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Examination of Application of Steel Slag to Sand Compaction Pile Method†

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Abstract:

JFE Steel carried out an on-site construction examination using five kinds of steel slag in order to find out whether steel slag can be used as a material in Sand Compaction Pile method with static load compaction. It showed equivalent performance in the result diameter of a pile and construction time compared with the conventional natural sand. Moreover, when the pile number and interval are the same, equivalent foundation improvement results were obtained even using any examined slag. Furthermore, the level of noise and vibration during construction did not show a significant difference among construction materials, and is much less than that of the standard regulation values. It has been confirmed that the construction under low noise and low vibration is feasible.

1. Introduction

The Great East Japan Earthquake of March 11, 2011 caused liquefaction of the ground in areas as distant as the coastline of the Kanto region around Tokyo, resulting in widespread damage in the form of leaning buildings, etc. The experience of that disaster has heightened the need for liquefaction countermeasures. One construction method which improves ground stability against liquefaction is the sand compaction pile (SCP) method. In this method, occurrence of liquefaction is suppressed by densification (i.e., strengthening) of the surrounding ground by compaction of that ground. This is achieved by forming large-diameter sand columns by placing a pile material such as sand or crushed stone in the soft ground and applying vibration, impact load, or static load in order to compact the material.

Various materials are used as SCP pile materials. In addition to natural sand and crushed stone, these include steel slag, beginning with blast furnace slag and converter slag, recycled crushed stone using waste concrete material, and others. The most widely used SCP compaction method is vibration, which is used in virtually all cases when constructing SCP in sea areas, for example, in soft ground stabilization works for ports and harbors. On the other hand, in ground improvement in inland areas, such as liquefaction countermeasures for tank foundations and building foundations, the high levels of noise and vibration caused by vibration compaction are a problem. Therefore, a low-noise, low-vibration sand compaction pile method (SCP compacted by static load) was developed for ground compaction by using hydraulic force to apply static load.

Steel slag has an extensive record of use as a material in the SCP method by vibration compaction as a marine construction method, mainly for ports and harbors, and its ground improvement effect has been verified in case studies[1]. However, SCP compacted by static load had virtually never been used for the primary purpose of liquefaction countermeasures for structures on land.

Therefore, in order to clarify the applicability of steel slag with grading control, "Smart Compaction™," as a pile material for SCP compacted by static load for liquefaction countermeasures, an on-site construction examination was carried out using "Smart Compaction™" materials, and their workability, ground improvement effect, and impact on the surrounding environment were confirmed.

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2. Ground Stabilization Method by Static Compaction

Various construction methods for SCP compacted by static load have been developed. In addition to the Geo-KONG[2] method developed by Geo Dynamic Co., Ltd., others include the SAVE Composer method[3], SDP-N method[4], KS-EGG method[5], and STEP method[6]. As of fiscal year 2008, these methods had been applied in more than 400 actual projects[7]. The method used in this on-site construction examination was the Geo-KONG method, which is one of the above-mentioned methods. In the Geo-KONG method, low-noise, low-vibration construction is possible by using an electric motor as the power source for rotary motion in order to penetrate the outer casing pipe into the ground, and using a hydraulic motor for up-and-down motion of the inner casing pipe for compaction.

The mechanism of compaction by the Geo-KONG method is illustrated in **Fig. 1**. First, the pile material is penetrated into the ground to the specified depth using a double casing pipe comprising the above-mentioned outer and inner casing pipes. The material is then pressed into the ground and the ground is compacted by tamping by raising and lowering only the inner pipe, while simultaneously pulling the casing pipe out of the ground.

The detailed construction procedure of the Geo-KONG method is as follows (**Fig. 2**):

(1) The casing is set at the piling position, and pile material is charged into the casing inner pipe in advance.

(2) The casing is rotated and penetrated into the ground to the specified depth while charging pile material.

(3) After penetration is completed, rotation is stopped.

