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Study on repair and reinforcement for pile foundation using jet grouting

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ABSTRACT: This paper describes a repair and reinforcement method for piles in which the foundation has been damaged by a large earthquake. The piles damaged by the 2016 Kumamoto earthquake (M_{JMA} 7.3) were repaired and reinforced by jet grouting. Then the effectiveness of repair and reinforcement was examined by a static axial compressive load test of the pile reinforced by soil improvement columns. Results from the static axial compressive load test proved that it has a performance not less than the allowable bearing capacity in the initial design. Furthermore, we confirmed that the unconfined compressive strength by laboratory tests and radius of the soil improvement columns satisfied the design value.

1 INTRODUCTION

In recent years, there have been many cases of earthquake damage in Japan, in which the function of the entire building is impaired by damage to an integral part of the ground, and foundation structure, such as ground liquefaction around the building and damage to foundation beams and piles due to ground deformation. Even in the 2011 off the Pacific coast of Tohoku Earthquake and the 2016 Kumamoto Earthquake, it has been reported that buildings with their pile foundations damaged are inclined. However, for repairing and reinforcing the piles of existing buildings, the investigation of damage by excavating the ground surrounding the foundation and the restoring work are expensive and time-consuming. As a result, many of them have to be demolished and removed even if no significand damage is observed to the superstructure. Based on the experiences of recent large-scale disaster, from the viewpoint of prompt reconstruction, there is a strong need for a technology that enables continuous use of buildings by repair and reinforcement. Therefore, a jet grouting method which has been applied as a soil improvement method directly beneath existing buildings in recent years was focused on. Jet grouting methods are considered to be effective because it is not necessary to excavate into the ground to damaged parts of damaged piles. In this study, we used JET-CRETE, one of the jet grouting techniques, which can arbitrarily set the shapes and design strength of the improved soil columns and can be applied even in a small place. This paper aims to evaluate the effectiveness to repair and reinforcement using a jet grouting method for damaged piles by an examined field static axial compressive load test.

2 OUTLINE OF FIELD EXPERIMENT

2.1 *Structure and foundation details*

A building damaged by the 2016 Kumamoto earthquakes was constructed in 1984. The structure and foundation are shown in Table 1. The building was already decommissioned and removed, and the superstructure was dismantled. Therefore, the substructure below the first floor was used for the test.

Table 1. Overview of structure and foundation

Completion	1984.10
Number of floors	5stories
Building area	406.1 m^2
Total floor area	2,030.4 m^2
Structural type	Reinforced Concrete Ramen
Foundation type	Pile foundation
Pile details	PHC piles diameter=500mm, length=39.0m, n=38
Pile length	39.0 m
Bearing capacity	1,100 kN (design, long-term)

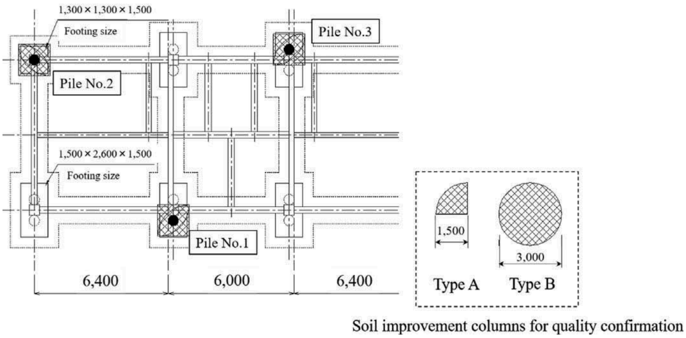

Figure 1. Plan view of the foundation, piles No. 1-3 and soil improvement columns (including types A and, B for quality confirmation)

