Lateral Resistance of Piles in Ground Improved by Compaction Method Using Iron and Steel Slag
-An Experimental Study-

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Abstract

In Japan, efficient use and recycling of materials from production, distribution, consumption, through to disposal are actively promoted. Thus, iron and steel slag is recycled in cement, road subbasecourse, and so on. Slag has hydraulic and expansive properties, which might be useful in some of its applications. The authors have been researching these applications in pile foundations, and have carried out a series of load tests on full-scale nodular piles in ground improved by compacted slag. This paper presents test results that showed that compacted slag around piles increased their lateral resistance.

Keywords— *Iron and steel slag, soil improvement, Lateral load test, Lateral resistance*

INTRODUCTION

In Japan, efficient use and recycling of materials from production, distribution, consumption, through to disposal are actively promoted. Thus, iron and steel slag is used for raw materials of cement and for road subbasecourse. Furthermore, the development of applications that best utilize slag's characteristics, particularly its hydraulic property and expandability, is required. In recent years, a method has been developed for compacting highly expandable slag around nodular-piles to increase the vertical bearing capacity of the pile-soil system [1].

However, in many cases, lateral resistance is a more important factor than vertical bearing capacity in determining the number of piles, pile diameter, and so on. The importance of an earthquake-proof pile foundation began to be recognized after the 1995 Hyogoken-Nanbu Earthquake. Pile foundations are required that have sufficient bearing capacity and deformation performance against large earthquakes. This has focused attention on developing a method for improving the lateral resistance of pile foundations.

One method of increasing the lateral resistance of pile foundations is to improve the ground around them. The most commonly used ground improvement method is the Deep Mixing Method [2], [3].

The authors are also carrying out research for the efficient use of slag. For example, they have been developing a method for increasing the lateral resistance of pile foundations by improving the ground over the whole pile length and the partial surface of the ground with slag [4]. This paper presents results of experiments showing that slag around piles has increased their lateral resistance.

KINDS AND BASIC CHARACTERISTICS OF IRON AND STEEL SLAG

2.1 Kinds of iron and steel slag

Iron and steel slag is generated in iron and steel production. This includes blast-furnace slag produced in the iron smelting process and steelmaking slag generated in the steel manufacturing process in a converter or an electric furnace. Blast-furnace slag ejected during melting and cooled down rapidly is called granulated slag. Granulated slag has a hydraulic property, and it is used as a raw material for cement and for fine aggregate.

However, steelmaking slag has an expandability property. An aging process is carried out to restrain expandability, and this material is used for the raw materials of road subbasecourse and so on. It also has a slight hydraulic property.

The chief ingredients of both are SiO_2 and CaO, as shown in Table 1, which shows the chemical composition of blast-furnace slag and steelmaking slag.

Table 1: Chemical composition

Type	SiO_2	CaO	Al_2O_3	MgO	T-Fe	S	MnO	TiO_2	Others
Steelmaking slag	11.3	37.3	3.9	15.7	20.4	0.04	6.1	1.5	3.8
Blast-furnace slag	33.8	42.0	14.4	6.7	0.3	0.84	0.3	1.0	0.7

2.2 Characteristics of slag used in experiment

Two kinds of slag were used for ground improvement in these experiments: mixed slag (weight ratio 80% steelmaking slag before aging process + 20% granulated slag) and steelmaking slag (100% steelmaking slag after aging process). Fundamental examinations comprising expansion test, permeability test and tri-axial compression test (CD) were carried out to examine mechanical characteristics.

A test piece (dimension: ϕ 100× 200mm) was cured by leaving it at normal temperature in a closed plastic bag. The particle size distribution used for the examination was the same as that of the iron and steel slag used in the field tests, as shown in Fig.1. Curing periods were 1, 3, 6, and 12 months. The results of expansion tests and permeability tests were obtained up to 6 months in the incumbent stage, and the results of tri-axial compression tests were obtained up to 3 months. The results of these tests on mixed slag and steelmaking slag are shown in Fig. 2-3. The following can be understood from these figures.