(4) Pile material is supplied into the ground and a pile is formed while simultaneously pulling out the double casing pipe. During this operation, the pile material is tamped by raising and lowering only the inner pipe by approximately 30 cm at a frequency of 8–12 times/min.

(5) The casing is pulled out to the ground surface, thereby completing formation of the pile.

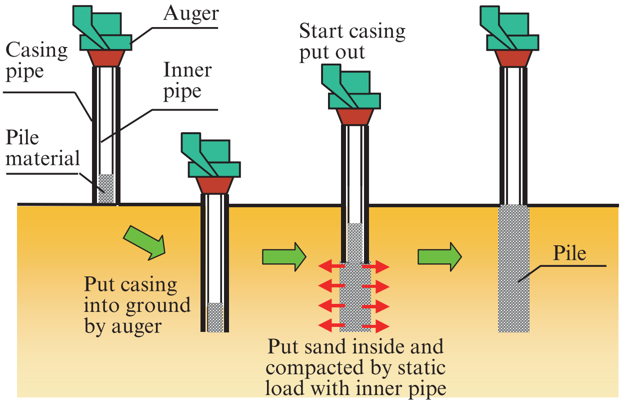


Fig. 2 Construction procedure of Geo-KONG method

The results of verifications[2] of this method by test construction, etc. show that it is possible to obtain a ground improvement effect equal to that by vibration compaction, confirming that design evaluation is possible by applying the conventional design type of ground improvement by the vibration compaction method[8].

Assuming application of various types of steel slag (described in the following) as pile materials for this method, it was necessary to examine whether grading distribution, specific gravity (maximum dry density), and other properties of the slag would affect workability, noise and vibration levels, and the ground improvement effect.

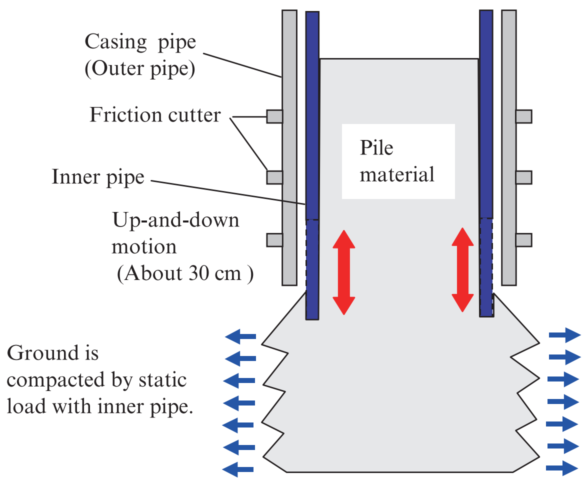


Fig. 1 Casing with a double pipe (Geo-KONG method)

