13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 38

PROOF EXPERIMENT USING ARTIFICIAL EARTHQUAKE CONCERNING EFFECT OF PERMEABLE GROUTING METHOD AS MEASURES AGAINST LIQUEFACTION

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SUMMARY

In this study, we conducted a field experiment to confirm the liquefaction resistance of Permeable Grouting Method.

From the result of the measured data of the acceleration in the ground, the steel sheet-pile displacement, the steel sheet-pile back earth pressure, the excess pore water pressure, and the ground subsidence, it is found that improved soil by this method has remarkable resistance against liquefaction. From the observation of the improved region after the experiment, any phenomenon such as evidence of sand boil was not found at all.

Thus, through this real large scale field experiment, the capability of the Permeable Grouting Method for prevention of liquefaction occurrence and for reducing the earth pressure were proved.

INTRODUCTION

On November 13, 2001, Port and Airport Research Institute and fourteen organizations in Japan and the U. S. have conducted joint research on "Full-scale Experiment Concerning Improvement of Earthquake-proof Functions in Ports and Waterfront Cities" [1] on the reclaimed ground at Tokachi Port, Hokkaido. A full-scale model of the steel sheet pile quay with 5.5m in depth was constructed. The liquefaction and the vibration of the ground were reproduced by the blast with the emulsion dynamite where three dimensions were arranged behind the quay. We confirmed the effect of countermeasure against liquefaction by the Permeable Grouting Method as one of the joint researches.

In this paper, at first, the outline and characteristic of the Permeable Grouting Method is shown. Next, the results of the experiments are shown. This paper describes the comparison of the acceleration and the sheet pile displacement, etc. in the area improved by the Permeable Grouting Method and in the original ground respectively. Moreover, it is found that the Permeable Grouting Method is effective to the countermeasure against liquefaction and the earth pressure decrease by conducting the full-scale experiment.

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PERMEABLE GROUTING METHOD

Outline of the method

The Permeable Grouting Method [2-5] was developed aiming to prevent liquefaction beneath or near the existing structure. As shown in Figure-1, in this method, the ground is improved by boring the ground, injecting the chemical grout of the solution type and solidifying that grout. Though it is necessary to install the boring hole in the ground, the preventing liquefaction is possible directly against the ground right under the existing structure. By injecting the chemical grout, it became possible to produce improved soil in an area of 4m in diameter under certain ground conditions. Therefore, the injected chemical grout has good permeability and permanent. Photo-1 shows the shape of improved soil with a diameter of 2.5m, which was confirmed by excavation at the test site in Matsuzaka City in Japan after the injection of chemical grout.

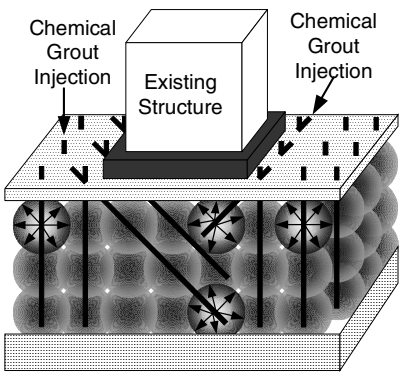


Figure-1 Image of Permeable Grouting Method

Photo-1 Shape of Improved Soil

Characteristic of the method

Comparison with the conventional chemical grouting method

As shown in Table-1, the difference from the conventional chemical grouting method is as follows.

1) The chemical grout must infiltrate a wide-ranging ground (about 4m in maximum diameter) from one injection exit.
2) Strength of the improved soil must be low strength (About q_u=100kN/m^2).
3) The chemical grout must have permanent.

So, to enlarge the range of infiltration especially, the gel time of the chemical grout will be set in several hours. And, as shown in Figure-2, the length of the injection exit is about 50cm longer than usual length of about 10cm. Thus, in the injection exit having become long, more chemical grouts' being injected into the ground by low pressure became possible.

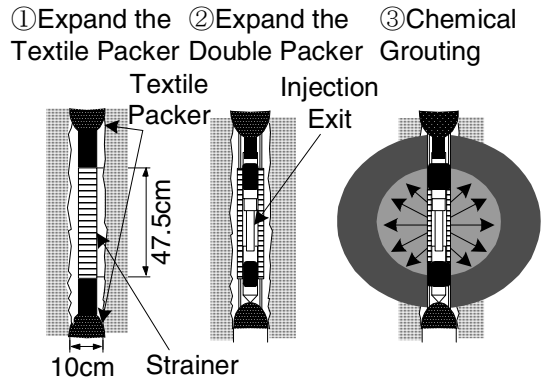


Figure-2 Strainer-Type Grouting Plant

Comparison with other solidification methods

The Permeable Grouting Method has the following difference with the solidification methods with cement etc. like the Premixing Method [6]. As shown in Figure-3, when the sandy soil is solidified by the Premixing Method, only the contact point of the particle of the sand is solidified with cement and the

