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Development of high-speed type jet grouting method

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ABSTRACT: Jet grouting method uses high-pressured grout slurry to erode and mix in-situ soil to install soil-cement mixture columns. With a lot of excellent characteristics, it is also important to get full use of grouting energy to achieve efficient construction together with quality control. Thus, we've independently developed high efficient jet grouting device with two nozzles oppositely. With the confirmation by full-scale test, "V-JET Method" with large-diameter and high-speed installation was put into practical application with economic efficiency and lower impact on the environment than conventional methods. Furthermore, "Eroding Measurement Technique" was also developed for sound collection during jet grouting to ensure the quality of column diameter.

1. INTRODUCTION

Jet grouting method uses high-pressured grout slurry to erode and mix the in-situ soil to install soil-cement mixture columns. The method has been developed more than 40 years since it was applied in practice in Japan. Jet grouting method has a lot of excellent characteristics. It carries out installation with small drilling holes of approximate 10cm diameter to produce column from 2m to 5m diameter. It also applies for wide range of soil conditions and high improvement strength, *etc*. [1)].

However, it is hard to uniform the diameter of columns under the influence of ground conditions and jet grouting parameters such as grouting quality, lift rate and eroding times, *etc*. Therefore, we usually carry out conservative consideration on design stage and field test demonstrates if the consideration is correct. On the other hand, general parameters (grout flow rate, grout pressure, lift rate, *etc*.) in jet grouting work are on considerably safe side. As a result, they may need large amount of grout slurry and cost comparing to other soil improvement techniques. Moreover, such conservative consideration tends to produce large quantities of sludge disposal that has serious environmental impact.

It is important to get full use of grouting energy together with achieving efficient eroding and mixing for jet grouting construction. Moreover, the issues to be solved are such as design and construction to control column diameter, efficient quality control with eroding measurement by real-time.

To cope with the above subjects, we independently developed high efficient jet grouting device with two nozzles on opposite sides of the device. With the confirmation by basic experiment and full-scale test, jet grouting method "V-JET Method" with large-diameter and high-speed installation was put into practical application. Furthermore, "The Eroding Measurement Technique of the Ground" was developed in the manner of pre-installing several pipes into the ground for sound collection during jet grouting.

Efficient jet grouting device with small energy loss has been simultaneously developed. Also, it is crucial to discover appropriate parameters.

This paper reports results of full-scale test and summaries investigation result of excavated column comparing with the parameters for installation. Further variation of the column diameter is discussed concerning sound monitoring results.

2. OVERVIEW OF V-JET AND FULL-SCALE TEST

V-JET method, as shown in Figure 1, can be classified as "Double fluid jet grouting" by using high-pressured grout slurry together with shrouding high speed air. The grout slurry shall be transferred by high-pressured hose together with double tube rods and grouted by horizontal jet grouting device with designated rotation and lift rate to install an improved column in the ground.