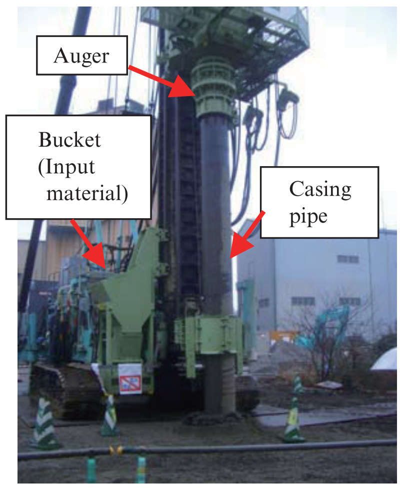


Photo 1 A view of construction examination

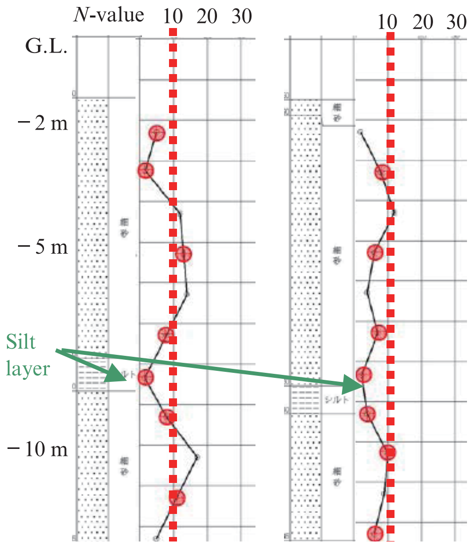


Fig. 3 Typical cross section of construction site

3. On-Site Construction Examination

3.1 Test Site and Cross Section of Construction Site (Ground Properties)

The on-site construction examination was carried out at the Oihama District of JFE Steel's East Japan Works (Chiba). A view of the construction is shown in **Photo 1**. The typical cross section and *N*-value distribution of the construction site are shown in **Fig. 3**. The ground is loose sandy ground with *N*-values on the order of 5–10. A thin silt layer exists around G. L. −8 m. The sandy layer sometimes contains mixed shells, in which case the *N*-value exceeds 10. Because a layer of hard steel slag roadbed material existed from ground level to G. L. −1.2 to −1.6 m, this material was removed in advance and replaced with sand when constructing the SCP in this study. The ground-water level (water table) is around G. L. −1.4 m.

3.2 Test Cases and Properties of Pile Materials

Six types of pile materials were used in this construction examination, as shown in **Table 1**. Two types of blast furnace slag materials were used, these being granulated blast furnace slag and air-cooled blast furnace slag. Two types of steelmaking slag were used, i.e., converter slag with and without steam aging processing (hereinafter, "converter slag with/without aging"). An artificial stone made by a steel slag hydrated matrix (hereinafter, "artificial stone") was also used, and for a comparative evaluation of the workability of the above-mentioned steel slag pile materials, piles were constructed using a natural sand (produced in Kisarazu) which is generally used in SCP. Table 1 also shows maximum dry density and maximum particle diameter (control value) of the test materials. **Figure 4** and **Photo 2**

Table 1 Materials for construction examination

No.	Material	Number of piles	Density (g/cm^3)	Maximum particle diameter (mm)
1	Converter slag (Steamy aging processing)	4	2.48	40
2	Natural sand	16	1.52	5
3	Air-cooled blast furnace slag		2.01	25
4	Converter slag		2.67	40
5	Artificial stone made by steel slag hydrated matrix		2.01	40
6	Granulated blast furnace slag		1.46	5

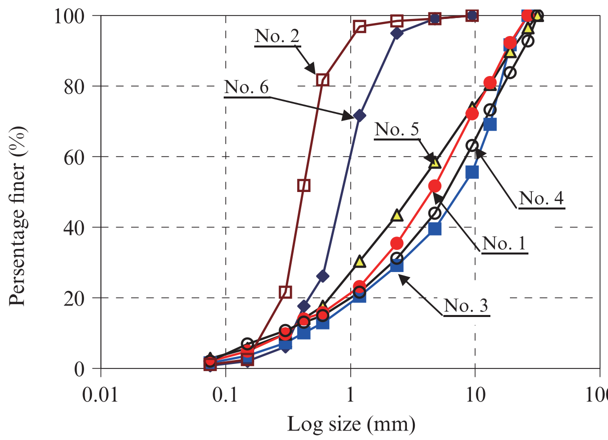
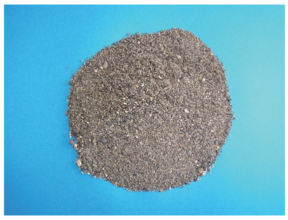


Fig. 4 Grading curve

(1) No. 1 Converter slag (Steamy aging)



(2) No. 2 Natural sand

(3) No. 3 Air-cooled blast furnace slag

(4) No. 4 Converter slag (Unaged)

