shin *et al.* (2012) devised a cylindrical vibrator and proposed an optimal condition producing high permeation efficiency based on the results of laboratory experiments. Mohammed *et al.* (2015) utilized a direct blow-type oscillatory injection pump to conduct an injection experiment on an artificial joint and showed that it improved the injection performance. The ultrasound was used to enhance the physical properties of cement grout (Shin *et al.* 2013, Poinot *et al.* 2013, Choi *et al.* 2016). Recently, Kim *et al.* (2018a) devised and manufactured an oscillatory injection pump in which the frequency and amplitude of steady-state vibration could be accurately controlled (Fig. 1(a)). They performed comprehensive laboratory-scale grout injection tests in order to assess the groutability enhancement effect based on the variation of injection pressure, oscillation frequency, and water-cement ratio (w/c ratio). The groutability enhancement was theoretically studied using clogging theory and they used the groutability criterion (GC) proposed by Kim *et al.* (2009) for the assessment. The groutability enhancement effect induced by the oscillatory grout injection, which was proven experimentally by Kim *et al.* (2018a), was also theoretically studied by utilizing and combining clogging theory with dynamic flow theory by Kim *et al.* (2018b).

Many researchers have conducted not only laboratory scale tests but also field tests to evaluate improvements of cement-based penetration grouting (Fattah *et al.* 2015, Chang *et al.* 2016, Gang *et al.* 2016). The current study is the extension of the studies by Kim *et al.* (2018a, b). Firstly, oscillatory grout injection tests were conducted on an artificial rock joint in this paper to verify the enhancement effect in rock joint grouting, while assessment of the enhancement effect of oscillatory grouting in soil grounds was the main topic of the previous studies (Kim *et al.*, 2018a, b). And secondly, field injection tests at three job sites were performed to verify the effectiveness of the oscillatory injection method in-situ. The authors performed various tests to verify the effectiveness of oscillatory

*Corresponding author, Ph.D. Candidate
E-mail: jeehee83@korea.ac.kr
[a]Post-Doctoral Researcher
E-mail: orbitm23@korea.ac.kr
[b]Professor
E-mail: inmolee@korea.ac.kr
[c]Ph.D. Candidate
E-mail: kth1226@korea.ac.kr

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


(a) Oscillatory injection pump



(b) Variation of injection pressure during oscillatory injection

Fig. 1 Oscillatory injection method

injection. A core boring, borehole image processing system (BIPS) analysis, phenolphthalein test, and scanning electron microscopy (SEM) analysis were performed to verify the degree of injection. A variable head test and a Lugeon test were conducted to verify the permeability reduction effect. A standard penetration test (SPT) and an elastic wave test were carried out to verify the ground improvement effect.

2. Grout injection test on an artificial rock joint

In order to investigate the groutability enhancement of a rock mass, the oscillatory grout injection test was performed on an artificially-manufactured rock joint in the laboratory.

2.1 Overview of the experiment

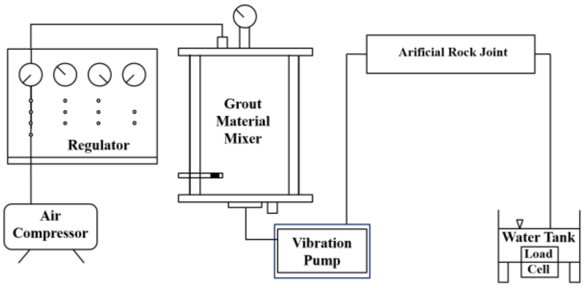
The fluid flow through a rock joint can be explained by the parallel plate model following the Navier-Stokes law (Batchelor 1967). The transmissivity (*T*) of a viscous fluid in a rock joint is proportional to wd^3, as follows

$$T \propto \frac{wd^3}{12} \tag{1}$$

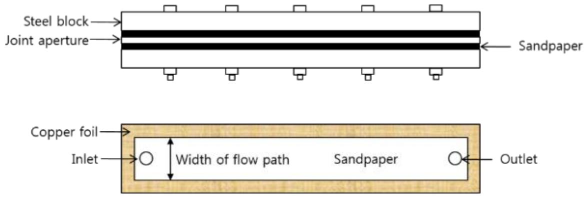
where w and d are the width and aperture of a joint, respectively. According to Eq. (1), the transmissivity is proportional to the cube of a joint aperture. This cubic law is used to explain the relationship between a joint aperture and transmissivity in most studies. However, the transmissivity of a real fluid flowing in a joint depends not only on the joint aperture, but also on the roughness of the joint surface and the viscosity of the fluid (Goodman 1976).

Permeation through a rock joint is not possible if the joint aperture is narrower than the threshold value, which is also a function of the particle size of the grout material (Byle and Borden 1995). Accordingly, when the grouting of a rock joint reaches an injection limit because of a narrow aperture of the rock joint (i.e., narrower than the threshold value of joint aperture), the particle size of the grout material should be reduced or the injection pressure increased to expand the aperture and facilitate the injection.

Instead of adjusting an injection pressure or grout material, this study assumed that the oscillatory injection method could overcome the injection limit. The experiments of this study aimed to prove this assumption in-situ. The static grout injection and the oscillatory grout injection tests were conducted on artificially-manufactured joints by varying the joint apertures. The injection volume and the threshold joint aperture enabling injection through the joint were obtained from these tests.