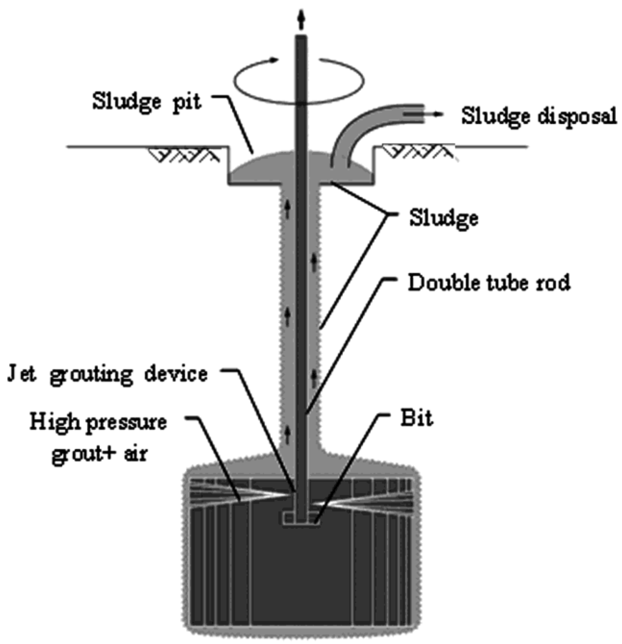

Figure 1. Overview of innovative jet grouting technique

It is an important subject how eroding and mixing can be carried out efficiently by jet grouting method. In particular, it is essential to transfer injected grout slurry by high pressure pump to the ground without any energy loss. It is crucial to minimize energy loss in to achieve efficient performance in jet grouting. Therefore, the development of V-JET method has focused to use the energy as efficient as possible. Such innovative jet grouting succeeds high speed jet grouting and drastically reduces the grout slurry and sludge disposal. Since this jet grouting device is so important to influence eroding performance of jet grouting, we carried out several jet grouting tests of different parameters in the water tank and confirmed the most efficient parameters of jet grouting device for field test.

Full-scale test was carried out to confirm workability by developed system and quality of the column under the parameters. As shown in Figure 2, trial columns were installed in clayey sand layer of about 10 *SPT-N* value and gravel layer of about 30 *SPT-N* value. As shown in Table 1, 6 trial columns were installed under different parameters, which were based on the experience so far and were representative in grout flow rate, air flow rate, rod rotation and lift rate. And two types of jet grouting device (type I and type II) are applied to fit required grout flow rate.

This field test involved measuring grout and air pressure, grout and air flow rate, sludge volume, specific gravity and sand content in the sludge. In addition, erosion measuring system was advanced in the field test. The advanced system collected sound of jet grouting eroding pre-installed steel pipes and analyzed amplitude to assume the situation of jet grouting breaking the ground. And, the correlation with the analyzed amplitude and column diameter was investigated by column excavation.

Table 1. Cases and main parameters for field test

Case		A	B	C	D	E	F
Jet grouting parameters	Jet grouting device type	Type I	Type I	Type I	Type I	Type II	Type II
	Grout pressure (MPa)	37	35	37	35	34	34
	Grout flow rate (l/min)	320	400	400	400	600	600
	Air pressure (MPa)	0.95	0.95	0.90	0.95	0.95	0.95
	Air flow rate (m^3/min)	10	14	13	14	15	15
	Rods rotation (rpm)	4	5	5	4	4	3
	Lift rate (m/min)	13	6	10	16	14	20

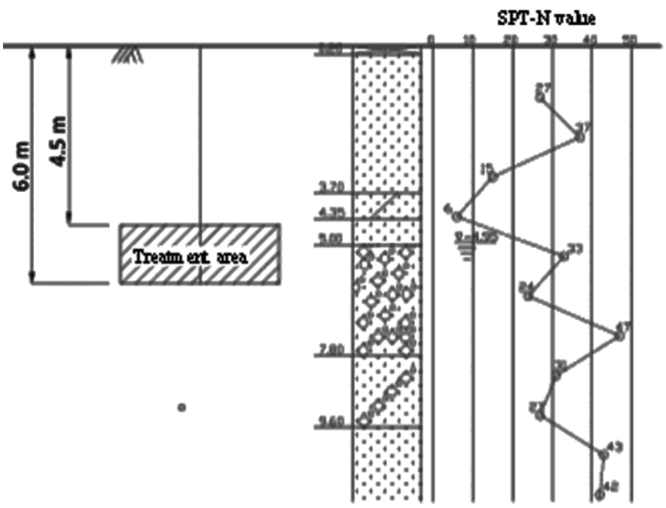

Figure 2. Soil condition and treatment depth

3. PRINCIPLE OF EROSION MEASURING OF GROUND AND ADVANCED MEASURING SYSTEM

The variation of eroding sound with time was carefully analyzed. Mountain-shaped pattern in amplitude as shown in Figure 7 were confirmed whenever jet grouting reaches pipes. The strength of erosion by jet grouting is proportional to the amplitude of the pattern. Thus, the performance of jet grouting was evaluated by investigation of amplitude and pattern in erosion measuring analysis.