(a) The coefficient of permeability decreased with time. In particular, the coefficient of permeability of mixed slag was small from the early stage, because it contains granulated slag with the hydraulic property.

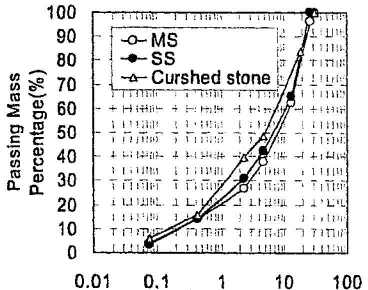
(b) The expansion ratio increased with time. This tendency was more pronounced in mixed slag than in steelmaking slag.

The material constant obtained from the tri-axial compression test is shown in Table 2. The following can be understood from Table 2.

(a) Mixed slag had greater cohesion than steelmaking slag, and it increases with the curing period. This is a result of the hydraulic property.

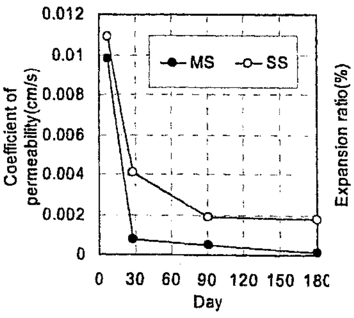
(b) There was no difference between the internal friction angles.

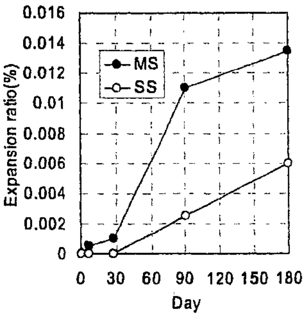
(c) The elastic modulus of mixed slag is greater than that of steelmaking slag, and it changes little with lateral pressure. However, steelmaking slag increases under lateral pressure. This shows the influence of the hydraulic property of granulated slag.



MS; Mixed slag SS; Steelmaking slag

Fig. 1: Particle size distribution





MS; Mixed slag SS; Steelmaking slag

Fig. 2: Result of permeability

Fig. 3: Result of expansion test

Table 2: Material constant obtained from tri-axial compression test

Slag	Curing month	Cohesion (kN/m^2)	Internal friction angle (°)	Elastic modulus E_{50}(kN/m^2)		
				Lateral pressure(kN/m^2)		
				20	50	100
MS	1M	144.9	53.7	77228	109423	115225
	3M	259.5	48.4	129568	150050	121750
	3M/1M	1.79	0.90	1.68	1.37	1.06
SS	1M	45.0	49.6	16645	33567	51037
	3M	55.8	50.0	23232	44944	62006
	3M/1M	1.24	1.01	1.40	1.34	1.21

OVERVIEW OF TESTS

3.1 Test Ground

In the test ground, there was a layer containing slag and iron scraps around the surface. At 1.0m to 12.0m below the ground, there were loose silt layers with N-values of 0 to 7 and silty sand layers with N-values of 8. The surface ground to a depth 0.75m below ground level was replaced with sand, because the condition of the ground near the surface greatly influences lateral resistance. The underground water level was about 1.6m below the surface, and the substituted sand was in a humid condition. The soil boring log of the neighboring ground is shown in Fig. 4.

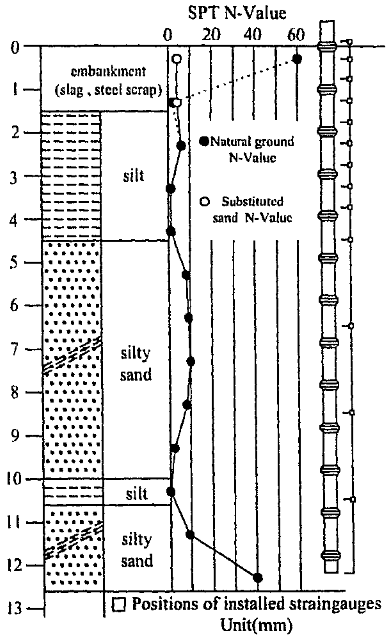


Fig. 4: Soil boring log

Table 3: Concrete nodular pile

Max diameter Do (mm)	Minimum diameter D (mm)	Equivalent cross section Ae (mm^2)	Prestress (N/mm^2)	Bending stiffness EI (N・mm^2)
500	400	7.03×10^4	8.0	4.20×10^{13}