(a) Schematic diagram of the experimental setup



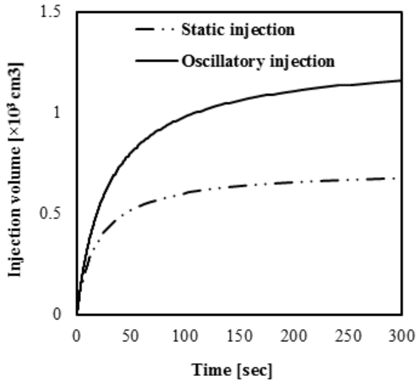
(b) Schematic diagram of the artificial rock joint


(c) View of the artificial rock joint

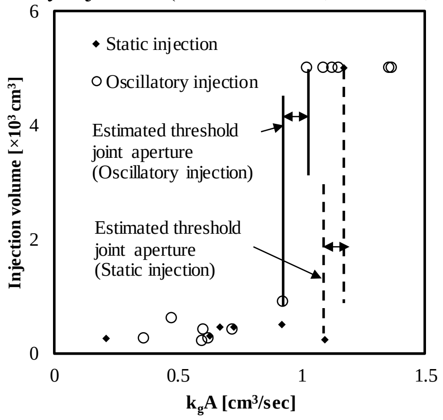
Fig. 2 Experimental setup of the artificial rock joint

2.2 Experimental setup and conditions

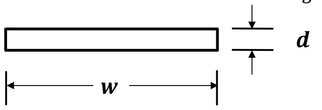
The experimental setup for grout testing on the artificial



(a) Comparison of results between the static injection and the oscillatory injection (Micro cement, w/c=1.0, 500 kPa)



(b) Injection volume according to k_gA value



$A = wd$

(c) Schematic view of rock joint aperture

Fig. 3 Experimental results of the artificial rock joint surface experiment

rock joint was similar to that for soil grounds, which was devised by Kim *et al.* (2018a). The only difference was that an artificial rock joint was used instead of a chamber to reproduce the ground (see Fig. 2(a)). As shown in Fig. 2(a), the experimental setup consisted of an air compressor, grout material mixer, vibration pump, artificial rock joint, and a water tank for measuring the discharge. As shown in Fig. 2(b), the artificial rock joint was fabricated by stacking two 3,000-mm long and 50-mm thick steel blocks, and inserting copper foil with a thickness of 0.1~0.2 mm between them. The artificial rock joint had a length of 3,000 mm and the width of flow path was 60 mm. Sand paper was attached to both sides of each steel block to simulate the joint roughness. Fig. 2(c) shows the artificial rock joint.

When the artificial rock joint was assembled, water was injected to saturate the joint surface and then the permeability coefficient of the artificial rock joint was measured. Then, the grout material was injected into the joint. The injection continued until the grout material completely permeated into the artificial rock joint or until no additional grout could be injected so that the discharge converged to a certain value. After the completion of the injection, the artificial rock joint was disassembled to check the degree of injection.

Micro cement with the fineness of 6,000 was used as the grout material with the w/c ratio of 1.0. The injection pressures applied in the experiment were 300, 500, and 700 kPa. The frequencies of 5, 7.5, 10, 12.5, and 15 Hz were applied.

2.3 Result of injection tests on the artificial rock joint

Fig. 3(a) presents the result of the injection experiment, where the grout material was injected into the artificial rock joint at a pressure of 500 kPa and frequency of 10 Hz. As shown in Fig. 3(a), in comparison with the static grout injection, the oscillatory grout injection almost doubled the injection volume. This result indicated that the oscillatory injection increases injection volumes, not only in soil grounds, but also in jointed rock masses. As mentioned in the previous section, the transmissivity of a rock joint is affected by both the characteristics of the grout materials and the joint roughness. Accordingly, the minimum aperture (threshold joint aperture) enabling injection into the joint also changes according to the characteristics of the joint surface (i.e. joint roughness) and grout materials. In other words, the injection volume is a function of joint aperture d and/or k_gA as follows

$$k_gA = k_gwd \tag{2}$$

where k_g is the permeability coefficient of the grout material, A is the cross-sectional area of the joint, w is the width of the flow path, and d is the aperture of the joint (see Fig. 3(c)).

Fig. 3(b) illustrates the experimental results of injection volumes versus k_gA values. As shown in Fig. 3(b), the injection volume increases abruptly when the aperture of the artificial rock joint reaches a threshold value (i.e. threshold joint aperture). Fig. 3(b) also clearly shows that the threshold joint aperture with oscillatory injection decreases by 87% of that subjected to static injection. This means that the grout material can smoothly flow into a rock joint, even with smaller apertures, when the oscillatory grout injection is applied.

3. Overview of the field experiment

3.1 Field overview

In case of the rock grouting, the aperture of rock joints is the most influential factor controlling the groutability, as mentioned in the previous section; however, the aperture of a real rock joint is difficult to quantify at an actual site. Accordingly, a field (in-situ) injection experiment must be performed to evaluate the effect of injection under field conditions.

The field experiments were conducted at three job sites. Table 1 presents the overview of each site. Geological features of each site and the tests conducted are also provided in the table. At Site 1 (S1), the experiments were done on the bedrock layer of a reservoir embankment. At

Table 1 Overview of job sites

		Site 1 (S1)	Site 2 (S2)	Site 3 (S3)
Overview		Bedrock of a reservoir embankment	At a reservoir embankment	At a reservoir embankment
Geological composition		Weathered soil (Silty sand), Weathered rock, Soft rock, Hard rock	Fill (Sand, Gravel), Weathered soil (Silty clay), Weathered rock, Soft rock	Fill (Sand, Gravel), Weathered soil (Silty clay), Weathered rock, Soft rock
Target ground of injection		Soft rock (6–11 m)	Weathered soil (3–8 m), Soft rock (10–15 m)	Weathered soil (8–13 m), Soft rock (23–28 m)
Hole number	Static injection	A, C	A, C	A
	Oscillatory injection	B, D, E, F	B, D	B
Tests	Test categories	Borehole test, Phenolphthalein method, BIPS, SEM analysis	Borehole test, Phenolphthalein method	Borehole test, Phenolphthalein method
	Permeability reduction	Field permeability test (Lugeon test)	Field permeability test (Lugeon test, variable head test)	Field permeability test (Lugeon test, variable head test)
	Ground improvement	Elastic wave test	Standard penetration test	Standard penetration test