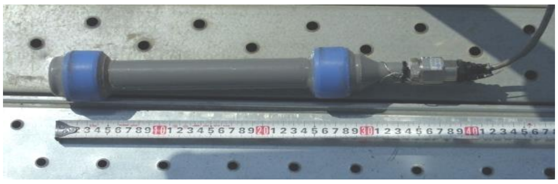

Figure 3. Sound collector

Figure 4. Automatic hoist device

Figure 5. Control device

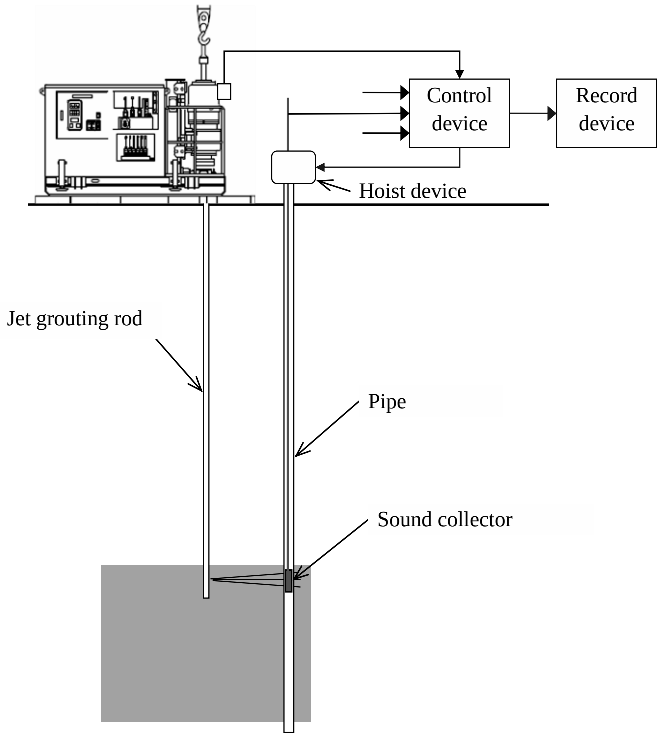

Figure 6. Eroding measurement system

Advanced measuring system is composed of sound collector, hoist device and control device as shown in Figure 6. Sound collector is inserted into pre-installed steel pipe to collect the sound as shown in Figure 3. Hoist device raises sound collector together in accordance with the rod withdrawal as shown in Photo 2. Control device can collect and record the data of eroding sound and grouting depth as shown in Photo 3. Firstly, several pipes shall be installed by boring at designated location in estimated column area before grouting. The locations of pipes shall be on 3 or 4 different distances from the column center. Secondly, the sound collectors inside pipes shall measure and record the sound of jet grouting eroding the pipes. Then, the data of sound records shall be analyzed to evaluate how jet grouting break or fragment the ground.

Table 2. Jet grouting parameters and construction results

Case		A	B	C	D	E	F
Jet grouting parameters	Jet grouting device type	Type I	Type I	Type I	Type I	Type II	Type II
	Grout pressure (MPa)	37	35	37	35	34	34
	Grout flow rate (l/min)	320	400	400	400	600	600
	Air pressure (MPa)	0.95	0.95	0.90	0.95	0.95	0.95
	Air flow rate (m^3/min)	10	14	13	14	15	15
	Rods rotation (rpm)	4	5	5	4	4	3
	Lift rate (m/min)	13	6	10	16	14	20
Construction results	Specfic gravity of sludge	2.00	2.02	2.00	2.00	2.03	1.92
	Slurry content in the sludge	0.28	0.39	0.37	0.38	0.33	0.66
	Averagecolumn diameter (m)	3.53	3.92	4.55	4.65	5.21	5.12
	Average copressive strength (N/mm^2)	7.7	3.5	5.1	6.6	20.3	23.3
	Unit grout flow rate (m^3/m^3)	0.43	0.20	0.25	0.38	0.39	0.58

❖All of grout pressure and flow rate, air pressure and flow rate are actual values

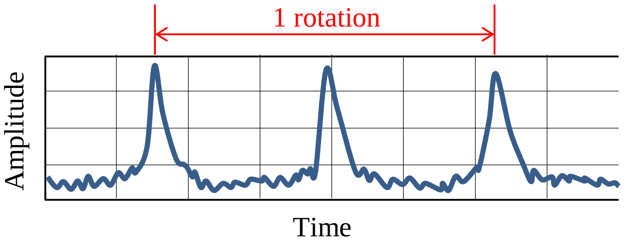

Figure 7. Amplitude pattern (model)