Table-1 Comparison with Conventional Chemical Grouting Method

	conventional chemical grouting method	Permeable Grouting Method
Grout	Cement Type Water Glass Type	Colloidal Silica
Scale of Grouting	Limited Area	Wide Area
Penetration Area	about Diameter of 100cm	Max Diameter of 400cm
Unconfined Compressive	about 200 ~ 1000kN/m^2	about 50 ~ 100kN/m^2
Durability	Temporary	Long Term Strength

ground is not liquidized, but the pore water remains between the particles of the sand. In the Permeable Grouting Method, because the pore water in the particles of the sand is substituted by the chemical grout and the grout gels and the pore of the soil is completely full of the gel, there is a feature that not only uniting particles of sand but also the pore water is driven out. Therefore, in the improved ground by the Permeable Grouting Method, even if a big earthquake occurs from the design earthquake and the liquefaction resistance is insufficient, it is thought that the sand boil and the second liquefaction of the ground in the surrounding according to the spread of the excessive pore water pressure does not happen because of no pore water in the ground.

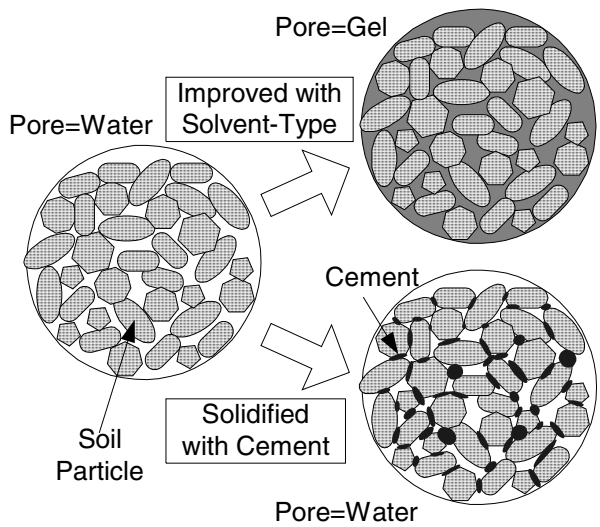


Figure-3 Improved Image by Solidification Methods

Characteristic of the chemical grout

The chemical grout used by this method is a solvent-type permanent chemical with Na^+ ion removed, which causes degradation, from water glass using an electro-osmosis membrane. Figure-4 shows the comparison of durability between the conventional chemical grout and the Special Silica used by this method. This Figure is a graph showing the leaching ratio of SiO_2 from a solid substance that causes strong degradation of improved soil. Furthermore the data other than that of Special Silica in the graph was quoted from Yonekura (1992) [7]. As is apparent from the Figure, the conventional chemical has over 10% leaching ratio, whereas Special Silica has only a few percent. We can tell from this that the improved soil by Special Silica has long durability.

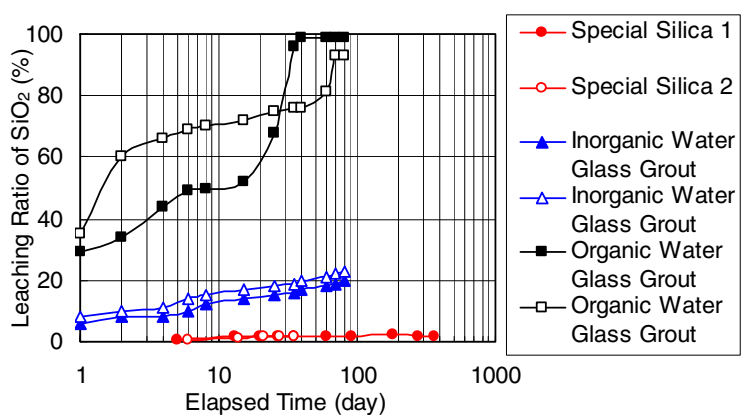


Figure-4 Leaching Ratio of SiO_2 from Solid Substance

Characteristic of the improved soil

Figure-5 shows the liquefaction resistance of the untreated soil of the Niigata sand and the improved soil to q_u=100kN/m^2 of the Niigata sand. From this Figure, the liquefaction resistance of the improved soil becomes twice or more the untreated soil. Figure-6 shows the time scale history of the cyclic deviator stress ratio, the axial strain and the excess pore water pressure ratio and the effective stress pass of the untreated soil of the Rokko masado under the cyclic triaxial test. Similarly, Figure-7 shows a result of the improved soil of q_u=60kN/m^2 of the Rokko masado. In the untreated soil, when the excess pore water pressure ratio approaches 1.0, the axial strain is rapidly generated, the effective stress becomes zero and the liquefaction is generated. On the other hand, in the improved soil, when the excess pore water pressure ratio approaches 1.0, the axial strain is not rapidly generated, the effective stress does not become zero and the liquefaction is not generated. Therefore, for the improved soil, even if the loads bigger than the liquefaction resistance acts, the liquefaction that usual sand becomes like the liquid is not generated and it is thought that the improved soil has stickiness like clay.