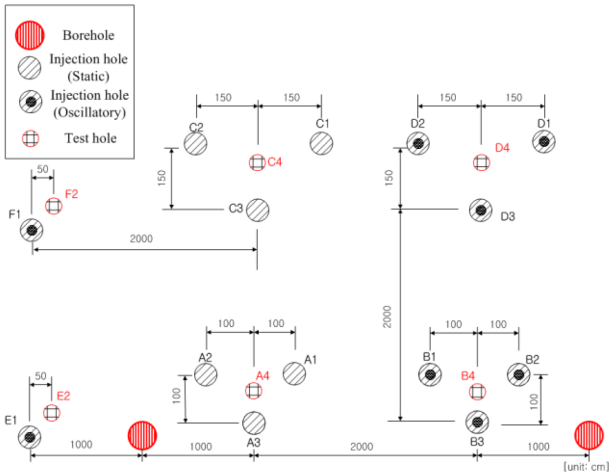
Site 2 (S2) and Site 3 (S3), tests were performed on the reservoir embankment itself. As shown in Table 1, all the tests for measuring injection degrees, checking the permeability reduction, and verifying the ground improvement of the bedrock were performed at S1. At S2 and S3, experiments were done to confirm the effectiveness of the oscillatory injection compared to the static injection. Unlike at S1, in which tests were performed on bedrock layers, tests were also performed on soil layers and soft rock layers at S2 and S3.

3.2 Field experiment procedure

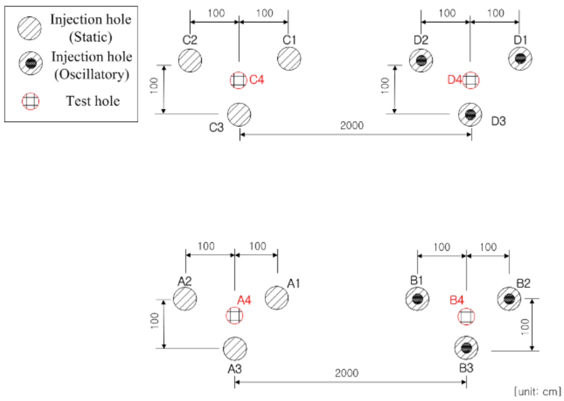
Site 1 (S1)

Based on the geological data of S1, areas exhibiting the most uniform distribution of rock joints were selected for a comparative study between the static and oscillatory injection methods. The distance between grout holes was also varied as 1.0 m and 1.5 m. Fig. 4(a) shows the arrangement of injection holes at S1.

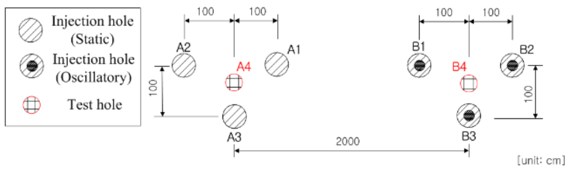
Each group of injection holes were 20 m apart to minimize the impact of injection between groups. At each injection hole, the injection was performed in a 5-m long section. The maximum injection volume was limited to 1,000 ℓ to prevent the holes from being affected by each other. The w/c ratio was set to 3 at each injection hole. Injection pressures of 300~500 kPa were applied to the soft rock layer. However, in case an injection pressure over 500 kPa occurred and a fractured injection was suspected or the injection volume of over 1,000 ℓ was recorded, the injection was stopped. The frequency of the oscillatory grout injection was set to 10 Hz at each site, which belonged to the optimal range proposed by Kim *et al.* (2018a, b).



(a) Arrangement of Site 1 (S1)



(b) Arrangement of Site 2(S2)



(c) Arrangement of Site 3 (S3)

Fig. 4 Arrangement of injection and test holes in the field experiment

Symbols A and B in Fig. 4 represent injection holes in which the static injection and the oscillatory injection were applied, respectively. As shown in Fig. 4(a), the center-to-center (CTC) spacing of injection holes at A and B was 1 m. A total of 1,000 ℓ of the grout material was injected in a 5 m length section composed of soft rock (depth of 6~11 m). In other words, 200 ℓ were injected every 1 m in depth. On the other hand, C and D injection holes (C for static injection and D for oscillatory injection) were arranged so that the CTC was increased to 1.5 m to compare the extent of ground improvement.

As the soft rock layer had a mean joint spacing of 5 cm or less, the effect of ground improvement was dependent on the length of the grouting section (injection length) per injection step. Accordingly, the injection length per injection step was changed to investigate this effect. At A through D, the injection length per injection step was 1 m. At E, it was decreased to 0.2 m and, thus, the maximum amount of 1,000 ℓ of the grout material was injected into the 5-m long section in 25 injection steps. At F, it was increased to as much as 5 m so that 1,000 ℓ of the grout material was injected at once for the whole 5 m long section.

After seven days of curing, cores were collected from the test holes marked by A4, B4, C4, and D4, and then the Lugeon test was performed in the test holes. In addition, cores were also collected at test holes marked by A5 and B5, which were 30 cm from A1 and B1, respectively, and E2 and F2, which were 50 cm from E1 and F1, respectively.

Site 2 and Site 3 (S2, S3)

The experiments at S2 and S3 were conducted similar to those at S1. Apart from S1, the injection tests were performed in the soil layers (weathered soil), as well as the soft rock layers. The CTC spacing was fixed to 1 m and the injection was performed for a 5-m long section for each hole. Figs. 4(b) and 4(c) illustrate the arrangements of injection holes at S2 and S3, respectively. As shown in Table 1, S2 consisted of the static injection holes A and C and the oscillatory injection holes B and D. S3 included the static injection hole A and the oscillatory injection hole B. The maximum injection volume for the 5-m long section at each hole was also limited to 1,000 ℓ; the w/c ratio was set to 3 and the frequency to 10 Hz, same as S1. The injection pressures of 100~300 kPa were applied to the soil layers (weathered soils). The injection was stopped if the injection pressure exceeded 300 kPa and fractured grouting was suspected. Injection pressures of 300~500 kPa were applied to the soft rock layers. The injection was stopped if the injection pressure exceeded 500 kPa, or the injection volume at each 1-m injection step exceeded 200 ℓ. After seven days of curing, cores were collected from the test holes and a field permeability test was performed.