2.2 *Damaged pile and soil improvement column*

A schematic view of the damaged piles and planned soil improvement areas is shown in Figure 1. We also constructed soil improvement columns (types A and B) for quality confirmation on the same site as shown in the same figure. The planar shapes of the soil improvement columns were type A with a quadrant shape (r = 1,500 mm) and type B with a total circle. The jet grouting specifications of types A and B were the same. Piles No. 1-3 were repaired and reinforced by two soil improvement columns which were constructed of type A. The test and confirmation components in each pile are as shown in Table 2. The photos of damaged piles No. 1 and No. 2 are shown in Figure 2, respectively. A compressive and shear failure occurred at the range of 1m from the pile head of pile No. 1. Conversely, some shear cracks occurred at the piles of No. 2 and No. 3 at the range of 1m from pile head.

Table 2. Test and confirmation details of piles No. 1-3, types A and B for quality confirmation

Pile No.1	Form, unconfined compressive strength, vertical bearing capacity
Pile No.2	Form, unconfined compressive strength
Pile No.3	Form, unconfined compressive strength
Type A (for quality confirmation)	Form, unconfined compressive strength
Type B (for quality confirmation)	Form, unconfined compressive strength

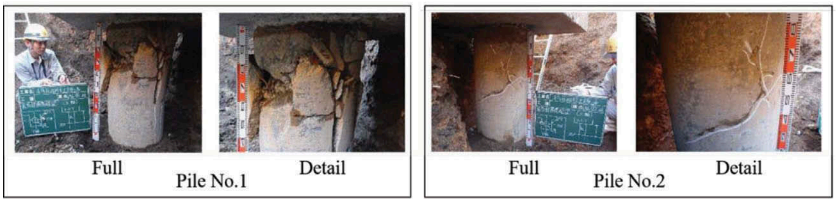

Figure 2. Photos of damaged piles No. 1 and No. 2

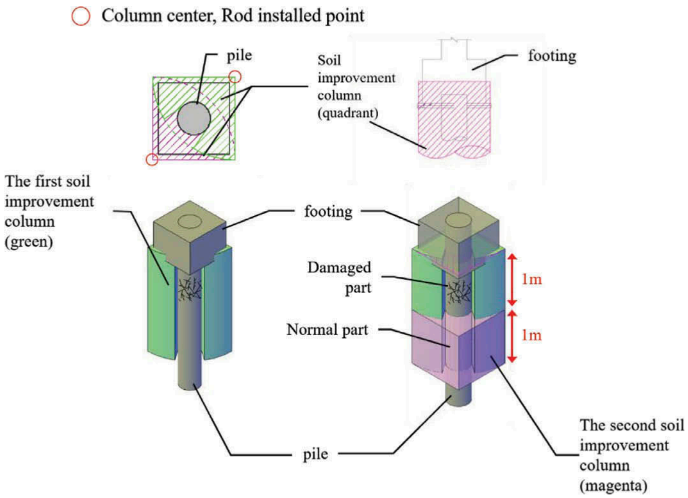

Figure 3. 3D illustration of repair and reinforcement for damaged pile foundation using jet grouting

2.3 *Concept of repair and reinforcement for damaged pile*

A schematic image of repair and reinforcement for a damaged pile using jet grouting is depicted in Figure 3. For the damaged pile, jet grouting rods are installed at two points of the footing diagonal position as shown in Figure 3, and jet grouting is made for one corner at a time at with quadrant form, and a rectangular improvement shape is built so as to embrace the pile. As for repair and reinforcement for the above method, the modulus and strength of the surrounding ground of the pile will increase. And, it can repair and reinforce the foundation structure including the pile. It is assumed that cement milk flows into the hollow portion of the damaged pile, thereby increasing the compressive and shear strength of the pile.