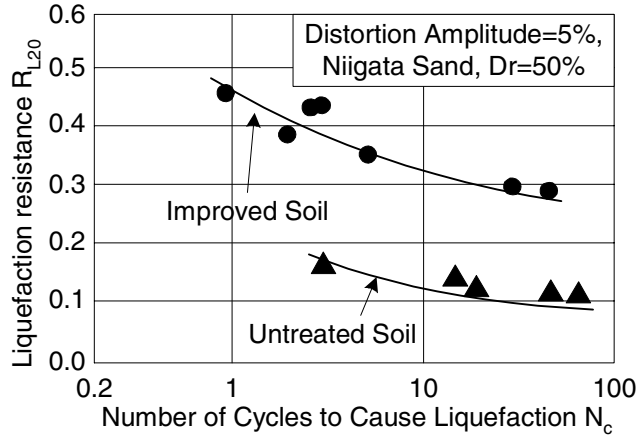


Figure-5 Liquefaction Resistance of Improved Soil and Untreated Soil

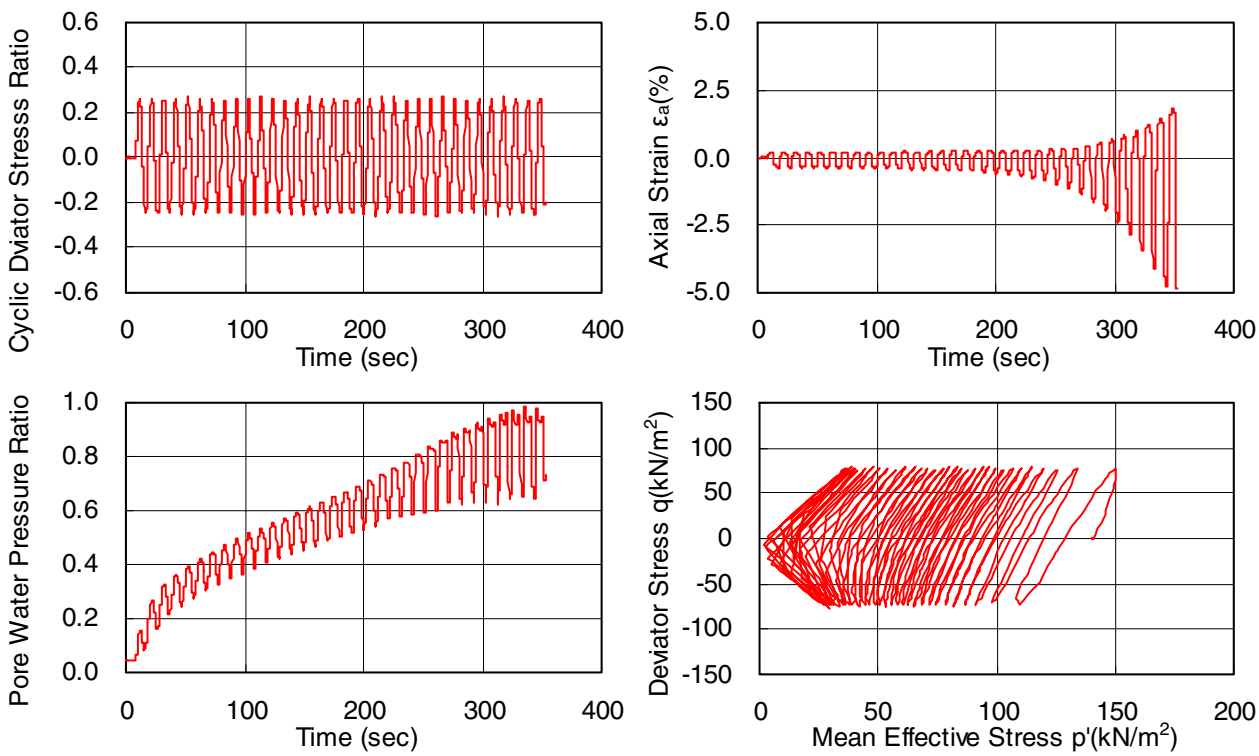


Figure-6 Results of Cyclic Triaxial Test of Untreated Soil

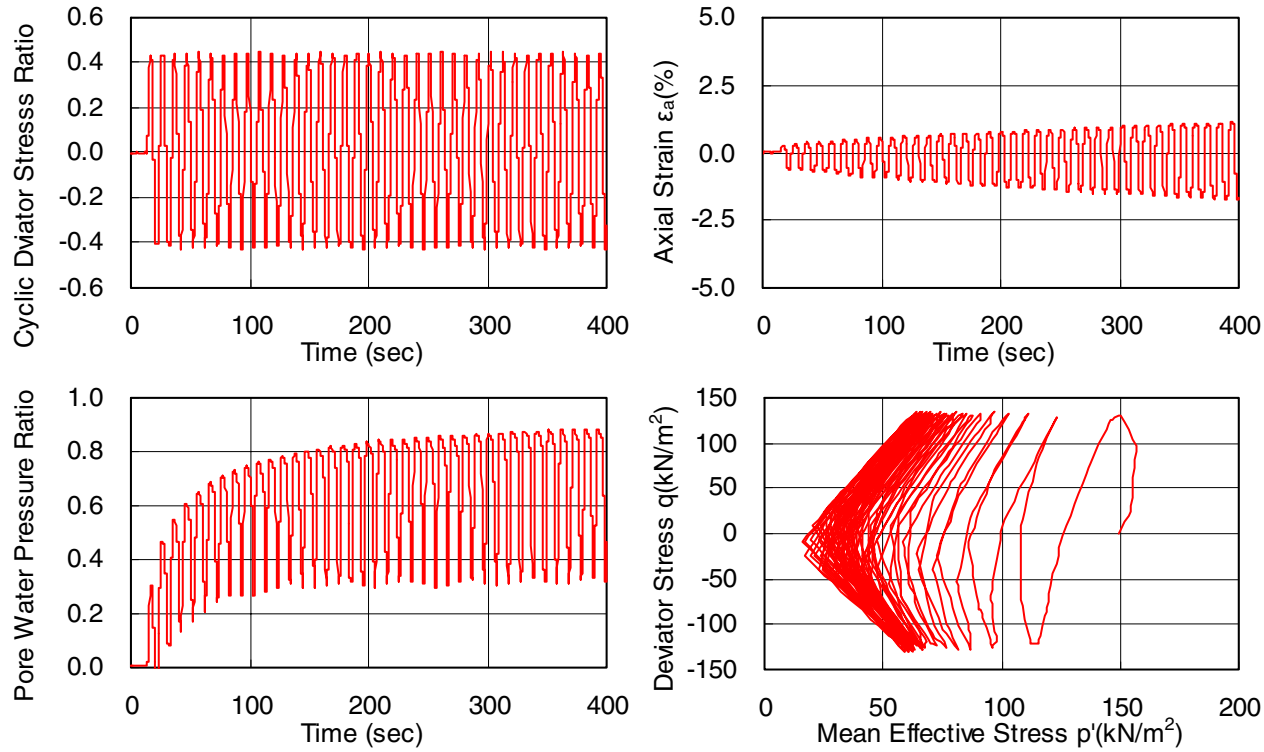


Figure-7 Results of Cyclic Triaxial Test of Improved Soil

Figure-8 shows the relationship between the unconfined compressive strength (q_u) and the liquefaction resistance (R_{ck}) of the improved soil. The liquefaction resistance (R_{ck}) is a shear stress ratio when the cyclic loads become 20 times and the distortion amplitude reaches 5% under the cyclic triaxial test. From this Figure, it is understood that R_{ck} strengthens when q_u strengthens, and there is a significant relation up to both. The liquefaction resistance is R_{ck}=0.5 in