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Technical Report

Centrifuge Model Test on the Design Method of Ground Improved by the Hydraulic-Slag Compaction Pile Method and its Reduction Effect of Deformation Induced by Level-2 Seismic Motion

Haruhiko SHINOZAKI* Takashi TSUCHIDA
Koji ICHII Yoshiyuki MORIKAWA
Hidenori TAKAHASHI Jun OHBAYASHI
Hiroki KINOSHITA Yutaka HIRASHIMA
Shigeo KOBAYASHI

Abstract

Hydraulic slag compaction pile material is developed by utilizing hydraulic property of iron & steel slag. The improved ground by hydraulic slag compaction pile has high strength and stiffness, so reduction of improvement area and that of deformation induced by seismic motion are expected. Then, design method and its reduction effect of deformation induced by level-2 seismic motion are verified with centrifuge model test.

1. Introduction

For the weakness of the social infrastructure in Japan, in particular, port facilities such as quays and breakwaters that were revealed by the Great East Japan Earthquake, the bill on national resilience, which should help prevent or mitigate disasters, has been introduced, and the earthquake resistance of port and harbour facilities has been actively discussed now.

Conversely, as the seabed of Japanese coastal areas mainly comprises soft clayey soil, enhancing the earthquake resistance of port facilities requires huge cost for ground improvement. Focusing on the hydraulic property of iron and steel slag, Nippon Steel and Sumitomo Metal Corporation has developed a material for sand compaction pile (CP) (hydraulic slag compaction pile; hereinafter “hydraulic slag CP”), which helps in reducing the cost.

In this study, we describe the results of centrifuge model tests performed to establish design method (stable calculation method under ordinary conditions) and verify the effect of the deformation reduction of improved ground by the hydraulic slag CP against a Level-2 earthquake.

2. Main Subject

2.1 Outline of the hydraulic slag CP method

2.1.1 Hydraulic slag CP method

The hydraulic slag CP method is ground improvement method which uses iron and steel slag instead of natural sand in the conventional sand CP method (hereinafte “SCP method”). By mixing 15% to 50% mass of air-cooled or granulated blast furnace slag with steelmaking, the slag CP exhibit more than 60 kN/m^2 unconfined compressive strength and recognized as a SCP material with angle of shear resistance $\varphi = 42°$ or more that is used in design. Thus, the shear stiffness also improves.[1)]

As shown in **Fig. 1**, with the hydraulic slag CP, the extent of ground improvement and the construction cost can be reduced as compared with the conventional SCP method (sand $\varphi = 35°$).

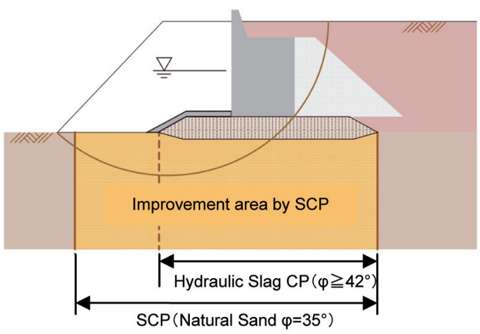

Fig. 1 Image of effect of hydraulic slag CP

* Senior Manager, Dr.Eng., Slag Technical Service Dept., Civil Engineering Div., Plant Engineering and Facility Management Center
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

2.1.2 Comparison with conventional methods and subjects in hydraulic slag CP development

The typical ground improvement methods used are the deep mixing (hereinafter the "DM method") and SCP methods. The DM method is a method in which a solidification material (e.g., cement) is mixed with the soft clayey soil in situ to develop a solid ground. The SCP method is a method in which compacted sand piles composed in the ground are imposed to exchange the soft clayey soil to improved ground. In both methods, the improvement specifications (improvement width, rate, etc.) are determined by ground stability against static external forces under ordinary conditions or Level-1 seismic force. Against a Level-2 seismic load, the amount of residual deformation of the quays on the improved ground with previously designed specifications is checked.

In particular, DM and SCP mainly differ in their design for stability under ordinary conditions because of the differences in structure, strength, etc.