2.4 *Improvement specification and section view of repair and reinforcement*

Figure 4 shows the geotechnical profiles and soil improvement in the depth direction of this construction site. This figure also shows soil properties of fill (silty clay). Soil to be improved is silty clay with N-values between 2 and 4. The necessary planar range of soil improvement is a square of 1.5m × 1.5m, which can cover the footing size (1.3m × 1.3m). And, the depth of improvement columns is 2m from the bottom of the footing. The improvement length of 2m is divided into 1m for the damaged area and, 1m for the non-damaged area as illustrated by Figure 3. The construction specifications of jet grouting are shown in Table 2. For the purpose

Soil properties of fill (silty clay)

Physical properties	soil particle density	ρ_s	(Mg/m^3)	2.605
	natural water content	w_n	(%)	76.9
	fine fraction content	Fc	(%)	93.6
	liquid limit	w_L	(%)	108.4
	plastic limit	w_p	(%)	32.8
	plasticy index	Ip	(-)	75.6
	mean grain size	D_{50}	(mm)	0.002
Elastic properties	praimary wave velocity	Vp	(m/s)	360
	shear wave velocity	Vs	(m/s)	160
	Poisson's ratio	ν	(-)	0.377
	shear modulus	G	(kN/m^2)	46,100
	Young's modulus	E	(kN/m^2)	126,900

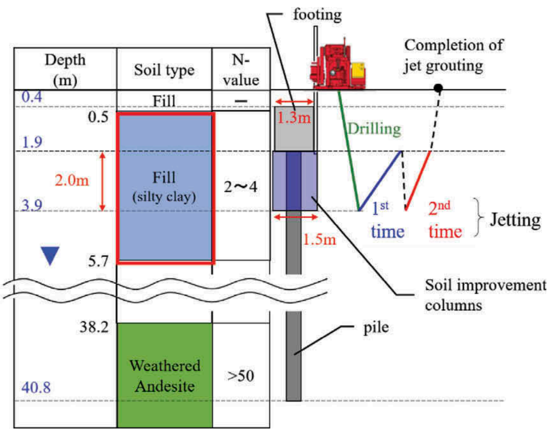

Figure 4. Soil layer of this site with soil properties and details of jet grouting construction

Table 3. Improvement specifications of Types A and, B

Type	A		B
Form	quadrant		circle
Radius		1.5 m	
Length		2.0 m	
Specified design strength		1,500 kN/m^2	
Variation coefficient, Vn		40 % (assumption)	
Number of jetting		2 times	
Cement per soil volume		463 kg/m^3	
Total number of constructions	7		1

of reducing the variances in strength of soil improvement columns, jet grouting is repeated two times for the same layer in the construction process.

3 QUALITY OF SOIL IMPROVEMENT COLUMNS

3.1 *Soil improvement columns*

The design strength of all soil improvement columns is 1,500 kN/m^2. The value of the specified design strength is given considering the maximum load of the axial loading test. The form, length and number of cores for laboratory tests are shown in Table 4.

3.2 *Confirmation of state around the damaged pile after jet grouting*

Confirmation of the filling condition of the damaged pile reinforced by the soil improvement material was carried out by visually confirming the cross-section of the pile head portion and observing the core sampled from the hollow portion of the pile. It is confirmed that the breakage portion and follow portion of the damaged pile have been filled with soil improvement material. The filling condition of pile head is shown in Figure 5. In addition, observing the core taken from the hollow part of the pile proved that the improvement material filled the area in the damage range (approximately 1m from the pile head) of the pile.

Table 4. Form, length, number of core sampling and of specimen for laboratory tests

	Planer form (planned)	Improvement length	Core samplings	Specimen
Pile No.1	square (W1.5 m, B1.5 m)	2.0 m	8	38
Pile No.2	square (W1.5 m, B1.5 m)	2.0 m	6	41
Pile No.3	square (W1.5 m, B1.5 m)	2.0 m	7	31
Type A	quadrant (r1.5 m)	2.0 m	6	55
Type B	circle (r1.5 m)	2.0 m	7	67