(5) No. 5 Artificial stone made by steel slag

(6) No. 6 Granulated blast furnace slag

Photo 2 Appearance of materials in Sand Compaction Pile

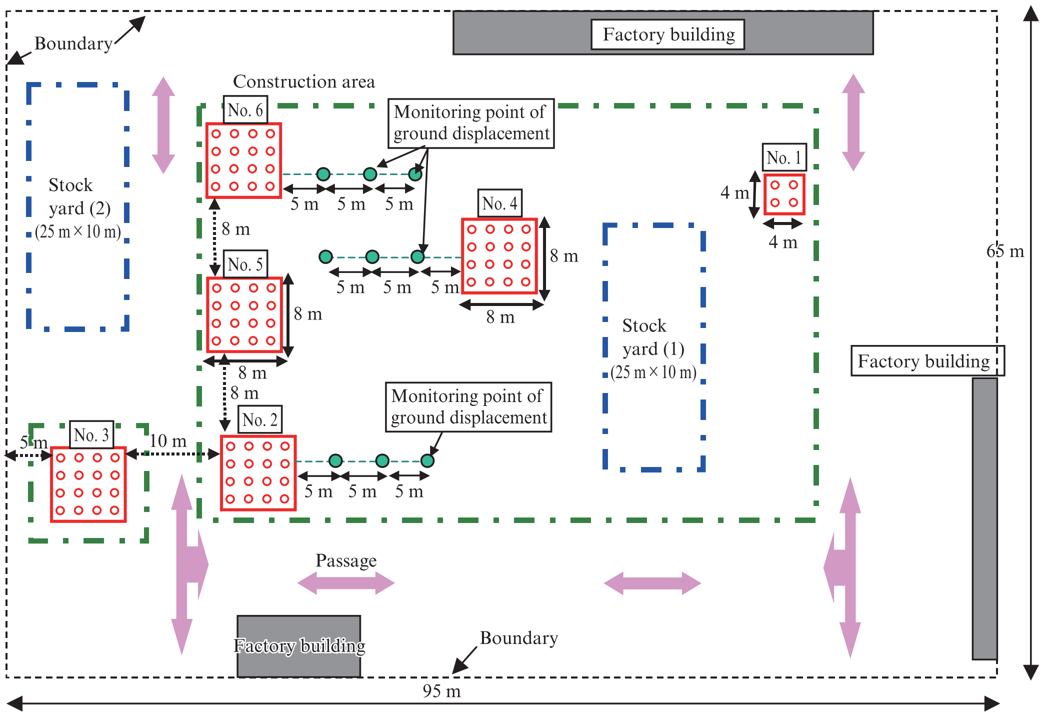


Fig. 5 Layout of a construction site

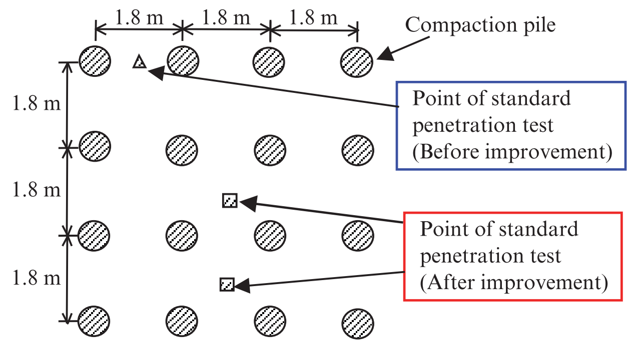


Fig. 6 Arrangement of sand compaction pile

(1)–(6) show the grading curves and external appearances of each material, respectively.

Figure 5 shows the layout of the construction site. To minimize the mutual effect of construction of the piles in neighboring cases, a dispersed layout was used, in which the piles of each material were constructed at a distance from the other materials. The number of piles constructed with one type of material was 4×4 = 16. However, due to space limitations, 2×2 = 4 piles were constructed only with No. 1, converter slag with aging. The length of each pile was 10 m, and the center-to-center distance was set at 1.8 m based on a placement ratio calculation, as described in the following section. The arrangement of the sand compaction piles is shown in **Fig. 6**. The target control value for the pile diameter was 70 cm.