4. Results of the field experiments

4.1 Measurement of injection degrees

4.1.1 Borehole test

After the grout injection tests were conducted on the soft rock layers at the three job sites, curing progressed for seven days. Then, the cores were collected and examined. Table 2 and Fig. 5 present the rock qualities (total core recovery (TCR) and rock quality designation (RQD)) before and after applying both the static and oscillatory injection methods at the three job sites. Table 2 and Fig. 5 show that the increase of the rock quality of the soft rock layers was more dominant with the oscillatory injection at all sites (average TCR increase of 3.6 more and average RQD increase of 3.4 more compared to those of the static injection). Cores were used to perform a phenolphthalein test, SEM analysis, and an elastic wave test, of which the results are presented below.

4.1.2 Phenolphthalein test

To identify the filling rates of grout material into the rock joint at three sites, the phenolphthalein test was executed for core boxes collected both before and after injection. A 1% phenolphthalein solution was sprayed and

Table 2 Rock quality before and after injection (unit: %)

Site	Method	Hole	TCR/RQD First 1.5 m	TCR/RQD Second 1.5 m	TCR/RQD Third 2 m
S1	Static (CTC=1.0 m)	A1 (Before)	62 / 0	100 / 0	100 / 0
		A4 (After)	66 / 0	100 / 3	100 / 3
	Variation		4 / 0 ↑	0 / 3 ↑	0 / 3 ↑
	Average		**1.3 / 1.7 ↑**		
	Oscillatory (CTC=1.0 m)	B1 (Before)	62 / 0	79 / 12	100 / 0
		B4 (After)	72 / 0	100 / 0	100 / 9
	Variation		10 / 0 ↑	21 / 0 ↑	0 / 9 ↑
	Average		**10.3 / 3 ↑**		
S2	Static (CTC=1.0 m)	A1 (Before)	100 / 25	100 / 37	100 / 11
		A4 (After)	100 / 25	100 / 37	100 / 14
	Variation		0 / 0 ↑	0 / 0 ↑	0 / 3 ↑
	Average		**0 / 1 ↑**		
	Oscillatory (CTC=1.0 m)	B1 (Before)	100 / 17	100 / 23	100 / 20
		B4 (After)	100 / 22	100/ 28	100 / 28
	Variation		0 / 5 ↑	0 / 5 ↑	0 / 8 ↑
	Average		**0 / 6 ↑**		
S3	Static (CTC=1.0 m)	A1 (Before)	65 / 0	100 / 5	100 / 0
		A1(After)	85 / 0	100 / 9	100 / 3
	Variation		20 / 0 ↑	0 / 4 ↑	0 / 3 ↑
	Average		**6.7 / 2.7 ↑**		
	Oscillatory (CTC=1.0 m)	B1 (Before)	85 / 0	100 / 0	100 / 0
		B4 (After)	100 / 5	100/ 5	100 / 8
	Variation		15 / 5 ↑	0 / 5 ↑	0 / 8 ↑
	Average		**3 / 6 ↑**		

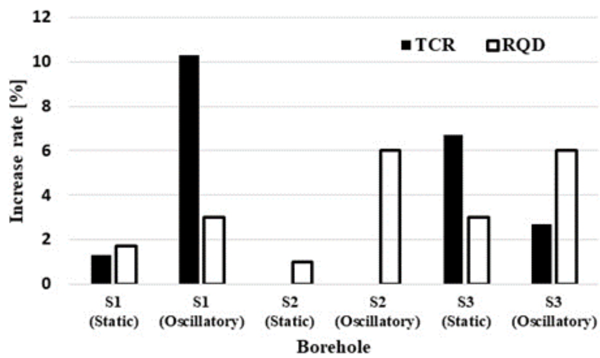
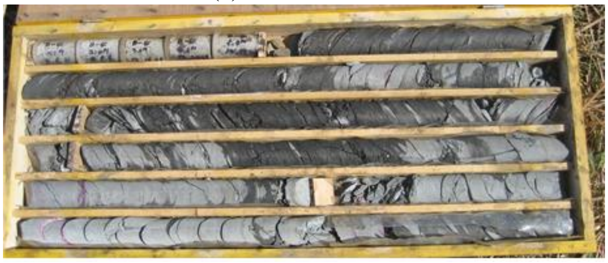


Fig. 5 Comparison of rock quality increases

discoloration occurred due to the presence of calcium hydroxide $Ca(OH)_2$ in the cement hydrate. Fig. 6 shows the phenolphthalein reaction, which was checked by visual inspection, for core boxes collected from test holes. Table 3

(a) Hole A4 at S2



(b) Hole B4 at S1

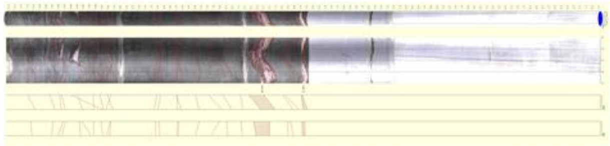
Fig. 6 Joints showing phenolphthalein reaction

Table 3 Number of joints showing the phenolphthalein reaction at each test hole

Site	Test hole	Injection Interval per each injection steps	Center-to-center spacing of injection holes (CTC)	Number of joints showing the phenolphthalein reaction
S1	A4 (Static)	1 m	1 m	3
	B4 (Oscillatory)	1 m	1 m	12
	C4 (Static)	1 m	1.5 m	4
	D4 (Oscillatory)	1 m	1.5 m	7
	E2 (Oscillatory)	0.2 m	-	13
	F2 (Oscillatory)	5 m	-	2
S2	A4 (Static)	1 m	1 m	3
	B4 (Oscillatory)	1 m	1 m	7
S3	A4 (Static)	1 m	1 m	4
	B4 (Oscillatory)	1 m	1 m	6

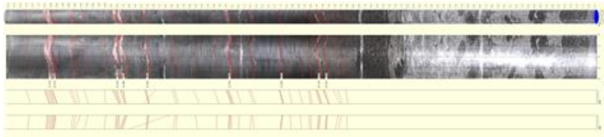
presents the number of joints that exhibited a phenolphthalein reaction at each site.