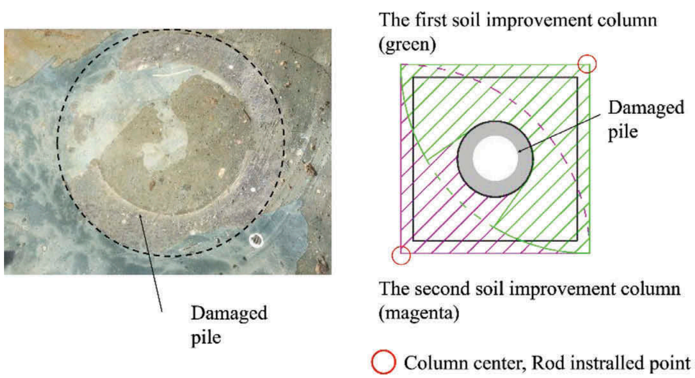

Figure 5. Photo and plan view of the damaged pile reinforced by soil improvement columns (GL -0.5m) after jet grouting (by mechanical cutting)

Table 5. Horizontal distance of core sampling (from jetting points)

Core No.	Soil improvement columns				
	Pile No. 1	Pile No. 2	Pile No. 3	Type A (quadrant)	Type B (circle)
1	630	600	650	750	750
2	470	350	400	750	750
3	370	450	630	1050	1050
4	550	550	450	1500	1050
5	390	450	530	1500	1500
6	600	400	600	1500	1500
7	350	-	550	-	-
8	600	-	-	-	-

unit:mm

3.3 *Unconfined compressive strength characteristics of soil improvement columns*

The strength properties of the soil improvement columns were evaluated by laboratory test of the cores taken from columns. An unconfined compression test was carried out, complying with the Japanese industrial standard "JIS A 1216: Method for unconfined compression test of soils". The quality was examined by calculating the acceptance value according to the inspection method B shown in the Building Center of Japan guideline (BCJ guideline), comparing the acceptance value of the Equation 1 and the average value of the unconfined compression strength.

$$X_L = F_c + k_b \cdot \sigma_n \tag{1}$$

where X_L = acceptance value (kN/m^2); F_c = specified design strength (kN/m^2); k_b = coefficient of judgement (1.3) and σ_n = standard deviation of compressive strength.

The depth of core sampling was approximately 1.5m from the top of the soil improvement columns (Pile No.1-3). The sampling depth for Types A and, B was for the full length of the improved area. The horizontal distance of the sampling points are shown in Table 5.

Average strength of all the columns satisfied the acceptance value X_L. Figure 6. shows the unconfined compressive stress obtained from laboratory tests with the acceptance value as (q_u – 1.3 σ) of each pile and types A and, B, respectively.