3.2 Outline of test pile

The test piles were pretentioned high strength concrete nodular piles of max diameter D_0=500mm to minimum

Table 4: Test cases

Case	Pile			Curing month (M)	Improvement of ground around pile		Improvement of subsurface ground			
	Diameter(mm)		Type		Improvement material	diameter Ds(mm)	Improvement material	Breadth		Depth F(mm)
	Max	Min						B1(mm)	B2(mm)	
Case1	500	400	Single pile	1	Crushed stone	750	-	-	-	-
Case2				1	MS	750	-	-	-	-
Case3				1,3,6,12			-	-	-	-
Case4				1,3,6,12			SS	2000	2000	750
Case5			Two piles in series	1,3,6,12	MS	750	SS	2000	3000	750
Case6				1,3,6,12			SS			1500

MS:Mixture of two kinds of slag (80% Steel slag before the aging process + 20% Blast furnace slag)
SS:100% Steel slag after the aging process

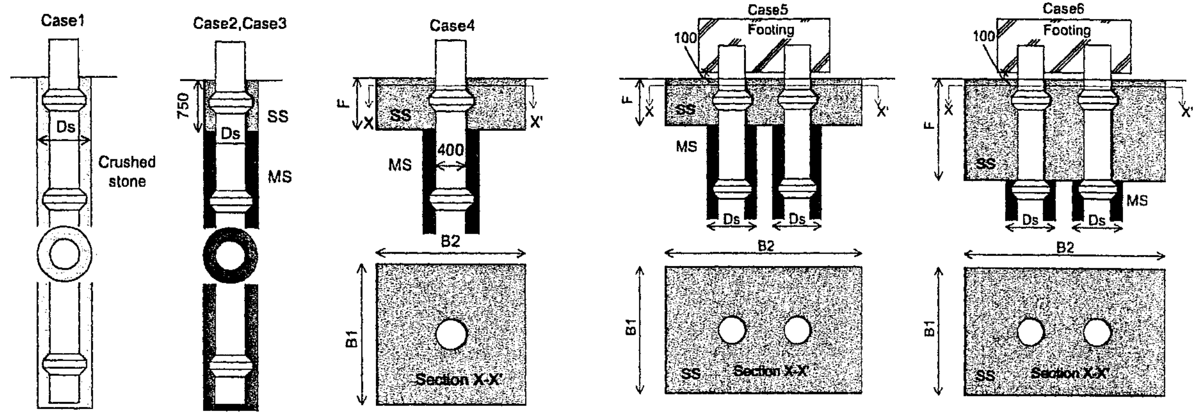


Fig. 5: Details of cases

diameter D=400mm, and length 13m, as described in Table 3. Strain gauges were installed at 12 locations.

3.3 Test case

The main specifications of each test case are shown in Table 4, and outline figures are shown in Fig.5. The ground improvement comprised improvement of ground around the pile near the surface (called improvement of ground around pile) and the improvement of subsurface ground around pile over its whole length (called subsurface ground improvement). The improvement of ground around the pile was provided in all cases. However, subsurface ground improvement was provided only in Cases 4-6.

The materials used for ground improvement around the piles were iron and steel slag and crushed stone (Case 1) for comparison with iron and steel slag. The crushed stone had about the same particle size distribution as the iron and steel slag (see Fig.1). Each improvement diameter Ds was 1.5 times the max pile diameter D_0 over the whole pile length. There was a concern that expansion of slag would adversely influence the footing slab and so on when slag with expansibility was used near the surface. Thus, in application to the actual pile foundations, the improvement of ground around the pile (Case 2 and Case 3) with steelmaking slag whose expansion was restrained from the surface to a depth of 0.75m below ground level, and mixed slag with expandability and hydraulic property below 0.75m below ground level.