More joints exhibit the phenolphthalein reaction when the oscillatory injection was applied at each site compared to the static injection method. This indicates that permeation of grout material through rock joints was improved by the oscillatory injection method. At S1, it was found that more rock joints showed the phenolphthalein reaction near injection holes when the injection length per injection step was decreased, thus increasing the number of steps. Consequently, when the oscillatory injection method is adopted, it will be more effective if a smaller injection length per injection step is utilized, which will increase the number of injection steps.



(a) Hole A4 at S1

(b) Hole B4 at S1



(c) Hole C4 at S1

(d) Hole D4 at S1

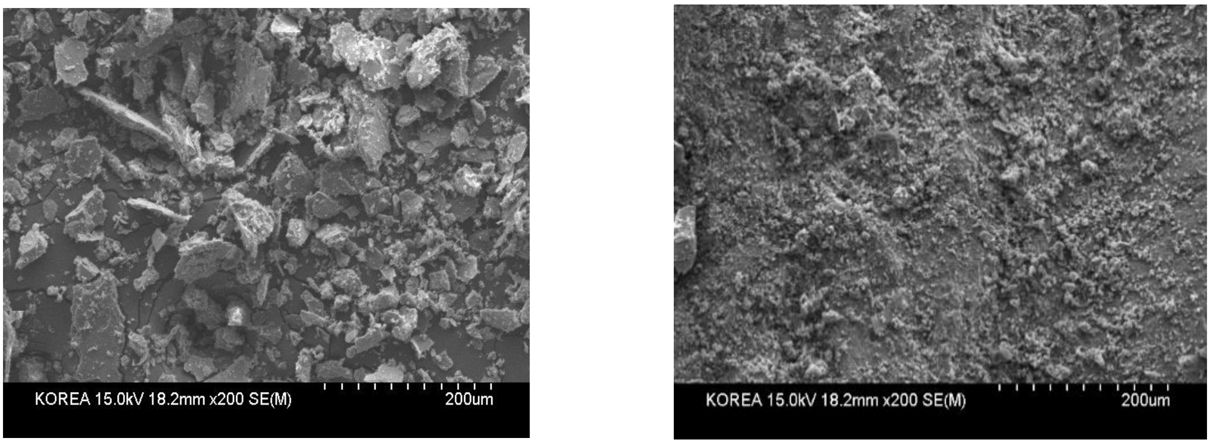
Fig. 7 BIPS images

Table 4 Filling rates of the grout material at each hole

Site	Test hole	Number of joints			Filling rate (%)	Increase rate (%)
		Total	Open	Closed		
S1	A4 (Static)	24	4	20	83.3	-10
	B4 (Oscillatory)	8	2	6	75	
	C4 (Static)	40	18	22	55	81.8
	D4 (Oscillatory)	17	0	17	100	

4.1.3 Borehole image processing system (BIPS)

After the grout injection was performed for the soft rock layer (6~11 m) and waiting seven days for curing at S1, the borehole image processing was conducted at test holes A4, B4, C4, and D4. Fig. 7 shows the scanned images and Table 4 presents the scanning results. Based on the scanning results and the visual inspection results using the phenolphthalein method, joint filling rates with the grout material were obtained and are listed in Table 4 for both the static and oscillatory injection methods. Table 4 shows that the joint filling rates were high (75~83 %) for both the static and oscillatory injection methods when the injection spacing is as small as 1.0 m (A4 and B4 in Fig. 7). However, if the injection hole spacing is increased to 1.5 m (C4 and D4 in Fig. 7), even though the filling rate increases from 75% to 100% with oscillatory injection, it drops significantly for static injection. Accordingly, it can be concluded that the oscillatory injection method enabled grout materials to permeate through smaller joint apertures and/or enabled permeation through the joint farther away by the vibration effect.



(a) Before oscillatory injection (b) After oscillatory injection

Fig. 8 SEM images (Hole B4 at S1)

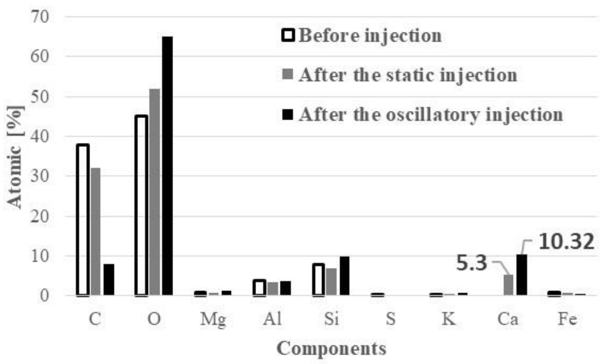


Fig. 9 Comparison of components before and after injection using static (C4) and oscillatory (B4) injection at site S1

4.1.4 Scanning electron microscopy (SEM) analysis

After the phenolphthalein reaction test was completed to see whether the grout material was well injected using cores collected at S1, small pieces of specimen or powder-type specimens were prepared from both clean cores and grouted cores. The composition of the prepared specimens was analyzed using the SEM analysis. Fig. 8 provides SEM images of B4 before and after the oscillatory injection. The SEM analysis of each specimen collected after the injection showed an increase in the density of the Ca ion, which is one of the main components of cement. Fig. 9 presents the analysis results of compositions at C4 and B4, to which both the static and oscillatory injection methods were applied, respectively. In comparison to C4, where the static injection method was applied, B4 with the oscillatory injection method showed that the density of the Ca ion increased by a factor of almost two. Based on the fact that the density of injected Ca ion had a higher increase with the oscillatory injection, it can be concluded that the grout injection volume filling the rock joint is larger with the oscillatory injection.