q_u=80-100kN/m^2, and this is corresponds to the liquefaction resistance for usual dense sand, and considerably large liquefaction resistance.

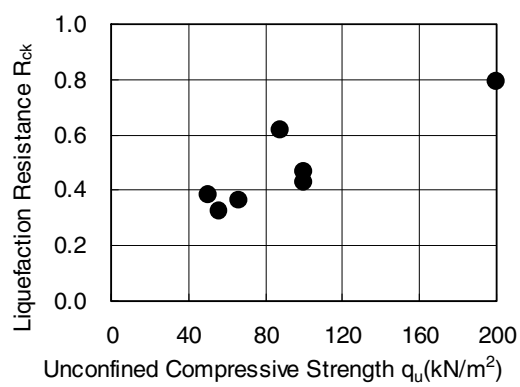


Figure-8 Relationship between R_{ck} and q_u

FULL-SCALE PROOF EXPERIMENTS

Outline of experiments

Experiment yards

Figure-9 shows the whole arrangement of the experiment yard. Earthquake-proof design steel sheet pile quay (design seismic coefficient, k_h=0.15) and traditional design steel sheet pile quay (k_h=0) were constructed in the Tokachi Port landfill. The structural type of the quays was raking pile type, they were 5.5m in front depth, and extended 25m. The range of 75m behind the quay walls was maintained as the experiment yard. Each participated in the joint research organization set up the experiment equipment