To meet the specifications of improvement width, improvement depth of subsurface ground around pile, subsurface ground improvement was provided to Case 4 in the range of 2.0m (four times the max diameter D_0) ×2.0m× depth 0.75m. Moreover, for Case 5, which comprised two piles in series, subsurface ground improvement was provided in the range of width ($B1$) 2.0m× depth ($B2$) 3.0m× depth (F) 0.75m. For Case 6, the depth of subsurface improvement was twice that of Case 5. The subsurface ground improvement was achieved with steelmaking slag whose expansion was restrained.

Incidentally, the pile-center distance for two piles in series was 1.0m (four times the max diameter D_0). A rigid footing (1.0m × 2.0m × 0.8m) was provided to fix the pile heads, and a clearance of 100mm was provided between the footing bottom and the earth surface.

3.4 Test pile construction method

1) Construction of test pile and improvement of ground around pile

Test piles were constructed by the pre-boring method using a specific auger for compaction. The construction flow is shown in Fig.6 and the construction processes are shown in Fig. 7. A test pile is inserted in a hole excavated using the auger, and then the casing is inserted. Fixed material for improvement of ground around the pile is packed into the clearance between the excavation and casing from the surface and compacted.

2) Substitution of surface ground and construction of subsurface ground improvement

To provide for a layer of gravel with slag and iron scraps around the surface of the test ground, the ground was dug to a depth of 1.5m. Then, to achieve the required ground improvement around the pile and the subsurface, the test pile was enclosed with a wooden pattern frame. Sand was packed outside the frame and the fixed improvement material inside the frame, and these were compacted while pulling up a wooden pattern frame (see Photo.1). Using vibration to achieve an N value of about 4, the improved part and sandy ground were compacted.

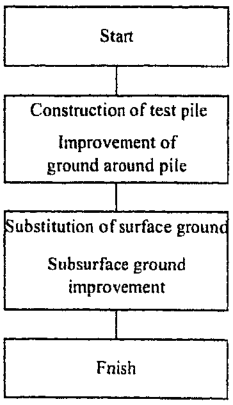


Fig. 6: construction flow

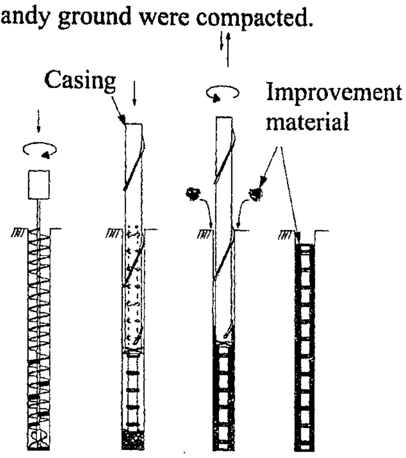


Fig. 7: Construction method and improvement of ground around pile

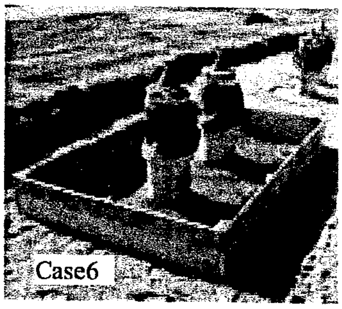


Photo. 1: Construction of subsurface ground improvement

TEST METHOD

Lateral load tests were carried out on Case 1 and Case 2 up to almost the ultimate condition after one-month curing. To examine the influence of change with time of the physical and mechanical characteristics of the slag, as well as to examine the effect of the subsurface ground improvement on the lateral pile resistance, lateral load tests were carried out for Cases 3-6 after curing periods of 1 month, 3 months, 6 months, and 12 months.

The lateral load tests within the curing period of 6 months were finished when a load that did not cause damage to the subsurface improved ground, and the lateral load tests for the 12-month curing period were carried out up to almost the ultimate condition.