3.3 Setting of Placement Ratio

In order to set the placement ratio, the PL-value (liquefaction index) of the ground before and after improvement (predicted) was calculated by the method provided in the Recommendation for the Design of Building Foundations[9]. A design earthquake of magnitude (M) 7.5 and maximum acceleration of 3 m/s^2 were assumed. The calculation results are shown in **Table 2**. The PL-values before improvement were calculated using the *N*-values and fine-grained soil contents (particle diameter: ≦75 μm), which were measured in advance for each case. For the predicted value after improvement, the increment of the *N*-value was calculated by the conventional design type of ground improvement method[8], assuming placement ratio of 11.9% (pile diameter: 70 cm, center-to-center distance: 1.8 m), and the PL-value after improvement was calculated based on those results.

Table 2 Calculation of liquefaction index, PL-value

No.	Material	PL-Value (Before improvement)	PL-Value (Predicted after improvement)
1	Converter slag (Steamy aging)	6.77	0.0
2	Natural sand	16.16	1.27
3	Air-cooled blast furnace slag	8.75	1.79
4	Converter slag (Unaged)	13.68	1.98
5	Artificial stone made by steel slag	14.77	2.23
6	Granulated blast furnace slag	15.74	2.82

The PL-values before improvement ranged from 6.77 to 16.62, and thus including ground with a high risk of liquefaction (15<PL) and ground with a risk of liquefaction (5<PL≤15). In contrast, the PL-values after improvement (predicted) were in the range of 0 to 2.82. As there was judged to be a low possibility of liquefaction (0<PL≤5), construction was carried out using the above-mentioned placement ratio (center-to-center distance: 1.8 m).

3.4 Examination Results

3.4.1 Ground improvement effect

Figure 7 (1)–(6) show the change in the *N*-values in the standard penetration test between piles before construction and approximately 2 weeks after construction for each case. The locations of the standard penetration test were shown in Fig. 6. The predicted values (denoted by solid lines) by the design type of ground improvement[8] are also shown in Fig. **7**. In order to investigate the degree of variation in the measured values, the standard penetration test after construction was performed at two locations with No. 2, natural sand, and No. 6, granulated blast furnace slag. In both cases, variation of the measured values was slight.

Although the change in the *N*-value before and after construction differed at each depth, increases in the *N*-values could be confirmed with the exception of the silt layer which exists at a depth of approximately 7–8 m. Except for the case of No. 1, converter slag with aging, in which the number of piles was small (4 piles), the increases in the N-values of the other cases (with 16 piles) were on the order of 5–15, with an average of around 10, and there were no great differences in the ground improvement effect depending on the pile material. Moreover, the measured results were generally in agreement with the predicted values. In case No. 1, the average increase in the *N*-value was around 5, and thus was smaller than the predicted value.

Figure 8 shows a comparison of the predicted PL-values after improvement, as presented in Section 3.3, and the PL-values of the ground measured using the *N*-values measured after construction. The predicted PL-values and the PL-values based on actual measurements showed good correspondence in all cases except No. 1, in which only a small number of piles was constructed, confirming that the improvement effect could be obtained as expected. The results also confirmed that the improvement effect when using steel slag as the pile material is equal to that when using natural sand.

According to a past study[1], it was reported that, in ground improvement using converter slag, the *N*-value increased and the ground improvement effect was enhanced by the hardenability effect of converter slag