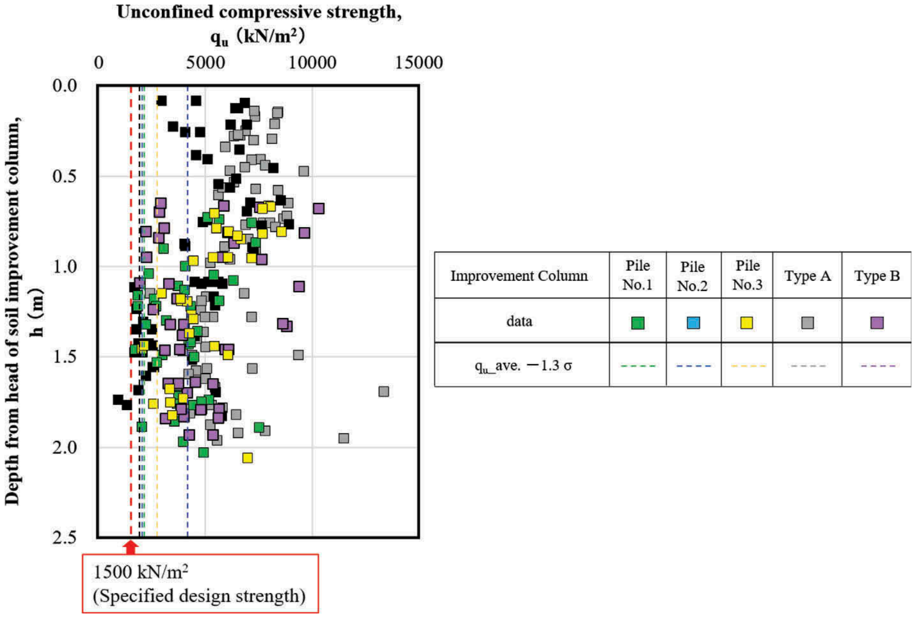

Figure 6. Distribution of unconfined compressive strength obtained from laboratory compression tests

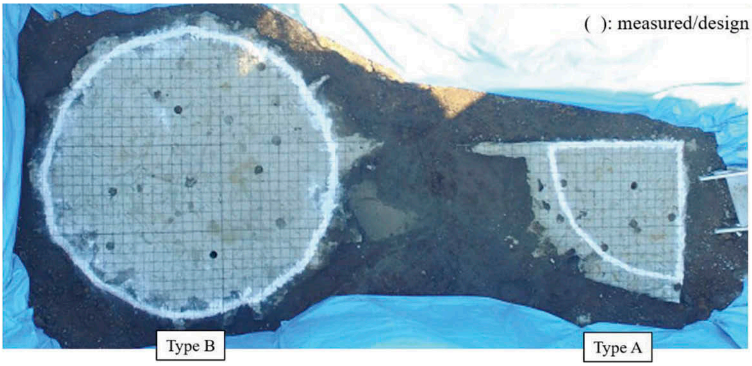

Figure 7. Confirmation of the heads of soil improvement column by excavation

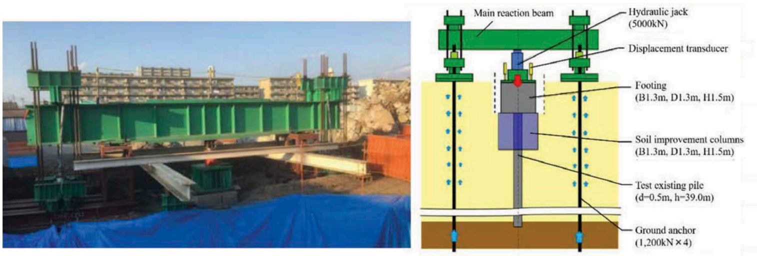

Figure 8. Axial loading test scene and test system

3.4 *Form of the soil improvement column*

The forms of the soil improvement column of types A and, B were observed by exposing the head of the columns by excavation. The radius of the improvement columns at every 10° was measured and compared with the planned values. A photograph of the column heads is shown in Figure 7. In addition, the minimum values of the radii of the improvement types A and B were 1,500 mm and 1,600 mm, respectively. The measurement results of the diameter of the improvement columns are also shown in Figure 7.

4 STATIC AXIAL COMPRESSIVE LOAD TEST FOR REPAIRED AND REINFORCED PILE

4.1 *Outline of the static axial compressive load test*

A static axial compressive load test for a damaged pile (pile No.1) reinforced by soil improvement columns was conducted after excavating the ground around the footing. Figure 8 shows the loading test view and test system including a reaction force devise.

4.2 *Setting loading value*

Detailed diagram of the static loading cycle is shown in Figure 9. This load cycle was based on JGS standard (JGS1811-2002; Method for Static Axial Compressive Load Test of Single Piles). The maximum loading value was 3,600 kN at the 6^{th} cycle which was determined as the value three times the design long-term bearing capacity of 1,100 kN. This maximum loading value nearly equaled the ultimate bearing capacity of Ru=3,273kN calculated by Equation 2.

$$R_u = \alpha \bar{N} A_p + \left(\beta \overline{N_s} L_s + \gamma \overline{q_u} L_c\right) \varphi \tag{2}$$