4.1 Loading method

The test pile arrangements are shown in Fig.8. Case 5 and Case 6 were used as reaction piles. Cases 1 and 4 were arranged around Case 6, and Cases 2-3 around Case 5. Cases 5 and 6 were carried out together by pushing one another.

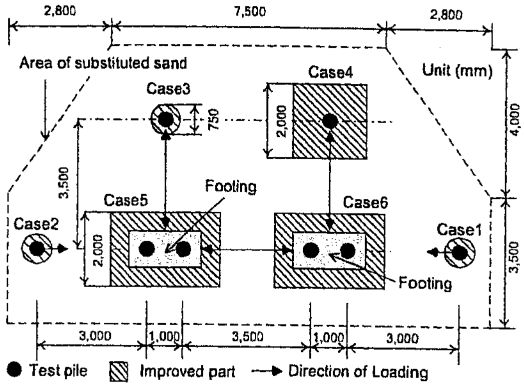


Fig. 8: Test pile arrangement

4.2 Data to be recorded

The lateral load tests were carried out in accordance with the standards of the Japanese Geotechnical Society [5]. The loading method consisted of one-direction multi-cycle loading.

Table 5 shows the standard load step sequence. Data to be recorded were lateral load, test pile displacements (loading point: G.L.+250mm, G.L.+100mm) and bending strains of test pile. However, displacements for Case 5 and Case 6 were measured at the top and bottom of the footing.

Table 5: Standard load step sequence

		Loading		Unloading
Loading method	Loading rate	$\frac{\text{(planned maximum load / number of step)}}{\text{number of step}}$		twice the rate used loading rate
	Period of loading	180sec		180sec
		900sec(No load)		
Items to be measured	Load	New load, Reload	0, 120sec	0sec
		No load	0,120,240,480,840sec	
	Displacement	New load, Reload	0, 120sec	0sec
		No load	0,120,240,480,840sec	

RESULT OF LATERAL LOAD TESTS

5.1 Effect of ground improvement by slag

The relations between lateral load *H* and lateral displacement *y* obtained from the lateral test carried out up to ultimate load are shown in Fig.9. The displacements for Cases 5 and 6 appear at the bottom edge of the footing, and the lateral loads are defined by those values divided by the pile number. The lateral load tests for Case 5 and Case 6 were finished when Case 5 reached the ultimate condition. The following points can be understood from Fig.9.

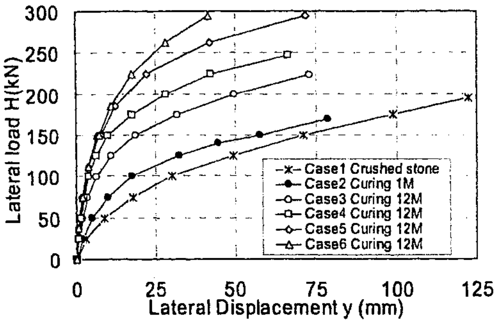


Fig. 9: Relationship between lateral load H and lateral displacement y

(a) By comparing Case 1 and Case 2, it can be seen that the initial lateral stiffness (lateral load / lateral displacement) of Case 2 shows greater improvement than Case 1 of ground around the pile. However, Case 2 is inferior by about 15% to Case 1 in lateral bearing capacity.

(b) By comparing Case 2 (Curing period 1 month) and Case 3 (curing period 12 months), it can be seen that the initial lateral stiffness of Case 3 is about three times that of Case 2, and the lateral bearing capacity is about 1.3 times with change of time of the physical and mechanical characteristics of slag.

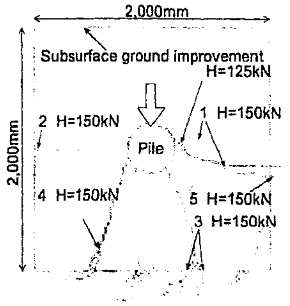
(c) Comparison of the existence of the subsurface ground improvement showed that the initial lateral stiffness of Case 4 (curing period 12 months) is about 1.5 times that of Case 3 (curing period 12 months) due to the subsurface ground improvement.