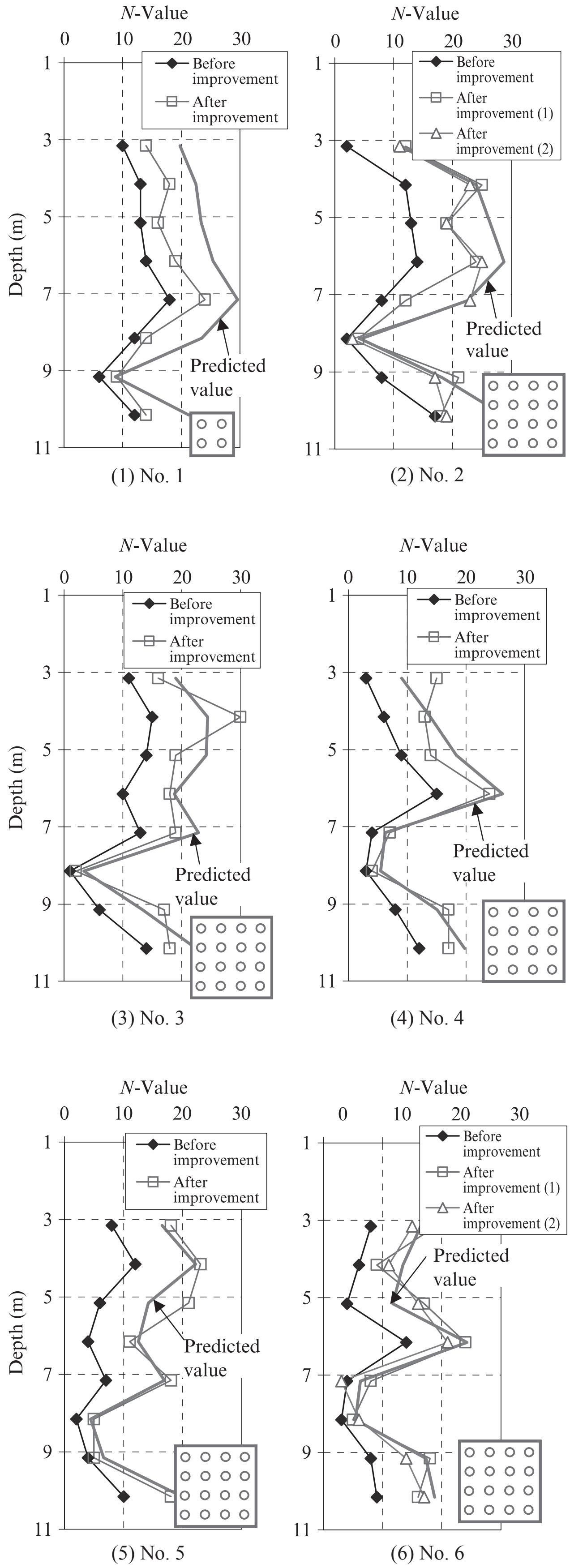


Fig. 7 Increased penetration resistances in ground improved by the Sand Compaction Pile method

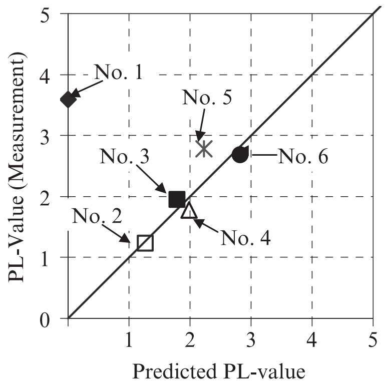


Fig. 8 Comparison of predicted liquefaction index (PL)-value and measured PL-value

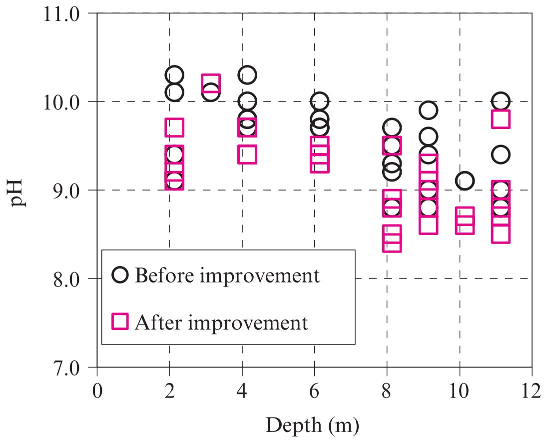


Fig. 9 pH Measured in each depth

with time after construction. Therefore, measurements of the change over time are planned for the future as part of this construction examination. Continuous measurement of the hardenability rate of the steel slag materials, and confirmation of changes over time in the ground improvement and permeability caused thereby, are also planned.