The ground improved by the DM method has a high strength, and its unconfined compressive strength is 1 500 kN/m^2–2 500 kN/m^2. Thus, it is similar in strength, deformation, and failure to low-strength concrete rather than soil. Therefore, it is customary to check the stability of solid body in the surrounding unimproved ground against turnover, sliding, etc. as well as the strength of the improved ground itself against a failure. In addition, if the improved ground fails, it sharply decreases in strength (brittle failure) and can cause the structures on it to fatal collapse. Therefore, sufficient safety is considered against failures.

Conversely, in the SCP method, there is relatively little difference in strength and strain at peak strength between the sand piles and surrounding soft ground. In addition, the sand piles do not sharply decline in strength (they show tough with residual strength). Therefore, the original ground and sand piles behave as a composite ground against shear force under ordinary conditions. The hydraulic slag CP has the strength characteristics with both components (c-φ) of DM and SCP, and the applicable design method has not been decided. To expect the effect shown in Fig. 1, it is necessary to apply the design method for SCP.

The "Technical standards and commentaries for port and harbour facilities in Japan," revised in 2007, requires the examination of the residual deformation of any quays designated as earthquake-resistant facilities under a Level-2 seismic load. Thus, the importance of resistance against the Level-2 seismic load has been increasing. Improved ground with the DM method has high strength and stiffness, and so, it is possible to appreciably restrain the deformation of the improved ground. Conversely, improved ground with the SCP method using natural sand allows a certain degree of deformation and its applicability is more or less limited. The hydraulic slag CP is superior in strength and stiffness to the sand pile. Therefore, it is expected to be able to restrain the deformation of ground more effectively than that improved by the SCP method using sand.

From the abovementioned facts, the following two subjects were studied as the major subjects in hydraulic slag CP development.

Verification of the failure mode of ground to determine the applicability of the circular slip calculation method—a stable calculation method under ordinary conditions—in the design of SCP.

Verification of the effect to restrain the residual deformation of improved ground with slag CP against a Level-2 earthquake.

Solving the above problems requires evaluations with a full-scale system consisting of the SCP piles, ground, and structure. However, since there are no established methods for the numerical analysis of such a system, we used a modest-scale centrifuge model that permits reproducing even phenomena tens of times larger in scale and has a proven performance.

2.2 Verification of the failure mode of ground under ordinary conditions by the static centrifuge model test [3)]

2.2.1 Test procedure

Mark II [2)] owned by the Port and Airport Research Institute was used as the apparatus of the centrifuge model test. **Figure 2** shows the schematic model. The model container is made of steel that is 20 cm deep, 120 cm wide, and 60 cm high (interior dimensions). The front part is a transparent glass so that the deformation behavior of the model ground during the test can be observed even under centrifugal acceleration. For the supporting layer of the soil layer prepared in the model container, Toyoura silica sand that has relative density (Dr) of 86% to 91% was used. For a clayey ground, kaolin was used. Kaolin in the form of slurry with an initial water content of 120% was poured in the model container. It was initially consolidated at 10 kN/m^2 and then at self-weight in a gravitational field of 50 g.

The 1/50 scale model of SCP was difficult to be arranged with high accuracy at a high replacement ratio of 70% or more, and a pseudo pile having an equivalent rectangular cross-section (wall type pile) which deformation behavior is the same as the one of an actual cylindrical pile at a high replacement ratio in the direction perpendicular to the normal line of the quay wall, was substituted. **Photo 1** shows the appearance of the model pile. The model pile was prepared as follows. Steelmaking slag and granulated blast furnace slag sieved under 4.75 mm, were mixed (mixing weight ratio = 8:2) and stuffed in a steel frame to a prescribed density. The mixture in a steel frame was cured for about one week in the water and then frozen. The frozen pile was removed from the steel frame and pushed into a hole of the same dimensions as the steel frame drilled in a clayey soil that was initially consolidated in a 50 g gravitational field and then expanded sufficiently in a 1 g gravitational field without distubance.