4.2 Permeability reduction performance

In order to examine the permeability reduction performance at the three job sites, a variable head test was conducted to obtain the permeability coefficient of a soil layer. In the variable test, water was injected into the injection section of the test hole (in a soil layer) and then the change of water level in the hole was measured. In the case of the injection section of a rock layer, the Lugeon test was conducted in accordance with the requirements of ASTM D4631-18 (2018). Table 5 presents the measured permeability coefficients before and after injection.

Table 5 Comparison of permeability coefficient before and after injection

Site	Permeability coefficient at rock layer (Lugeon test)				
	Before		After		Variation of permeability coefficient
	Injection hole	Permeability coefficient (cm/sec)	Test hole	Permeability coefficient (cm/sec)	
S1	A1 (Static)	6.38E-06	A4 (Static)	2.13E-06	1/3.00
	B1 (Oscillatory)	9.40E-06	B4 (Oscillatory)	1.71E-06	1/5.50
	C1 (Static)	9.48E-06	C4 (Static)	1.43E-06	1/6.63
	D1 (Oscillatory)	1.35E-05	D4 (Oscillatory)	1.12E-06	1/12.1
S3	A1 (Static)	3.28E-05	A4 (Static)	8.79E-06	1/3.73
	B1 (Oscillatory)	5.35E-05	B4 (Oscillatory)	2.1E-06	1/25.5

Site	Permeability coefficient at soil layer (Variable head test)				
	Before		After		Variation of permeability coefficient
	Injection hole	Permeability coefficient (cm/sec)	Test hole	Permeability coefficient (cm/sec)	
S2	A1 (Static)	8.04E-04	A4 (Static)	9.14E-05	1/8.79
	B1 (Oscillatory)	7.97E-04	B4 (Oscillatory)	2.62E-05	1/30.4
	C1 (Static)	4.47E-04	C4 (Static)	7.29E-05	1/6.13
	D1 (Oscillatory)	2.37E-05	D4 (Oscillatory)	3.15E-05	1/7.52
S3	A1 (Static)	1.21E-04	A4 (Static)	5.86E-05	1/2.07
	B1 (Oscillatory)	3.81E-04	B4 (Oscillatory)	3.81E-05	1/10.0

As for the permeability coefficient of a rock layer, while the permeability coefficient was decreased by 66~78 % when the static grout injection was performed, a decrease of 81~96 % was achieved with the oscillatory injection. In

Table 6 Comparison of SPT-N value before and after injection

Site	Before				After				Variation of the average N
	Injection hole	Depth	N value	Average N	Test hole	Depth	N value	Average N	
S2	A1 (Static)	3-5 m	3	3.5	A4 (Static)	3-5 m	5	5.5	**2 ↑**
		5-8 m	4			5-8 m	6		
	B1 (Oscillatory)	3-5 m	4	4	B4 (Oscillatory)	3-5 m	4	6	**2 ↑**
		5-8 m	4			5-8 m	8		
	C1 (Static)	3-5 m	6	6	C4 (Static)	3-5 m	9	9.5	**3.5 ↑**
		5-8 m	6			5-8 m	10		
	D1 (Oscillatory)	3-5 m	7	6	D4 (Oscillatory)	3-5 m	7	7.5	**1.5 ↑**
		5-8 m	5			5-8 m	8		
S3	A1 (Static)	8-10 m	7	7.5	A4 (Static)	8-10 m	10	9	**1.5 ↑**
		10-13 m	8			10-13 m	8		
	B1 (Oscillatory)	8-10 m	6	5.5	B4 (Oscillatory)	8-10 m	10	11.5	**6 ↑**
		10-13 m	5			10-13 m	13		

other words, when the oscillatory injection method was applied to the rock layer, the decrease rate of the permeability coefficient was improved by at least 33% compared to the static injection.

As for the permeability coefficient of a soil layer, both the static and oscillatory injection methods decreased these values to approximately 10^{-5} cm/sec. This value is sufficient for the reservoir embankment to retard the seepage and/or leakage of water through the soil layers. When the two methods were compared in terms of the permeability coefficient, the static injection achieved decrease rates ranging from 51% to 88% after injection, while the decrease rates in the range of 86% to 96% were achieved with the oscillatory injection. In other words, when the oscillatory injection method was applied to the soil layer, the decrease rate of the permeability coefficient was improved by at least 68%; the decrease rate is more dominant in soils than in rocks.

4.3 Ground improvement effect

4.3.1 Standard penetration test (SPT)

Standard penetration tests (SPT) were performed on soil layers of sites S2 and S3 for the test holes both before and after injection and seven days of curing. Table 6 presents the results of the SPTs. As shown in Table 6, the increase of the average SPT-N values for both the static and oscillatory injection methods were notable, even with seven day of curing. However, no significant difference in the increase of the N value was identified between the static injection and oscillatory injection, which is similar to the findings of Kim *et al.* (2018a). Kim *et al.* (2018a) concluded that the unconfined compressive strengths of the grouted soil obtained by the two injection methods were not very different, as shown in Fig. 10. The main advantage of the oscillatory injection is that the penetration depth will be significantly increased, which results in a larger grouted area compared to static injection. Therefore, once the soil layers are grouted, the strengths are similar between the two injection methods.