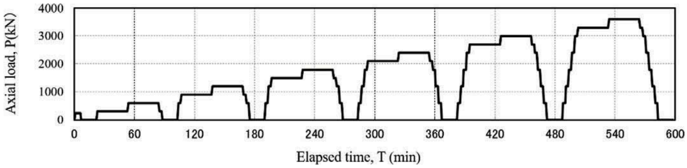

Figure 9. Axial loading cycle diagram (Planned)

where α = 200 (bearing capacity coefficient at pile tip by cement slurry method), $\beta\overline{N_s}$=15 (skin friction coefficient in sand layer, kN/m^2), $\gamma\overline{q_u}$=15 (value of unconfined compressive strength of clay layer, kN/m^2), $\bar{N}$=60 (upper limit value of average SPT N-value around the pile tip), A_p=0.197 (effective area of pile tip, m^2), L_s=16.0 (total length of the pile penetrated in sand layers), L_c=22.9 (total length of pile penetrated in clay layers), $\varphi = 1.57\ m$ (circumferential length of pile, m)

4.3 *Test results and interpretation of vertical bearing mechanisms*

The relationship between the axial load and the vertical displacement obtained from the axial loading test is shown in Figure. 10 a). From the loading test result, the settling amount of the footing at the stage of the maximum load (3,600 kN) was 8.7 mm. In general, the settling amount of the pile at the second limit resistance force used for determining the ultimate bearing capacity is 10% of the pile diameter, but this experiment has not reached that amount. Therefore, it is inferred that the actual ultimate bearing capacity of this damaged pile reinforced by soil improvement columns is even more than 3,600 kN as the allowable bearing capacity in the initial design. Figure 10 b) shows a diagram in which the vertical displacement of the footing is regarded as the vertical displacement of the pile head and is superimposed on the load-subsidence relationship diagram of a typical single pile behavior. In the case of pile and soil improvement columns in this study, it is postulated that the vertical bearing mechanism is different from a single pile. However, when this test result is applied to the load-settlement relation at the initial stage of loading, it can be inferred that a damaged pile reinforced by soil improvement columns has approximately twice the ultimate bearing capacity.

The interpretation of bearing capacity mechanisms is illustrated in Figure 11. Figure 11. a) shows the mechanism of a single pile, while Figure 11 b) shows that for a pile reinforced by soil improvement columns. The bearing capacity of a pile reinforced by soil improvement columns was divided into four components: 1) Tip resistance, 2) Skin friction resistance, 3) Bearing resistance beneath area of soil improvement columns, 4) Skin friction resistance between soil improvement columns and surrounding ground. Table 5. shows each value of 1) – 4) in Figure 11 b).where $R_p = A_e \cdot E \cdot \Delta S/L$, A_e:area of pile (m^2), E:young's modulus (kN/m^2), ΔS : settlement (mm), L: length (m), R_f = estimated value based on static bearing capacity equation, $R_{x1} = A_{x1} \cdot \tau_{x1}$, A_{x1}: compression area of soil mass beneath soil improvement columns, τ_{x1}: degree of resistance mobilized at compression area, $R_{x2} = A_{x2} \cdot \tau_{x2}$, A_{x2}: side area of soil improvement columns, τ_{x2}: shear strength of ground around the soil improvement columns = 31.25 kN/m^2 (cohesion of ground, $c = q_u/2$, $q_u = 12.5\ N = 12.5 \times 5 = 62.5$ kN/m^2)

b).