4. RESULT OF FULL-SCALE TEST

Table 2 summarizes actual parameters and result of investigations and tests of each case of field test. We measured the specific gravity of the sludge by jet grouting and the weight of sand content included in the sludge by sieve analysis. The slurry content in the sludge was estimated by cement content in the residue after sieve analysis for sand content. The specific gravities of sludge are approximate 2.0 except in case F, in which the specific gravity is 1.9. On the other hand, slurry content of case F is more than 0.6 and is greater than other cases. That is to say, the smaller volume jet grouting breaks the soil (namely treat the soil) per grout flow rate, the smaller specific gravity the sludge has.

The columns were carefully excavated as shown in Pohoto 4. As a result, average column diameter was derived from the average distance from the center on 4 or 8 directions with every 10cm deep. As column volume can be calculated by average column diameter, unit grout flow rate in Table 2 was derived from column volume and grout flow rate. Regarding to case A~D using jet grouting device type I, average compressive strength ranges from 3N/mm^2 to 8N/mm^2 and has normal correlation with unit grout flow rate. While, average compressive strength in case E and F by jet grouting device type II was considerably larger than other cases because high strength specimen was likely to be selected. Situation of sludge collection and result of core sampling that some property in these cases had caused trouble in uniform mixing.

Figure 8. Excavated jet grouting columns

The results by using jet grouting device type I was close to the expected dimension and quality of the column. However, case E and F by using jet grouting device type II indicated that the device and the jet grouting parameters had issues to be solved since several values of slurry content in the sludge and compressive strength are clearly different from other cases.

Table 3. Parameters for full-scale test

Case		A	B	C	D
Ground strength (SPT-N value)	Upper part (clayey sand)	10	10	10	10
	Lower part (gravel)	30	30	30	30
Grout pressure	P_m (MPa)	37	35	37	35
Nozzle diameter	d_0 (cm)	0.39	0.44	0.44	0.44
Air flow rate	Q_e (Nm^3/min)	5.0	7.0	6.5	7.0
Moving speed	Vtr (cm/s)	73.9	102.6	119.1	97.4
Eroding times	N	2.6	1.5	2.5	3.2
Eroding distance S_0 (cm)	Upper part (clayey sand)	170	189	227	236
	Lower part (gravel)	190	208	229	229
	Average	178	196	228	233