After, the model pile was driven into the model ground and a

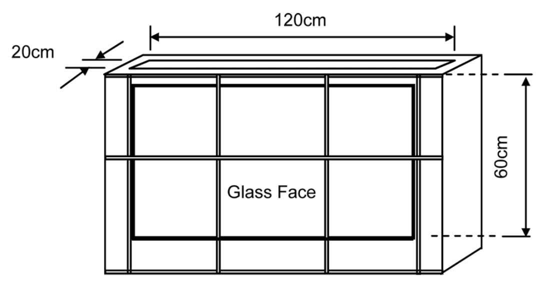

Fig. 2 Model container

Photo 1 Pseudo wall type SCP model

sand mat 2 cm thick was set on the surface of the clayey ground. The sand mat was laid by air pluviation of Toyoura sand. Its relative density was 74.6%. After the sand mat was laid out, a model caisson was laid on it. The model caisson, which is made of acrylic resin, measures 14 cm wide, 18 cm high, 19.5 cm deep and has a density of 1.136 g/cm^3. Its weight can freely be changed by stuffing sand, etc., in it. With the consideration of water level, the contact pressure is 1.24 kPa in the gravitational field (1 g) and 62.04 kPa in the 50 g field. After the model pile was installed in the model ground, the caisson model was placed by the centrifugal force (50 g field).

The backfilling part at the back of the caisson was made of crushed stone, which had a grain size of 4.75–9.5 mm. The backfilling part was 10 cm in bottom width, 4 cm in top width, and 12 cm in height. The reclaimed part at the back of the backfilling stone was prepared by using lead ball. It had a dry density ρ_d=6.45 g/cm^3 and a height of 12 cm. **Figure 3** shows the model ground (front). **Figure 4** shows the horizontal cross-section of the improved ground. The replacement ratio of the improved ground was 33%.

Table 1 shows the representative physical properties of the hydraulic slag CP used in the static centrifuge model test. Note that the strength of the slag was measured with specimens made in the same process as the model due to the frozen and defrosted process in the preparation.

The model was loaded using centrifugal acceleration. First, the centrifugal acceleration was raised to 6 g and the model deformation was measured and photographed. Next, the centrifugal acceleration was raised stepwise at an increment of 3 g and the model deformation at each step was measured and photographed. The loading was stopped at the time when the remarkable ground displacement was observed.Note here that in an NG centrifuge model test, the displacement of real-scale is N times and the pressure of real-scale is the same as that of the model scale.

2.2.2 Test results

Figure 5 shows the relation between horizontal displacement of caisson and landfilling pressure. The representative measuring point of horizontal displacement was point B within the improved ground right under the caisson side facing the sea. In the figure, 0 indicates the value in the 1 g field before the centrifugal acceleration was raised. The displacement is shown 50 times that of test model irrespective of the centrifugal acceleration applied to the model. From the figure, the ground displacement began to increase sharply when the landfilling load reached 127 kPa, suggesting that a ground failure had occurred at that time.

Photo 2 shows the appearance of the model pile that was taken out of the test apparatus removed of kaolin clay from the surface after test. The photo shows that the improved ground was, on the whole, deformed toward the sea side, and that a slip failure occurred beneath the improved ground (approximately 5 cm in model scale

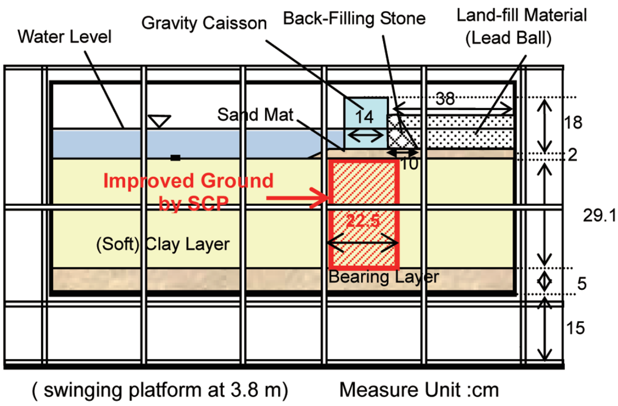

Fig. 3 Outline of testing model (front face)