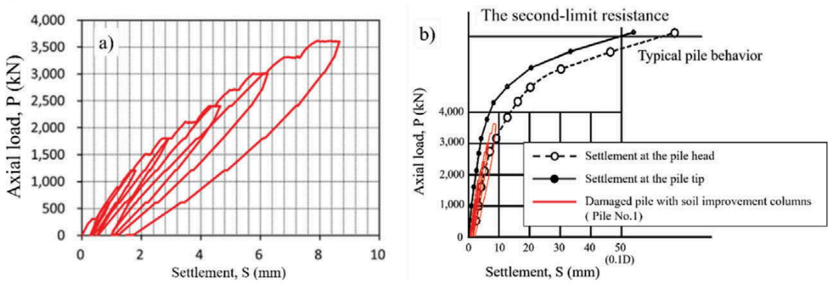

Figure 10 a). Load – Settlement relationship, b) Comparison between this test result and typical single pile behavior (The Japanese Geotechnical Society. 2002)

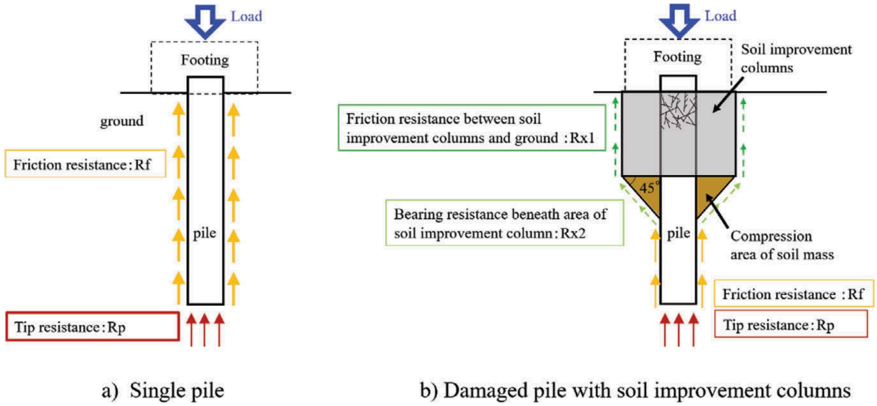

Figure 11. Bearing mechanisms of single pile and damaged pile reinforced by soil improvement columns

Table 5. Each resistance value 1) – 4) in Figure 11 b)

1)	R_p = 961kN
2)	R_f = 1,952kN
3)	$R_{x^1} = R_u - (R_p + R_f + R_{x^2})$ = 3,600 – (961 + 1,952 + 188) = 499 kN
4)	R_{x^2} = 188 kN

5 CONCLUSIONS

The static axial compressive load test of the damaged pile which was repaired and reinforced using jet grouting was conducted. The following two factors were revealed by confirming the quality of jet grout columns and the static axial compressive loading test.

1. Soil improvement columns by jet grouting satisfied the specified design strength. Results from visual observation by exposing the head of the columns by excavation, showed that the design diameter was also satisfied. In addition, the breakage portion and the hollow portion of the damaged pile has been filled with soil improvement columns.
2. It was confirmed that damaged pile reinforced by soil improvement columns has a performance not less than the allowable bearing capacity in the initial design by the axial loading test

In conclusion, it is proved that jet grouting is effective for pile repair and reinforcement as an axial load. The examination of lateral resistance of a pile reinforced by soil improvement columns will be conducted in the next plan.

REFERENCES

Japanese Standards Association, 2009. *Method for unconfined compression test of soils*, JIS A 1216. (in Japanese)

Shimamura, A., Inoue, N., Tai, H., Kusunoki, K. Kashiwa, H., Futaki, M. and Kuze, N., 2018. Study on repair and reinforcement for damaged pile using jet grouting parts 1–3 (in Japanese), *Proc. Annual Meeting of AIJ (Architectural Institute of Japan)*., *Tohoku*, 4–6 *September 2018*. 507–512.

The Building Center of Japan. 2009. *The guideline of design and quality control of ground improvement for buildings –Soil mixing using cement material - Revised edition* (in Japanese), 238–251, Tokyo: The Building Center of Japan

The Japanese Geotechnical Society. 2002. *Method for Vertical Load Test of Piles 1st revision edition* (in Japanese), Tokyo: The Japanese Geotechnical Society