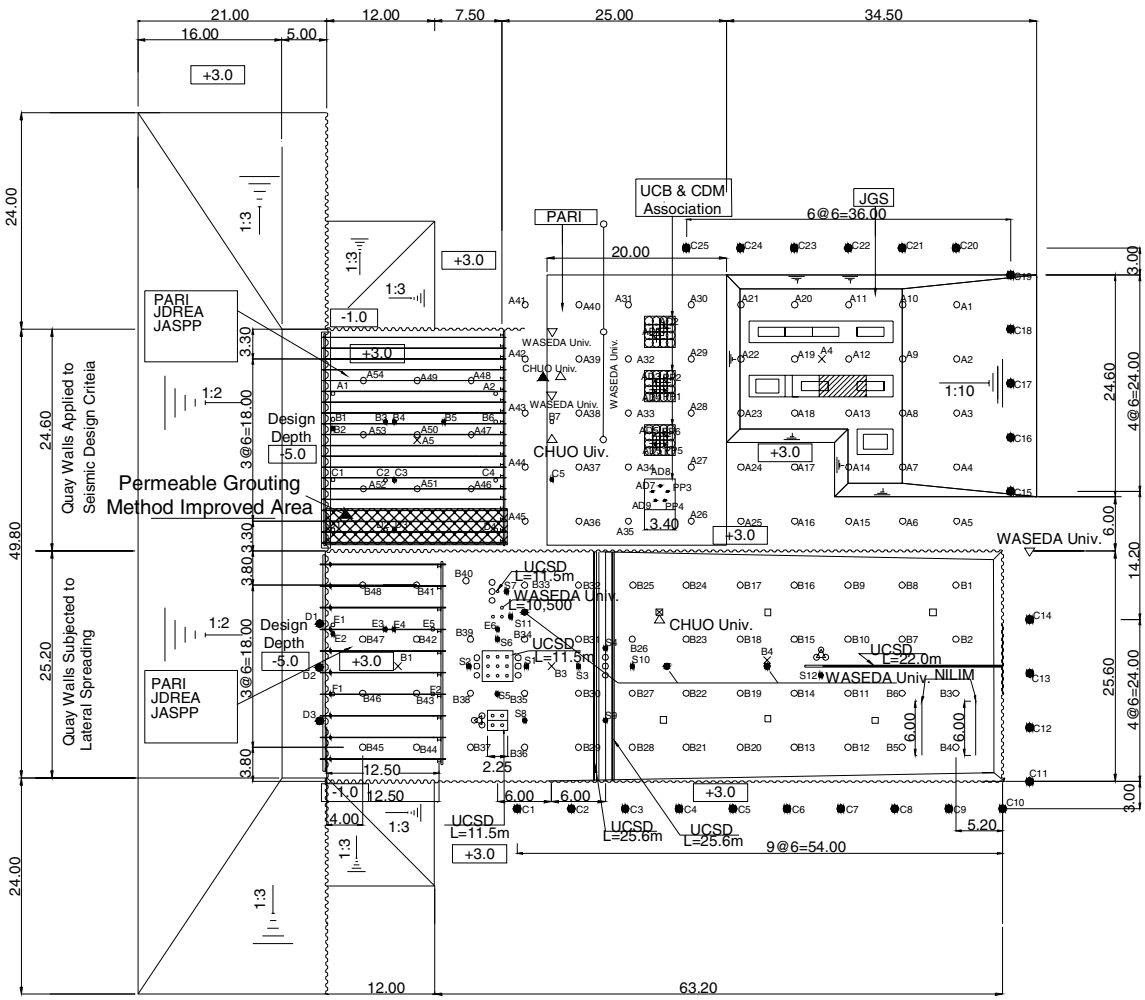


Figure-9 Experiment yards

within the range. The emulsion dynamite was used for generating an artificial earthquake. 102 holes were made in the experiment yard to mount dynamites. Furthermore, another 25 holes were made surroundings the area. Two dynamites were set up for each 127 holes in total. In the experiment yard, blasting started from a place that was the furthest from the quay at the earthquake-proof design quay and the traditional design quay, simultaneously. After blasting reached quays in the experiment area, the blast outside the area, which had been set up in a basic layer, was done. The blast was done at 0.7 seconds intervals and started about 7 seconds after the experiment begun. It reached the place between the raking piles about 39 seconds later and the blast in the area ended about 45 seconds later. Afterwards, the blast outside the area was done. The entire vibration time was about one minute.

Construction of Permeable Grouting Method

Using a part of the earthquake-proof design steel sheet pile quay coducted the experiment of the Permeable Grouting Method. Figure-10 shows the range improved by the Permeable Grouting Method and the arrangement of measuring instruments and apparatus. The difference of the behavior of the tie-rod and the tie-wire was observed in the earthquake-proof design quay with 25m. Therefore, since there may be an influence on other experiments if the foundation improvement work by the Permeable Grouting

Method is widely done; Plane arrangement of the improvement was 4.0m×20.0m. For the behavior comparison between the improvement region and the original ground area, the measurements of the acceleration meter, pore water pressure meter, earth load gauge, and the load cell (tensile meter) set up at the position in the figure, and the displacement gauge and the subsidence board was used.