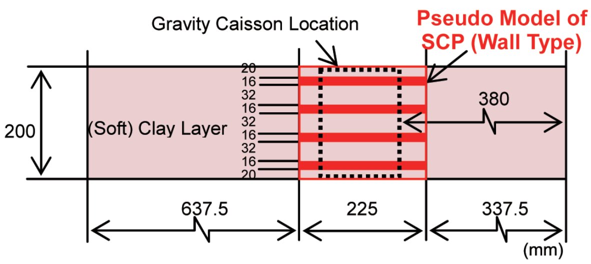

Fig. 4 Horizontal section of model ground (model scale)

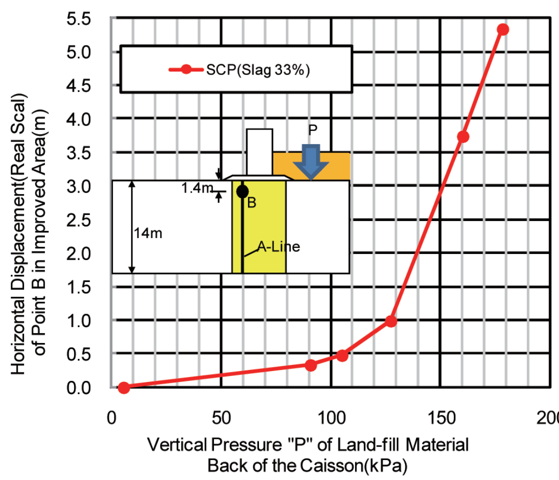

Fig. 5 Horizontal displacement of point B in improved ground by SCP (real scale)

Table 1 Property of slag CP

Property item	Slag SCP
Max particle size (mm)	4.75
D_{50} (mm)	0.58
U_c	11
Paricle density (g/cm^3)	3.19
Void ratio e	0.58
Un-confined compression	137.2
Cohesion (kN/m^2)	91.8
Internal friction angle φ_d	39.1

Photo 2 State of failure and deformation of ground after centrifuge model test

down from the bottom of improved ground). In addition, the clayey ground at the back of the improved ground reveals a failure such as a circular slip. Although the clayey ground before the improved ground showed a considerable displacement upward to the sea side, the presence of any remarkable failure, such as a slip surface, could not be observed.

During the centrifuge model test, the displacement of the ground at each centrifugal acceleration and landfilling pressure was measured by photographing a target embedded in the clayey ground at the glass side of the model container and analyzed by photographic images. **Figure 6** shows the results of the failure test about the displacement of ground with the increase in centrifugal acceleration. Following each displacements indicates as real scale at 50 times of that of the test model irrespective of the magnitude of centrifugal acceleration.

Figure 6 (a) shows the displacement of ground at a centrifugal acceleration of 21 g and a landfilling pressure 127 kPa. Figure 6 (b) shows the displacement of ground at a centrifugal acceleration 24 g and a landfilling pressure 160 kPa.

In Fig. 6 (a), the closer the distance from the bottom of the improved ground to the ground surface, the larger is the ground deformation toward the sea. In addition, in the clayey ground before the improved ground, the closer the distance to the ground surface, the larger is the obliquely upward displacement to the sea side. In the clayey ground at the back of the improved ground, on the other hand, a displacement toward the sea is observed. From Fig. 6 (b) (centrifugal acceleration: 24 g and landfilling pressure: 160 kPa), a slip failure running under the improved ground can be observed clearly.

Figure 7 shows the relation between caisson settlement obtained by a vertical displacement meter installed at the top of the caisson and landfilling pressure.. The amounts of caisson settlement shown are 50 times that of the model scale as real scale irrespective of the centrifugal acceleration. The figure shows that the amount of caisson settlement increased monotonously with the increase in landfilling pressure due to the increase in centrifugal acceleration, whereas that of caisson settlement sharply increased when the landfilling pressure reached 143 kPa (centrifugal acceleration: 23 g), and it indicates that the ground failed at the landfilling pressure of 143 kPa.