(d) Comparison of the different depths (subsurface ground improvement) showed that the initial lateral stiffnesses of Case 5 and Case 6 were the same, although Case 6 was twice the depth of Case 5. Therefore, improvement in the depth direction didn't influence the improvement of initial lateral stiffness of the pile.

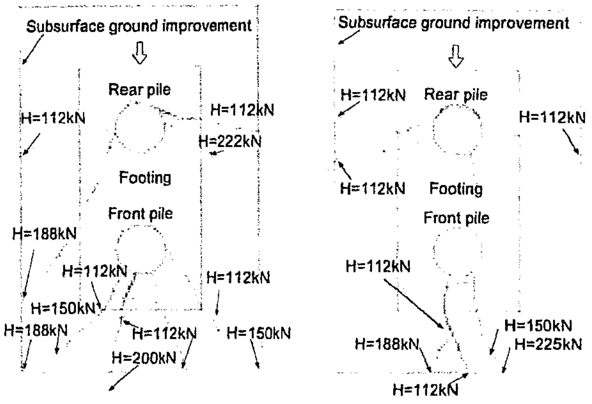
(e) Cases 4-6, provided with subsurface ground improvement, showed large lateral resistance to loads of 100-150kN. After this load, displacement increased nonlinearly, and the lateral stiffness decreased.

The crack development states in the subsurface ground improvement part observed visually during lateral load tests carried out at the curing period of 12 months are shown in Fig.10. The loads when cracks appeared are also shown. Micro-cracks began to form in each case at between 112-125kN. The subsurface ground improvement part thus became plastic, and it can be considered that (e) above occurred. However, it can be seen from Fig.9 that the load didn't decrease rapidly even when the subsurface ground improvement part became plastic.

As discussed above, piles provided with subsurface ground improvement can achieve large lateral resistance due to the stiffness of slag in the elastic range. It is also confirmed that lateral resistance didn't decrease rapidly after the subsurface ground improvement part became plastic.



Case 4



Case 5 Case 6

Fig. 10: Crack development state in subsurface ground improvement part

5.2 *Effect of change with time of physical and mechanical characteristics of slag*

The relations between lateral load H and lateral displacement y of Cases 3-6 for each curing period are shown in Fig.11. It can be seen from these figures that the lateral resistance increased with curing period. However, Case 5 and Case 6 with curing periods of 12 months showed a smaller tendency than those with curing periods of 6 months, because Case 5 and Case 6 were carried out after they were used as the reaction piles of Case 3 and Case 4.

To examine the increase in coefficient of lateral sub-grade reaction for each curing period due to the subsurface ground improvement, the coefficients of lateral sub-grade reaction k_h of Case 3 and Case 4 were computed. Assuming that the coefficient of lateral sub-grade reaction k_h is distributed uniformly in the depth direction, it was calculated in reverse using the elastic beam method proposed by Chang from the relations between lateral load and lateral displacement obtained from the lateral load test.

The coefficients of lateral sub-grade reaction for Case 3 and Case 4 are shown in Figs.12 and 13. The coefficient of lateral sub-grade reaction k_{h4} for lateral displacement 4.0mm (0.1*D*) calculated by the approximate curves shown in these figures are shown in Table 6. The ratio for the value of 1 month is shown in parenthesis in Table 6.

It was understood that the coefficient of lateral sub-grade reaction k_{h4} increased with increase in curing period. The increase rate of 12 months with that of 1 month was 1.70 for Case 3, 2.57 for Case 4, and the rate of Case 3 with Case 4 was 1.10 for 1 month and 1.67 for 12 months. A clear difference in effect appeared with change with time of the physical and mechanical characteristics of slag, although the effect of the subsurface ground improvement was the same as the effect of ground improvement around the pile after curing for 1 month.