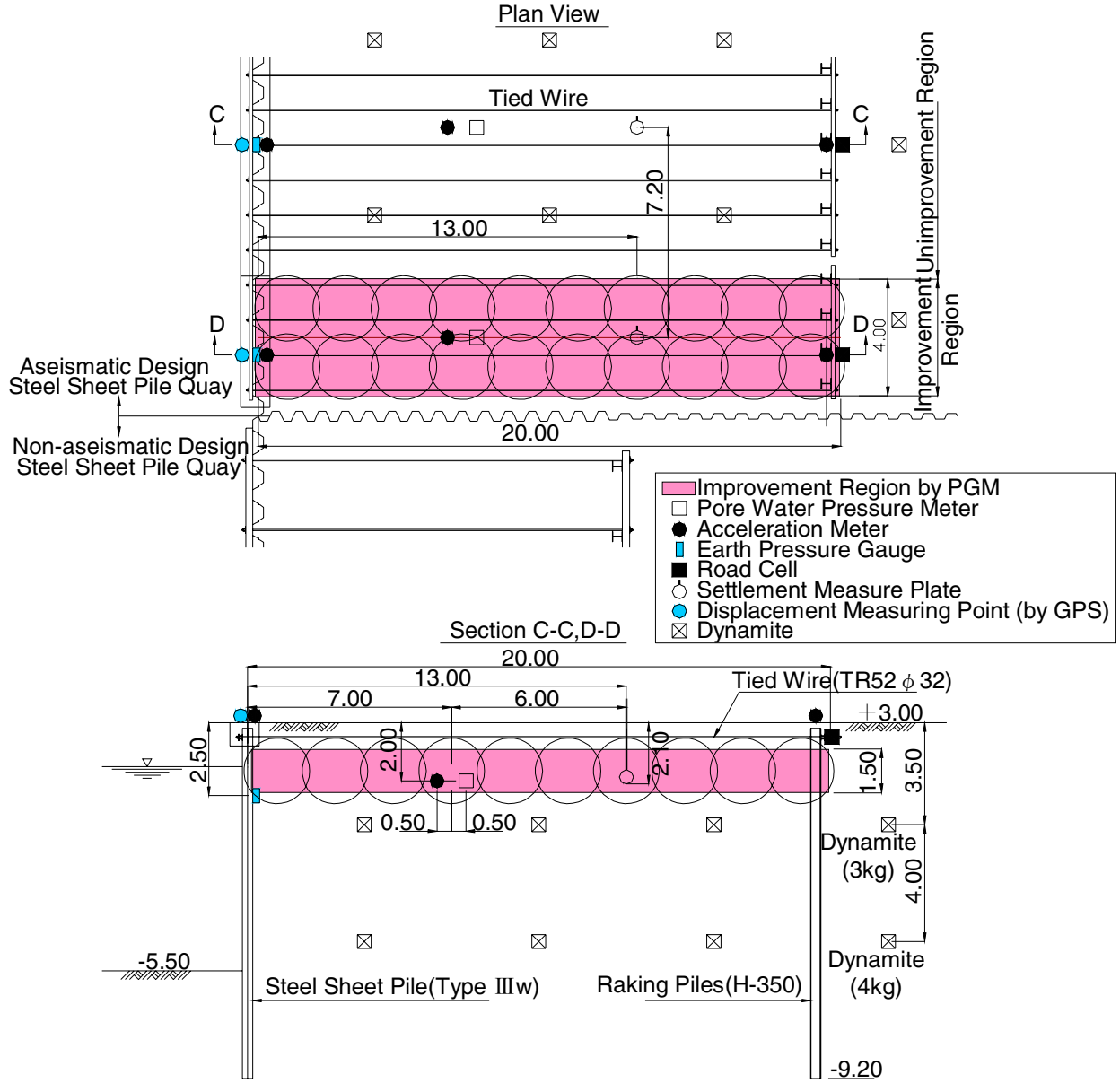


Figure-10 Improved Area by Permeable Grouting Method

Experiment results and consideration

Situation after experiments

Photo-2 shows the situation after the experiments. A rectangular above the line of the center part in the photograph is a range of the improvement by the Permeable Grouting Method. Though the outflow of the sand boil or underground water to the ground level is seen in the original ground around the improved range; As for the range where the ground has been improved by the Permeable Grouting Method, the generation of the liquefaction such as sand boils was not observed.

Dynamic characteristics

Figures 11 to 14 show the comparison of the dynamic characteristics between the improvement region and the original ground in the earthquake-proof design quay. The summary of the experiment results in this text pays attention to only the blast in the area where the influence exists directly within the range of the improvement. In the figures of the earth pressure, the excess pore water pressure, and the tension, the components with high frequency of 2Hz or more are removed in order to smooth data. From the measurement of the horizontal displacement at the top part of the steel sheet pile quay, it turns out that it is slightly smaller in the improved ground in comparison with that in the original ground (see Figure-11). Moreover, a remarkable difference is not seen about the tie-wire tension in dynamic characteristics of the improvement region and the original ground area (see Figure-12). It is likely that the pile head concrete, placed in the entire earthquake-proof design sheet pile quay, combined the improvement region with the original ground area. As for the tie-wire tension, the measurement value of the tension increment was 60kN/wire. Since the design by which the lateral seismic coefficient is assumed to be k_h=0.15 was 77kN/wire, it is judged that there was no big difference. The improved effect was able to be confirmed about the earth pressure (see Figure-13). Some decreases are observed in the improvement region while the earth pressure has increased gradually in the original ground area. This is because the improvement body is about to become independent for the sheet pile transformation. The excess pore water pressure (shown in Figure-14) is increased to the effective earth covering pressure level (about 30kN/m^2) in the original ground area. Therefore, the generation of the liquefaction can be confirmed from the measurement result. On the other hand, it does not increase up to the effective earth covering pressure in the improvement region. As a result, the liquefaction is not generated in the improvement region.