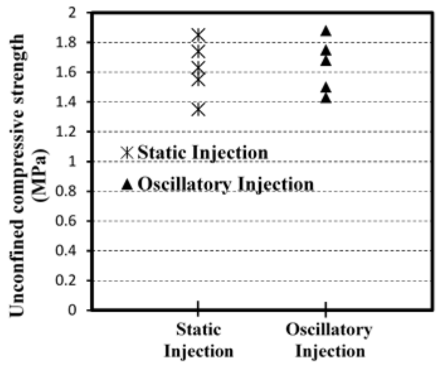


Fig. 10 Comparison of unconfined compressive strengths (after Kim *et al.* 2018a)

4.3.2 Rock mass stiffness

Elastic wave velocity was measured for rock specimens taken from site S1 to see whether the rock grouting could enhance the stiffness of the rock mass. Samples were taken from the grout injected rock cores, as well as non-injected natural cores. The bulk modulus can be estimated from the wave velocity as follows. The velocity of the compression wave has a correlation with the constrained modulus of the rock mass, as expressed in Eq. (3).

$$M = \rho V_{\alpha}{}^{2} \tag{3}$$

Here, M is the constrained modulus, ρ is the density of the specimen, and V_{α} is the velocity of the compressive plane wave. The velocity of the elastic wave was obtained by measuring the travel times between two sensors from one end to the other after slightly blowing/hitting one end. The number of joints, apertures, and joint spacings were

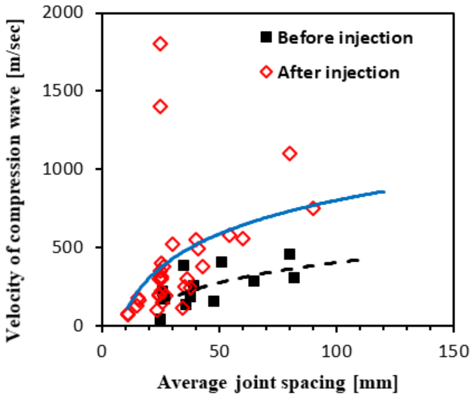
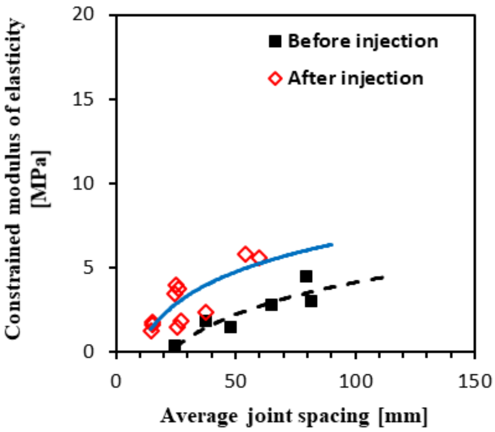
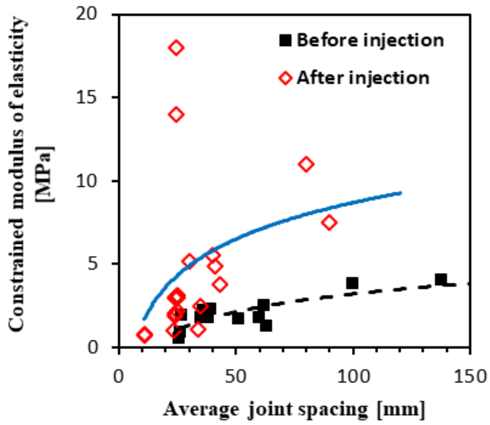


Fig. 11 Velocity of the compressive plane wave according to the joint spacing

Fig. 12 Specimen collected at B5 of site S1 after the oscillatory injection



(a) Static injection



(b) Oscillatory injection

Fig. 13 Comparison of constrained moduli between the static and oscillatory injection methods

also recorded. The velocity of compression waves measured from the intact rock specimens without any joints ranged from 2500 m/sec to 3000 m/sec. When a grout material is injected into the joint and filling it, the measured wave velocity might approach that of fresh parent rock.

Fig. 11 represents the velocity of the compression wave as a function of joint spacing with and without filling the joint with grout material. The figure clearly shows that the wave velocity increases with the increase of the joint spacing. Moreover, the wave velocity significantly increases when the joint is filled with the injected grout material. More importantly, the enhancement effect is more dominant when the joint spacing is smaller with a larger increase of the grout injection volume.

Fig. 12 presents the image of a specimen (B5 at S1 site) densely filled with the grout material, which was collected in an area where the oscillatory injection method was applied. Fig. 13 compares the constrained moduli (calculated using Eq. (3)) according to the joint spacing between the static injection and the oscillatory injection. When the static injection method was applied, the constrained modulus of rock mass was almost doubled, while the application of the oscillatory injection method increased the constrained modulus about three times. Accordingly, the oscillatory injection was more effective for improving the stiffness of the rock mass.

Table 7 Number of joints and injection volume

Site	Test hole	Number of joints			Injection volume (ℓ)	Injection volume per joint
		Total	Open	Closed		
S1	A4 (Static)	24	4	20	1714	85.7
	B4 (Oscillatory)	8	2	6	1485	247.4
	C4 (Static)	40	18	22	2443	111.1
	D4 (Oscillatory)	17	0	17	2644	155.5

4.4 Comparison with experiment on the artificial rock joint

As mentioned in Section 2, when the oscillatory injection method was applied to inject grout material into the artificial rock joint, permeation grouting was feasible and facilitated filling at joints with smaller apertures compared to the static injection method. In the field at site S1, the total injection volumes of the grout material that was injected into the jointed rock mass were also compared. Investigation of boreholes by BIPS revealed that many rock joints with apertures of 15~30 mm existed at a depth of about 7~9 m. The number of joints and the injection volumes at test holes were recorded, of which the results are presented in Table 7. Table 7 shows that the average injection volume per joint was increased 1.5 to 3 times for oscillatory injection over static injection.

Test hole A4 that utilized the static injection method had about three times more joints and wider joint apertures than test hole B4 that utilized the oscillatory injection method. However, there was no significant difference in the injection volumes considering the differences in a number of joints between the two holes. Moreover, as for C4 and D4 where the spacing between injection holes was wider (1.5 m), D4 (oscillatory injection) with fewer joints and smaller joint apertures showed a larger injection volume than C4 (static injection). This indicated that the oscillatory injection enabled the grout material to be injected into smaller joint apertures and also increased the penetration depth through the joint, resulting in an increase of the grout-injected area.