Thus, by the centrifuge model test using a wall-type model that simulates ground improvement with a high replacement ratio, the mode of failure of the ground improved by the hydraulic slag CP was a slip failure as in the case of a ground improved by the SCP method using natural sand. In addition, the failure slips location and landfill pressure of the model ground were calculated by using modified Fellenius' method as per the current design method for port and harbor facilities. The calculation results agreed with that of the test.

2.3 Verification of reduction effect of residual deformation in Level-2 earthquake by dynamic centrifuge model test[4,5]

2.3.1 Test procedure

Figure 8 shows the model ground. It was comprised a bearing sand layer and a normally consolidated clayey ground (thickness: 160 mm) on the sand layer. The clayey ground was prepared and the model pile was placed in the same way as the static centrifuge mod-

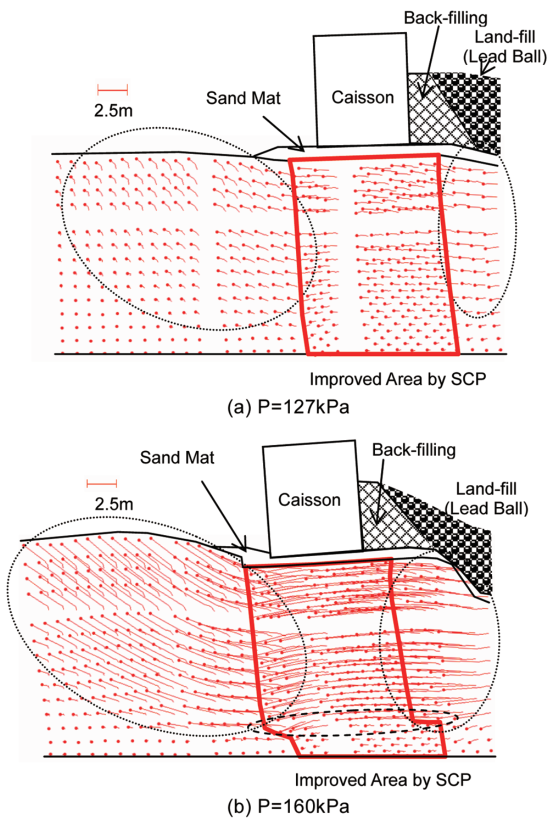

Fig. 6 State of deformation and deformation vector of ground improved by SCP (real scale)

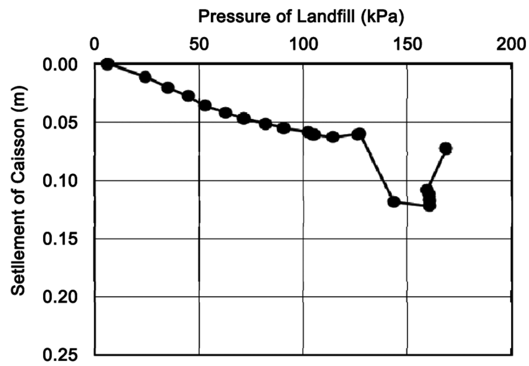

Fig. 7 Vertical displacement of caisson (real scale)

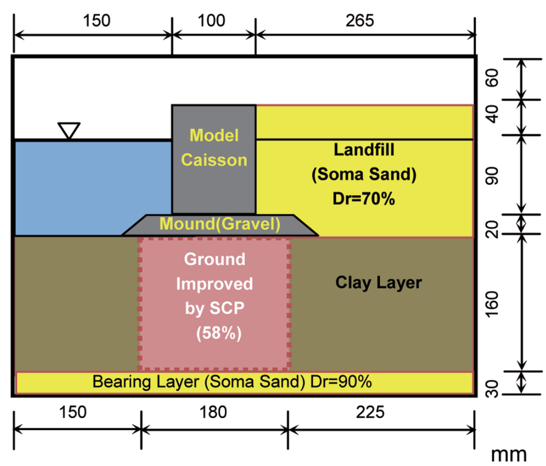

Fig. 8 Model ground used for dynamic centrifuge model test (model scale)

el test. **Table 2** shows the test cases, and **Table 3** shows the physical properties of the model piles used. As shown in **Fig. 9**, the SCP piles placed in the model ground were wall-type blocks (180 mm in length, 28 mm in thickness, 160 mm in height) made of iron and steel slag and Toyoura sand, respectively. Each pile were arranged at a replacement ratio of 58%. The model caisson was an acrylic box (5.125 kg) that is 130 mm high, 100 mm wide, and 195 mm deep. Its density was 2.02 g/cm³ by placing sand in it. Considering the level of water during the test, the contact pressure of the caisson in a 50 g gravitational field was approximately 85 kPa.