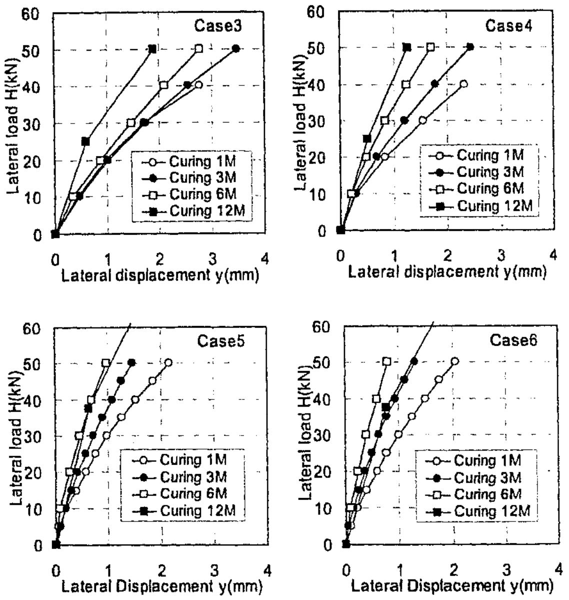


Fig. 11: Relationship between lateral load *H* and lateral displacement *y* of Case3-Case6

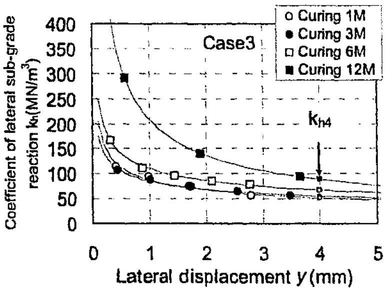


Fig.12: Relationship between k_{h4} and y (Case3)

Table 7: Comparison between k_{h4} and $_sk_{h4}$

Curing month	Cofficient of lateral subgrade reaction (MN/m^3)		
	k_{h4} obtained by the reverse calculation	$_sk_{h4}$ obtained by the equation (1)	$_sk_{h4}$ / k_{h4}
1M	57.8 (1.00)	132.7(1.00)	2.3
3M	82.5 (1.43)	184.6(1.39)	2.24

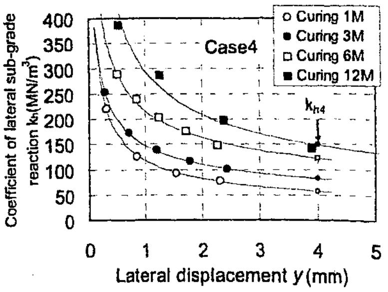


Fig.13: Relationship between k_{h4} and y (Case4)

Incidentally, the coefficient of lateral sub-grade reaction k_{h4} for Case 1 (crushed stone) for the curing period of 1 month calculated by the same method was 26.3MN/m^3. Compared to Case 1 with the curing period of 1 month, Case 3 with the curing period of 12 month was 3.4 times, and Case 4 with the curing period of 12 months was about 5.6 times.

Furthermore, using the elastic modulus obtained in the tri-axial compression test, we tried to evaluate the coefficient of lateral sub-grade reaction $_sk_{h4}$ for the subsurface ground improvement for Case 4. The subsurface ground improvement part was slag ground spread out in the horizontal direction to infinity over its whole depth, and the coefficient of lateral sub-grade reaction $_sk_{h4}$ was calculated from equation (1), as recommended by the Architectural Institute of Japan.

$$_sk_{h4} = k_{h0} \times y^{-0.5} \quad (1)$$

where, $$k_{h0} = \alpha \cdot E_{50} \cdot (B/0.01)^{-(3/4)} \quad (2)$$

in which k_{h0} is the coefficient of lateral sub-grade reaction (kN/m^3); y (=0.4) is lateral displacement (cm); α is 60 for clay and 80 for sand; E_{50} is elastic modulus (kN/m^2), and B is pile diameter (m).

The elastic modulus E_{50} (lateral pressure 20kN/m^2) adopted the value obtained from the tri-axial compression test. The coefficient of lateral sub-grade reaction $_sk_{h4}$ was calculated for the curing period of 3 months, in which the elastic modulus E_{50} was obtained in the incumbent stage. The coefficient of lateral sub-grade reaction k_{h4} obtained by the reverse calculation and $_sk_{h4}$ calculated by equation (1) are shown in Table 7. Although the rates of increase with the curing period are equal, the rates for the coefficient of sub-grade reaction $_sk_{h4}$ with coefficient of sub-grade reaction k_{h4} are about 2.3 times.