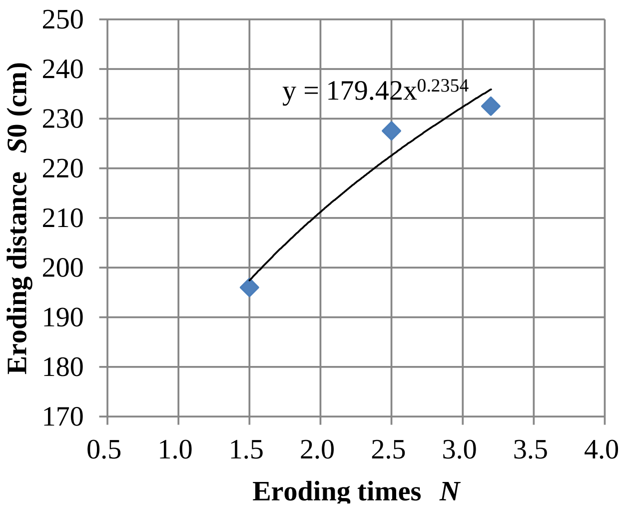

Figure 9. Correlation between eroding times and eroding distance

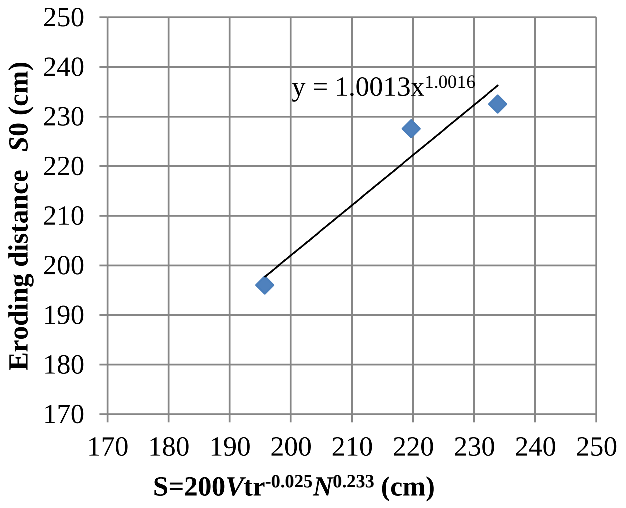

Figure 10. Correlation between moving speed and eroding distance

5. PRINCIPLE OF EROSION MEASURING OF GROUND AND ADVANCED MEASURING SYSTEM

Based on reference researches, column diameter, in other words, eroding distance S by jet grouting, is affected by grout pressure P_m, nozzle diameter (flow rate) d_0, grouting moving speed V_{tr}, eroding times N, and ground strength σ_c as

$$S = f(P_m, d_0, V_{tr}, N, \sigma_c) \quad (1)$$

which was reported by the research achievement[2]. In addition, the author also confirmed the high correlation between S and air flow rate Q_e[3]. This section focuses on the correlation between jet grouting parameters and column diameter of jet grouting device type I in full-scale test.

The above parameters of case A~D are summarized in Table 3. Ground strength was divided into upper part (clayey sand) and lower part (gravel) by *SPT-N* value. The moving speed refers to moving speed of jet grouting along outer boundary of the column with averaged diameter. And, eroding times refers to the times of grouting on the point of the arc. Furthermore, ground eroding distance refers to the average value of the distances measured from the column center.

Case B~D were carried out by the same parameters of grout pressure P_m, nozzle diameter d_0 and air pressure Q_e with different grouting moving speed V_{tr} and eroding times N. Correlation between eroding times N and ground eroding distance S_0 is shown in Figure 9. Besides, when the eroding distance S can be estimated on the assumption of $S=a.V_{tr}^{b}.N^{c}$, Figure 10 demonstrates validity in this assumption expressed in equation (2).

$$S=200V_{tr}^{-0.025}.N^{-0.233} \quad (2)$$

This correlation indicates that the ground eroding reaches longer distance if eroding times increases. As a reference, 10% of ground eroding distance will increase if eroding times increases from 2 times to 3 times. While, moving speed in the range of this time (V_{tr}=95~120cm/s) does not have significant influence on ground eroding distance.

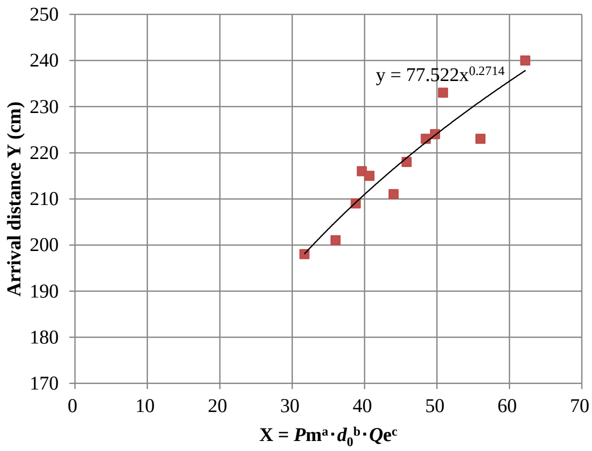

Figure 11. Evaluation of eroding distance based on performance function on jet grouting device