Photo-2 Situation after Experiment

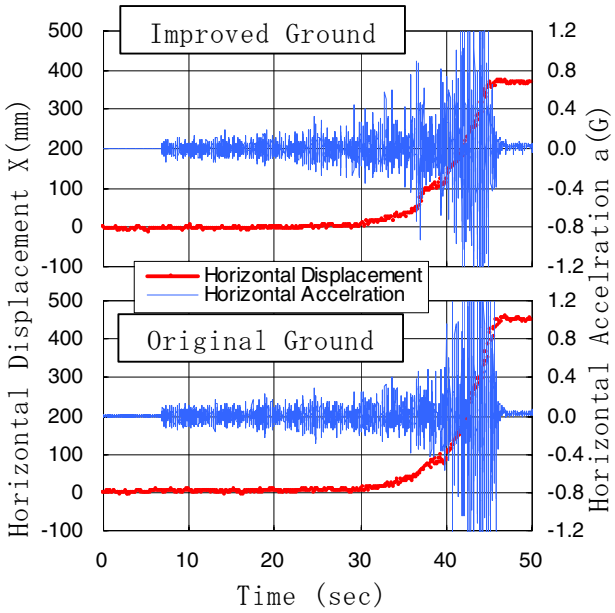


Figure-11 Results of Horizontal Displacement

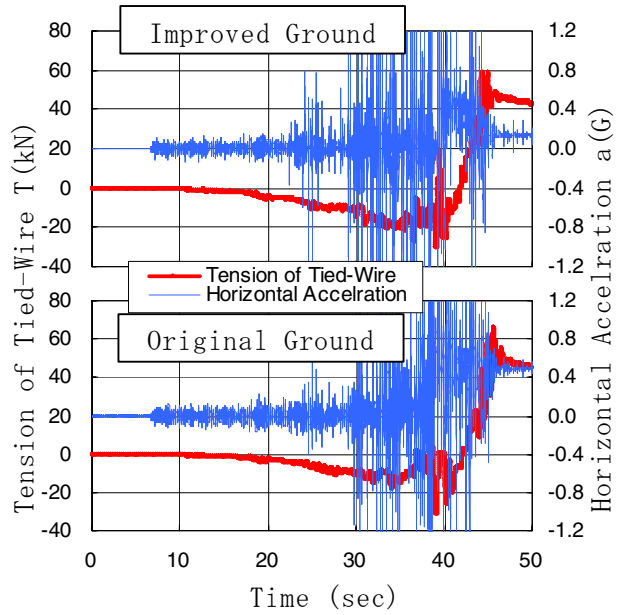


Figure-12 Results of Tension of Tied-Wire

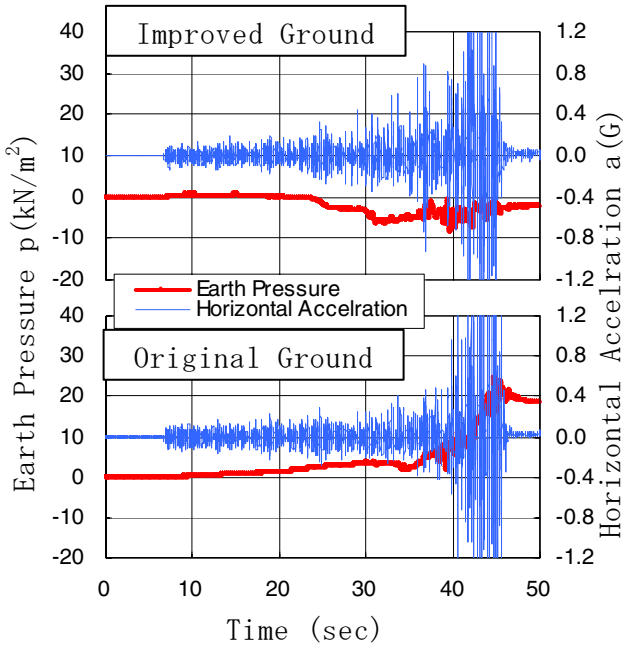


Figure-13 Results of Earth Pressure

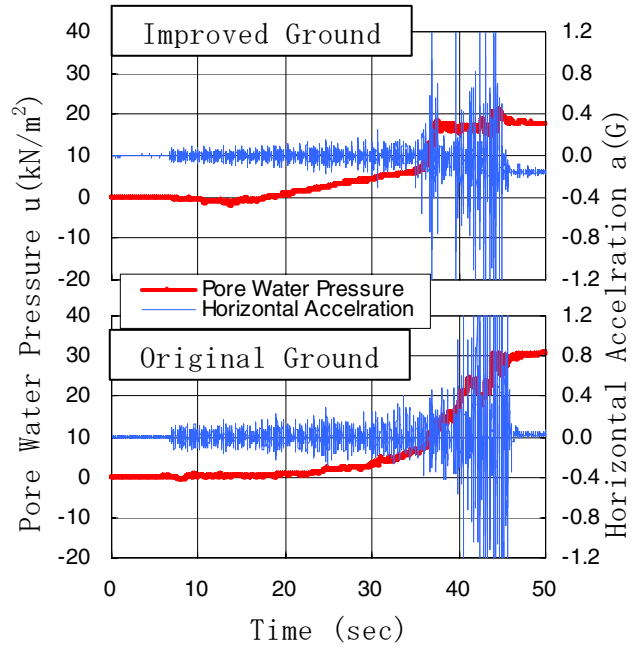


Figure-14 Results of Pore Water Pressure

Settlement measurement results

Photo-3 shows the situation of the settlement board of before and right after the experiments. Figure-15 shows the settlement measurement results. The settlement right after experiment was 0mm in the improvement region, and it was 80mm in the original ground area. The following day settlement was 21mm in the improvement region, 196mm in the original ground area, and the difference of about 180mm was generated from the experiment on the settlement board. The settlement at the improvement region is far smaller compared with the original ground though the settlement tendency cannot be specified since the measurement frequency was a little.

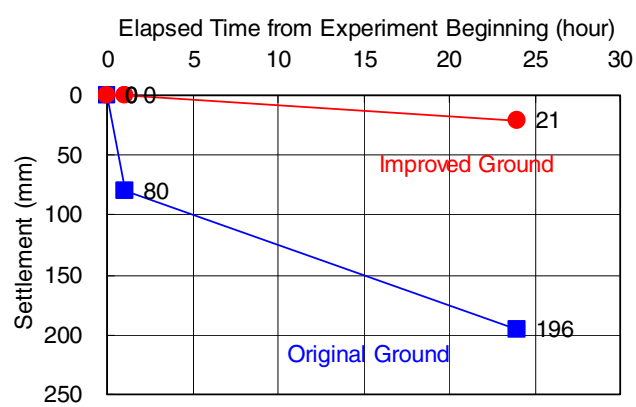
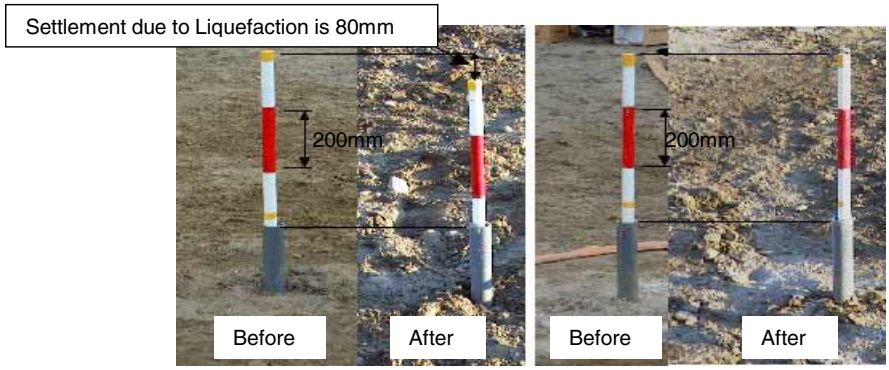


Figure-15 Results of Settlement

Unconfined compressive strength of improved soil

The unconfined compression test was done by using an obtained specimen from the locale by the Rotary Triple Tube Sampler before the experiment (the 28th in the age) of the vibration and after the experiment (the 56th in the age)(See Table-2). In any case, site strength of the improved soil is about 1/2 of the indoor strength. The construction of the Permeable Grouting Method has been proven to be appropriate. There was no decrease in the improved strength after the experiment. The unconfined compression test results show that there was no damage in the improvement body by the vibration experiment.



Original Ground Improved Ground
Photo-3 Behavior of Settlement Plate

Table-2 Unconfined Compressive Strength of Improved Soil

Specimen No.	Unconfined Compressive Strength q_u(kN/m^2)				
	Laboratory (Age 28 Days)	Site			
		Before Experiment (Age 28 Days)		After Experiment (Age 56 Days)	
		No.1	No.2	No.1	No.2
1	194	120	85	125	109
2	184	104	112	101	116
3	193	90	95	90	84
Average	190	105	97	105	103
		105		104	

CONCLUSION

We can get the effective experiment results about the Permeable Grouting Method as follows.

1. To Prevent the liquefaction
2. To Reduce the Earth Pressure

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