Table 2 Test case of dynamic centrifuge model test

Cace No.	Materials of model SCP	Shape of SCP	Improvement ratio
1	Toyoura sand	Wall type	58%
2	Slag	Wall type	58%

Table 3 Physical property of SCP model

Physical property	Slag	Natural sand
Particle density Gs (g/cm³)	3.05	2.66
Dry density ρ_d (g/cm³)	1.94	1.54
Internal rriction angle φ (°)	45.1	37.0
Cohesion (kN/m²)	68.6	–
Unconfined compression strength (kN/m²)	225.0	–

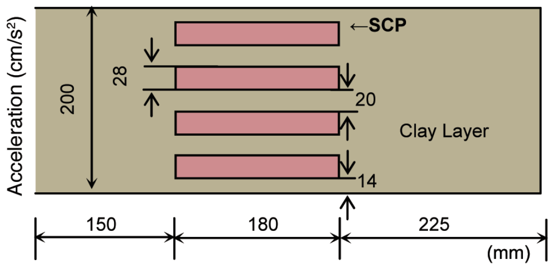

Fig. 9 Horizontal cross section of model ground (model scale)

Figure 10 shows the time-historical acceleration of the seismic motion input is shown in Fig. 10. In the tests, the displacement, response acceleration, water pressure, etc. of the model ground were measured under the amplitude magnification of seismic wave increased stepwise (0.1, 0.7, and 1.0 times of input seismic motion shown in Fig 10) with a vibration exciter installed under the model in a 50 g gravitational field.

2.3.2 Experimental results

Figures 11 (a) and (b) show the residual vertical displacements at point A—the center of the model caisson top—and point C −0.45 m under the improved ground surface—in Case 1 (sand) and Case 2 (slag), respectively, at each of the above vibration steps and the residual horizontal displacements at point B 1.3 m from the seaside end of the improved ground (the depth of point B is the same as point C). Figure 11 (c) shows the residual horizontal displacements at points on the vertical line passing through point B. From the figures, Case 2 (slag) is more effective to reduce the ground deformation than Case 1 (sand).

3. Conclusion

Centrifuge model tests were performed to verify the mode of failure of grounds improved by the hydraulic slag CP method under ordinary load condition and the effect of the slag CP to reduce the residual deformation of ground. The results are as follows:

Concerning the stability under ordinary condition of the ground improved by the hydraulic slag CP method, the mode of failure is a