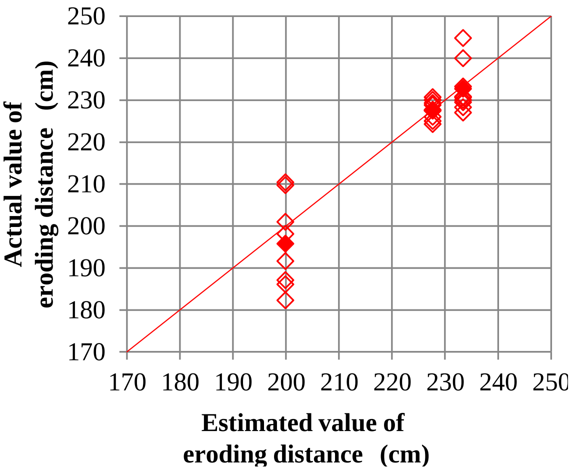

Figure 12. Correlation between actual and estimated eroding distance

Jet grouting test in the water tank was carried out to confirm the performance of jet grouting device type I used in the full-scale test this time. Figure 11 shows correlation between ground eroding distance and an essential energy for erosion. The essential energy is assumed to have function of grout pressure P_m, nozzle diameter d_0, air pressure Q_e and arrival distance Y of jet grouting. In this estimation, the essential energy of ground eroding was adjusted to suit the column diameter of the field test.

$$Y=77.5P_m^{0.271}\cdot d_0^{0.325}\cdot Q_e^{0.190} \quad (3)$$

Equation (3) shows that arrival distance Y is significantly influenced by nozzle diameter d_0. Namely, flow rate of jet grouting has important role for eroding the ground.

Discussion represented in Equation (2) and (3) can derive comprehensive correlation between ground eroding distance and each parameter as expressed in Equation (4). However, this equation is only applicable to sandy soil ground with *SPT-N* value from 10 to 30 because the equation does not include parameter in soil strength. Moreover, each parameter shall be applied in a range confirmed by the field test as indicated below.

$$S=64.0P_m^{0.271}\cdot d_0^{0.325}\cdot Q_e^{0.190}\cdot N^{-0.233}\cdot V_{tr}^{-0.025} \quad (4)$$

where, S= ground eroding distance (cm), $P_{m=}$ Grout pressure (MPa) (35< P_m < 40); $d_{0=}$ Nozzle diameter (cm) (0.35< d_0 <0.45), Q_e = Air flow rate (Nm^3/min) (5.0≦ Q_e <7.0); V_{tr}= Moving speed (cm/s) (95< V_{tr} <120), N= Eroding times (1.5 < N < 3.5)

Figure 12 shows the correlation between estimation from the equation above and actual value by full-scale test.

Even though dispersion occurred because each plot of ground eroding distance was collected in particular case, Figure 12 demonstrates general correlation. The result indicates that it is possible to get higher correlation if further data set is collected together with information of the influence on ground strength.

6. CORRELATION BETWEEN THE RESULT OF ADVANCED EROSION MEASURING AND COLUMN DIAMETER

Regarding to full-scale test, the advanced erosion measurement was applied to case C and E. The locations of each steel pipe for the measurement are summarized in Table 4.

Table 4. Locations of pipes for eroding measurement

Case	Grout depth	Location of pipe installation (from jet grouting center)
C	GL-4.5~6.0m	1.50m, 1.75m, 2.00m, 2.25m
E	GL-4.5~6.0m	2.00m, 2.25m, 2.50m, 2.75m

Figure 13 shows an example of analysis in erosion amplitude in case C. The closer the measuring pipe locates to jet grouting center, the larger and the sharper the amplitude has in mountain-shaped pattern. Figure 14demonstrates that jet grouting completely erodes the soil at pipe location and supports that degree of erosion at the pipes correspond to amplitude and sharpness of the pattern.

Degree of erosion by jet grouting was evaluated by considering of the correlation between amplitude and column diameter. Every erosion by jet grouting at the pipe location is recognized in peak amplitude at a regular interval and typically produce mountain-shaped pattern. The energy of erosion at the pipe location varies simply in proportion

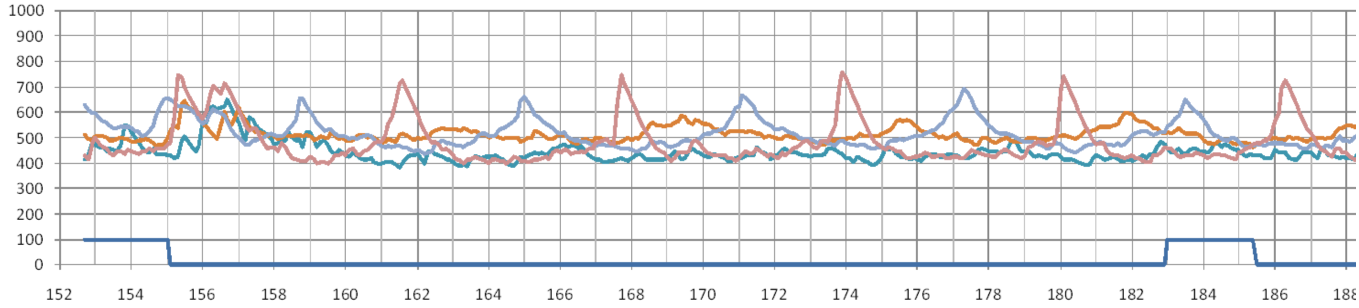

Figure 13. Amplitude patterns in the field test (case C)