3.4.2 Effect on surrounding ground

(1) Horizontal Displacement under Construction

As shown in the layout of the construction site in Fig. 5, horizontal displacement of the ground was measured at positions 5 m, 10 m, and 15 m distant from the front pile row in cases No. 2, natural sand, No. 4, converter slag without aging, and No. 6, granulated blast furnace slag. The maximum horizontal displacement under construction is shown in **Table 3**. In all cases, horizontal displacement was on an extremely slight level of 0.3 mm or less at the 10 m and 15 m positions. Although horizontal displacement on the order of 3–5 mm occurred at the nearest position (5 m), for example, these values are well within the allowable horizontal displacement of 16 mm[10] set for neighboring buildings.

(2) pH of Ground before and after Construction

Figure 9 shows the pH values of the ground at each measurement depth near the pile construction area before construction and approximately 2 weeks after construction. From this figure, a condition in which alkalinity in particular did not increase after the construction can be confirmed. It should be noted that the ground originally showed alkalinity of approximately pH 9–10 at G. L. −1.2 to 1.6 m because a layer of steel slag roadbed material exists at that depth.

In the future, measurement of the change over time in the pH of the surrounding ground and an evaluation of whether alkalinity has an effect or not, and if so, the range of that effect, etc. are planned by continuing long-term measurements.

Table 3 Maximum horizontal displacement under construction

No.	Material	Distance to a measuring point		
		5 m	10 m	15 m
2	Natural sand	3.6 mm	0.2 mm	0.1 mm
4	Converter slag (Unaged)	4.2 mm	0.3 mm	0.2 mm
6	Granulated blast furnace slag	4.5 mm	0.3 mm	0.1 mm

3.4.3 Evaluation of workability

(1) Diameter of Piles and Construction Time

An example of a finished compaction pile (No. 4, converter slag without aging) is shown in **Photo 3**.

As evaluation items for the workability of each case, **Table 4** shows the average finished diameter of the

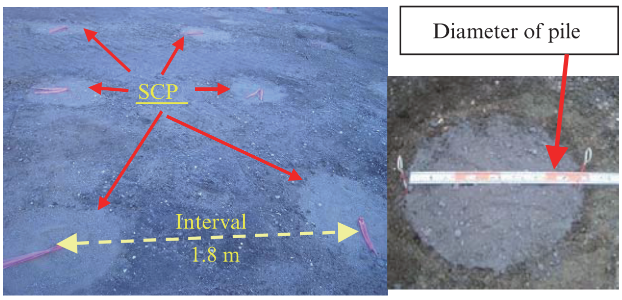


Photo 3 View of compaction pile (No. 4 Converter slag)

Table 4 Construction result for every material

No.	Material	Diameter of SCP (Average) (cm)	Construction time ratio, (Average)/(No. 2)
1	Converter slag (Steamy aging)	75.2	1.10
2	Natural sand	72.1	1.00
3	Air-cooled blast furnace slag	74.1	1.03
4	Converter slag (Unaged)	75.2	0.95
5	Artificial stone made by steel slag	76.3	1.03
6	Granulated blast furnace slag	72.4	1.02

piles and the average construction time ratio (indexed to the average construction time for No. 2, natural sand). Pile diameter was measured at two positions at right angles, and the average was calculated.

In all cases, the average diameter of the piles exceeded the target control value of 70 cm, and in the cases using steel slag, the results were equal or superior to that of natural sand.

In case No. 1, converter slag with aging, the average construction time per pile was slightly longer than that of the other cases. As the reason for this difference, because material No. 1 was being used for the first time in the present study, the pile material charging rate, compaction frequency, and other conditions were set conservatively. In the other cases, although the results were influenced to some extent by differences in the weather and the distance to the material yard, the average time was within ±5%. Thus, all the steel slags as well as natural sand were on the same level.