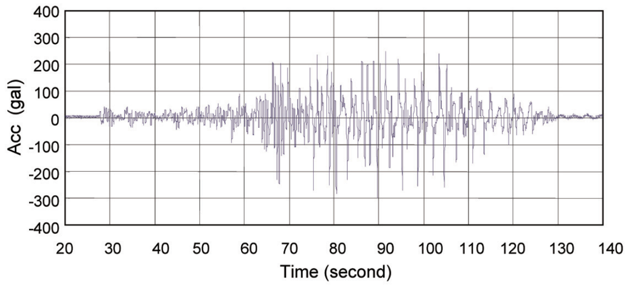

Fig. 10 Time history acceleration of input seismic motion

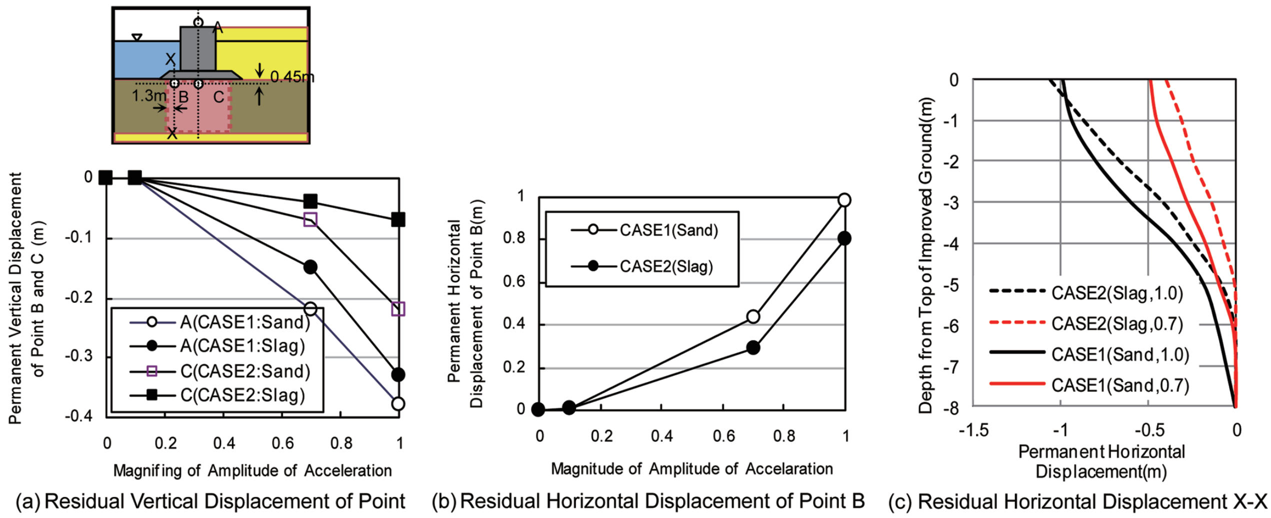

Fig. 11 Residual displacement of improved ground

slip failure as in the case of a SCP-improved ground using natural sand, and its failure behavior can be evaluated by the circular slip calculation method. Since the hydraulic slag pile is superior in shear strength as compared to the conventional sand pile, it will help reduce the extent of ground improvement required.

A dynamic model test on the ground improved by the hydraulic slag CP with a characteristic of high strength proved that the residual deformation of improved ground is less than the ground improved by conventional sand piles.

With abovementioned results, the hydraulic slag CP method could obtain the certificate of evaluation (No. 10001) in the confirmation and examination program of private technologies related to port and harbor facilities by the Coastal Development Institute of Technology.

In the construction of port and harbor facilities conducive to national resilience now in progress, the hydraulic slag CP method is effective to reduce the construction cost and enhance the earthquake resistance. Therefore, the application of this method is expected to spread widely in the future.

Acknowledgments

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Haruhiko SHINOZAKI
Senior Manager, Dr.Eng.
Slag Technical Service Dept.
Civil Engineering Div.
Plant Engineering and Facility Management Center
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

Takashi TSUCHIDA
Professor, Dr.Eng.
Department of Social and Environmental Engineering
Graduate School of Engineering
Hiroshima University

Koji ICHII
Associate Professor, Dr.Eng.
Department of Social and Environmental Engineering
Graduate School of Engineering
Hiroshima University

Yoshiyuki MORIKAWA
Head, Dr.Eng.
Soil Stabilization Group
Geotechnical Engineering Field
Port and Airpot Research Institute

Hidenori TAKAHASHI
Senior Researcher, Dr.Eng.
Soil Dynamic Group
Geotechnical Engineering Field
Port and Airpot Research Institute

Jun OHBAYASHI
General Manager, Dr.Eng.
Geotechnical Department
Fudo Tetra Corporation

Hiroki KINOSHITA
Group Leader, Dr.Eng.
No.2 Lab.(Chugoku-Branch)
Technical Division, Geotechnical Department
Fudo Tetra Corporation

Yutaka HIRASHIMA
Senior Manager
Slag Marketing Dept.
Slag & Cement Div.

Shigeo KOBAYASHI
General Manager, Head of Div., Dr.Eng.
Civil Engineering Div.
Plant Engineering and Facility Management Center