Figure 14. Excavated column and erosion around measuring pipes (case C)

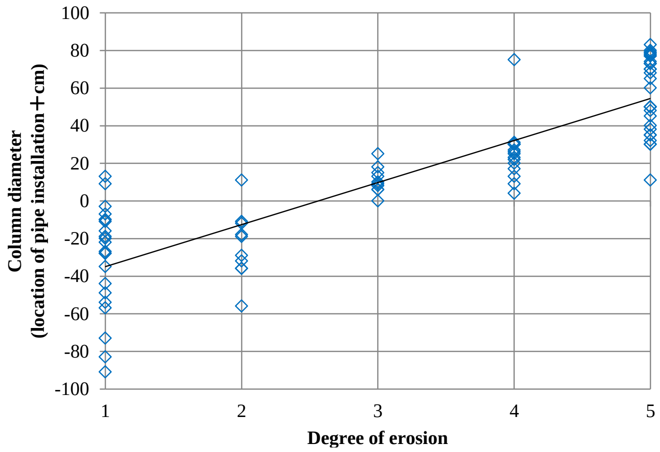

Figure 15. Degree of erosion per classification of amplitude

to amplitude of the pattern. Amplitude was divided into five grades by height of the peak and shape of the mountain-shaped pattern. Fugure-10 demonstrates that the column diameter correlates with amplitude of erosion sound. The deviation from pipe location to column edge indicates that amplitude more than level 3 ensures that erosion by jet grouting reaches the pipe location at least. Secondly, effective amplitude represented by difference between maximum amplitude and background amplitude at every depth investigated in order to evaluate vertical distribution of column diameter. Figure 16 shows the distribution of effective amplitude at every depth in case 3 of the field test. It is clear that stronger effective amplitude results from larger eroding energy at the pipe location.

Depth	Location of pipes from jet grouting center			
	1.50m	1.75m	2.00m	2.25m
4.5m	335	312	248	269
4.6m	342	316	257	294
4.7m	304	316	259	269
4.8m	339	414	278	228
4.9m	330	336	284	351
5.0m	320	266	213	284
5.1m	387	367	238	165
5.2m	368	304	247	222
5.3m	390	302	274	235
5.4m	406	273	225	288
5.5m	372	277	251	227
5.6m	406	262	166	248
5.7m	332	248	149	131
5.8m	361	250	126	104
5.9m	325	224	161	194
6.0m	290	220	88	130

Figure 16. Distribution of amplitude (Case C)

Thus, effective amplitude shows excellent correlation with column diameter as shown in Figure 12. In addition, the pipe location satisfies column radius if effective amplitude have more than 200.

In this way, proper erosion measuring system assists development of jet grouting device and establishment of proper parameters. The advanced erosion measuring system discussed in this section contributes to evaluation of required performance in jet grouting of the field test, especially when the jet grouting has special requirement (*e.g.* in column diameter, column strength and special soil such as organic soil or completely decomposed rock) differing from general requirement and condition.

7. CONCLUSIONS

Highly efficient jet grouting device has been developed to achieve high-speed installation of jet grouting column with large-diameter. This innovative jet grouting system provides remarkable advantages such as not only time saving and economic efficiency, but also less sludge disposal and smaller impact on the environment than in conventional technology.

Eroding sound measurement has been advanced in order to evaluate required performance in jet grouting. The advanced eroding measuring system enables to assess column diameter vertically and continuously. Moreover, this system provides proper parameters for the performance required in particular project, in development of any jet grouting techniques and in installation to special soil condition.

8. REFERENCES

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