(2) Noise and Vibration Level under Construction

Figure 10 shows the noise level (dB) by pile material, as measured at positions 5 m and 20 m from the piling machine in this construction. The noise level

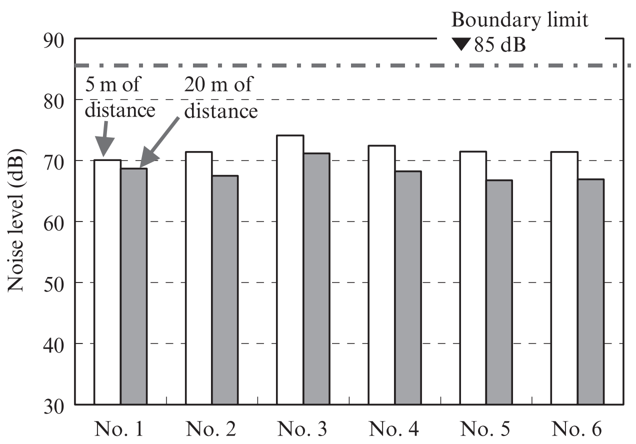


Fig. 10 Noise level

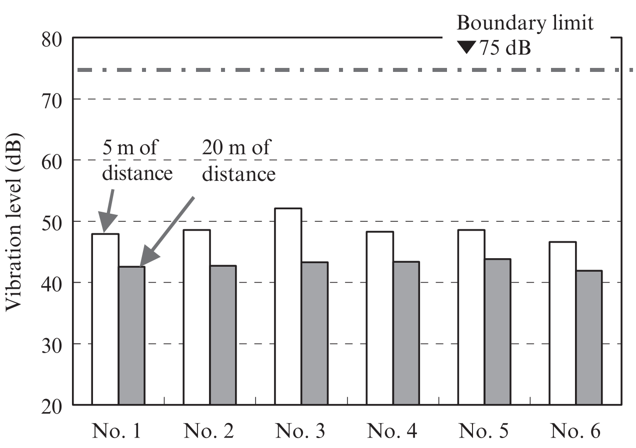


Fig. 11 Vibration level

when using steel slag did not differ greatly from that when using No. 2, natural sand, and in all cases, was substantially lower than the 85 dB level of the noise regulation value in a site boundary[11]. These results confirmed that low-noise construction is possible.

Figure 11 shows the vibration level (dB) by pile material, as measured at positions 5 m and 20 m from the piling machine. As with noise, the vibration level with steel slag did not differ greatly from that with No. 2, natural sand, and was substantially lower than the 75 dB level of the vibration regulation value in a site boundary[11] in all cases, confirming that low-vibration construction is also possible.

4. Conclusion

An on-site construction examination of the sand compaction pile (SCP) method by compaction under static load (Geo-KONG method) was carried out using five types of steel slag, i.e., granulated blast furnace slag, air-cooled blast furnace slag, converter slag (with and without steam aging processing), and artificial stone made by steel slag hydrated matrix. The results confirmed that the expected ground improvement effect can be obtained. In comparison with natural sand, which is used in conventional SCP, the improvement effect and workability (diameter of pile, construction time) of these steel slags were similar and comparable to those of natural sand.

No large differences between the steel slags and natural sand were observed in the noise and vibration levels during construction. The steel slags satisfied both the noise and vibration regulation values in a site boundary in the specified construction work by wide margins, confirming that application to low-noise, low-vibration construction methods is possible. In addition, alkalinity did not increase in the surrounding ground after construction in this examination, and the effect of ground changes due to compaction was also slight.

The verification results summarized above confirmed that steel slags are satisfactory for use in the sand compaction pile method by static compaction for liquefaction countermeasures. Moreover, since different steel slags have various distinctive features, such as specific gravity, grading distribution, hydration solidification characteristics, etc. depending on the type of slag, pile materials with greater ease-of-use are considered possible in the future by selecting the optimum pile material and construction method corresponding to the required functions.

"Smart Compaction™" products are contributing to recovery and reconstruction projects following the Great East Japan Earthquake, and will also contribute to building a safe and secure society in the future, for example, by countermeasures and strengthening against feared large earthquakes. At the same time, these products are also helping to reduce environmental loads by effective utilization of steel slag. The authors are confident that wide diffusion of these products will make an important contribution to society.

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