5. Conclusions

The groutability enhancement effect of the oscillatory grout injection method, which was verified by laboratory-scale tests and theoretical assessment (Kim *et al.* 2018a and b), was also verified in this study by performing field tests and by injecting into artificially-manufactured rock joints with vibrations. The conclusions drawn from this study can be summarized as follows.

• Grout injection into the artificial rock joint revealed that the threshold joint aperture, defined to be the minimum aperture of a rock joint through which permeation grouting is feasible, decreases by 87% using the oscillatory injection compared to the static injection. This indicated that the grout material could be smoothly injected into the smaller joints by oscillatory injection.

• In-situ borehole investigation using BIPS revealed that the joint filling rate was dominantly higher for oscillatory injection compared to the static injection as the spacing between injection holes becomes greater. This means that the oscillatory injection enabled grout material to permeate through smaller joint apertures and/or enabled permeation into the joint farther away by the vibration effect.

• Borehole coring results showed that an increase of the rock quality of the rock mass was more dominant with the oscillatory injection at all sites (average TCR increase of 3.6 more and average RQD increase of 3.4 more compared to those of the static injection). The phenolphthalein test and the SEM analysis revealed that the oscillatory injection achieved a larger injection volume of grout material and a greater penetration into rock joints.

• Field permeability tests revealed that when the oscillatory injection method was adopted, the decrease rate of the permeability coefficient was improved by at least 33% more in rock layers and at least 68% more in soil layers compared to the static injection.

• The elastic wave tests on the cored rock samples revealed that the oscillatory injection increased the constrained modulus by a factor of three, while the static injection increased by a factor of two. Therefore, the oscillatory injection was more effective for improving the stiffness of the rock mass.

References

ASTM (American Society for Testing and Materials) (2018), *Standard Test Method for Determining Transmissivity and Storativity of Low Permeability Rocks by in situ Measurements using Pressure Pulse Technique*, ASTM D4631-18, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Batchelor, G.F. (1967), *An Introduction to Fluid Dynamics*, Cambridge University Press, Cambridge, U.K.

Byle, M.J. and Borden, R.H. (1995), "Verification of geotechnical grouting", *Geotechnical Special Publication,* No.57, ASCE Committee on Grouting, 1-77.

Chang, M., Mao, T.W. and Huang, R.C. (2016), "A study on the improvements of geotechnical properties of in-situ soils by grouting", *Geomech. Eng.*, **10**(4), 527-546. https://doi.org/10.12989/gae.2016.10.4.527.

Choi, M.S., Kim, Y.S. and Kim, Y.U. (2016), "Effect of ultrasound on the formation of a lubrication layer in concrete pumping", *J. Adv. Concr. Technol.*, **14**(3), 95-101. https://doi.org/10.3151/jact.14.95.

Date, K., Wakita, S., Yamamoto, T., Nakashima, Y., Hoshino, Y., Aoki, K. and Mito, Y. (2003), "Development of dynamic grouting technique for the ground improvement", *Proceedings of the ITA World Tunnelling Congress 2003: (RE)Claiming the Underground Space*, Amsterdam, The Netherlands.

Fattah, M.Y., Al-Saidi, A.A. and Jaber, M.M. (2015), "Improvement of bearing capacity of footing on soft clay grouted with lime-silica fume mix", *Geomech. Eng.*, **8**(1), 113-132. https://doi.org/10.12989/gae.2015.8.1.113.

Goodman, R.E. (1976), *Methods of Geological Engineering in Discontinuous Rocks*, West Publishing, New York, U.S.A.

Kim, B.K., Lee, I.M, Chung, H.Y., and Ryu, Y.M. (2018b), "Groutability enhancement effect of oscillatory grout injection: Theoretical assessment", *Geomech. Eng.*, under review.

Kim, B.K., Park, J.J., Kwon, Y.S., Jung, K.B. and Lee, I.M.

(2018a), "Groutability enhancement by oscillatory injection in cement-based permeation grouting", *Geotech*. *Test*. *J*. https://doi.org/10.1520/GTJ20170036. ISSN 0149-6115.

Kim, J.S., Lee, I.M., Jang, J.H. and Choi, H.S. (2009), "Groutability of cement-based grout with consideration of viscosity and filtration phenomenon", *Int*. *J*. *Numer*. *Anal*. *Meth*. *Geomech*., **33**(16), 1771-1797. https://doi.org/10.1002/nag.785.

Mohammed, H.M., Pusch, R. and Knutsson, S. (2015), "Study of cement-grout penetration into fractures under static and oscillatory conditions", *Tunn*. *Undergr*. *Sp*. *Technol*., **45**, 10-19. https://doi.org/10.1016/j.tust.2014.08.003.

Poinot, T., Benyahia, K., Govin, A., Jeanmaire, T., and Grosseau, P. (2013), "Use of ultrasonic degradation to study the molecular weight influence of polymetric admixtures for mortars", *Constr*. *Build*. *Mater*., **47**, 1046-1052. https://doi.org/10.1016/j.conbuildmat.2013.06.007.

Shin, E.C., Shin, H.S., and Ryu, B.H. (2012), "Effect of vibration on infiltration grouting using cylindricality device", *Proceedings of the Korean Geo-Environmental Society Conference*, Seoul, Korea.

Shin, J.H., Moon, J.H., Song, Y.K., and Kim, Y.U. (2015), "Ultrasonically enhanced physical properties of cement grout", *KSCE J*. *Civ*. *Eng*., **19**(6), 1693-1696. https://doi.org/10.1007/s12205-015-1267-2.

Zheng, G., Zhang, X., Diao, Y. and Lei, H. (2016), "Experimental study on the performance of compensation grouting in structured soil", *Geomech*. *Eng*., **10**(3), 335-355. https://doi.org/10.12989/gae.2016.10.3.335.

GC