Table 6: Coefficient of lateral sub-grade reaction

Curing month	Cofficient of lateral sub-grade reaction k_{h4}(MN/m^3)		
	k_{h4} obtained by the reverse calculation		
	Case3	Case4	Case4/Case3
1M	52.4 (1.00)	57.8 (1.00)	1.10 (1.00)
3M	55.5 (1.06)	82.5 (1.43)	1.49 (1.35)
6M	67.7 (1.29)	123.1 (2.13)	1.82 (1.65)
12M	89.0 (1.70)	148.3 (2.57)	1.67 (1.52)

5.3 Digging test

To investigate the form of the improvement part after the lateral load test for the curing period of 12 months, the ground was dug up to a depth of 1.5m. The crack position of the pile body for this test is shown in Table 8. The knowledge obtained from the test is stated in the following.

(a) The subsurface ground improvement part improved by steelmaking slag with a slight hydraulic property solidified for a thickness of 100-50mm on the surface of the earth, and a thickness of about 10-5mm on the surrounding of improvement part. However, the inside slag didn't solidify very much (see Photo. 2). The surface on the earth side is where the supply of water is most abundant due to rain and so on, and it could be thought that solidification advanced. Furthermore, because the ground in the neighborhood was sandy and water permeability was large, water from rain and so on permeated inside. As a result, solidification was promoted in the surrounding improvement part. It is considered that the solidification of steelmaking slag with a slight hydraulic property didn't progress because permeability to the inside of the improvement part was obstructed by solidified parts. It is understood that a moderate water supply is necessary for the solidification of steelmaking slag.

(b)For the improvement of ground around the pile improved by steelmaking slag from surface to a depth of 0.75m, solidification on the earth surface and the surrounding improvement part was similarly advanced, but its inside didn't solidify very much.

(c) For the improvement of ground around the pile at depths below 0.75m, the solidification progressed to the inside of the improvement part due to the potential hydraulic property of the granulated slag contained in the mixed slag, and a column body was formed. Moreover, the sandy ground around the circumference was left under the compacted condition, to a thickness of about 100mm around the improvement part, without collapsing against digging (see Photo. 3). It can be considered that the sandy ground around the improvement part was compacted due to the expandability of steelmaking slag in the mixed slag before the aging process. Incidentally, for Case 1 in which crushed stone was used for the improvement of ground around the pile, this tendency wasn't observed.

(d) In Cases 1-4, carried out under free conditions at the pile head, a crack in the pile body appeared in the neighborhood of the boundary (depth of 0.75m) of the two kinds of slag. This is considered to be caused by stress concentration at the boundary, where the stiffness of ground improvement was greatly different, because lateral load tests were carried out under the condition where maximum bending strain occurred in the ground part. However, in Cases 5-6, which were carried out under fixed conditions at the pile head, no crack appeared in the pile body below the ground. However, a crack appeared around the projected pile head. This phenomenon shows that stress didn't concentrate at the boundary.

With regard to the subsurface ground improvement, solidification around the extreme surface of the earth only influenced the improvement of the lateral resistance of the pile, because the inside slag didn't solidify very much. Therefore, even though the depth of the surface improvement was two times, no great difference was seen in the initial lateral stiffness of the pile (mentioned in 5.1(d)). However, for the pile foundation structure, water isn't supplied to the extreme surface of the earth of the subsurface ground improvement part directly. The way of curing on this test is thought to be greatly different from that in the actual environment. Thus, if mixed slag with a larger hydraulic property than steelmaking slag is used as the ground improvement material, lateral pile resistance can be expected to increase, as the solidification is promoted to the inside of the subsurface ground improvement part. Therefore, the expansion pressure of slag is grasped quantitatively, and its influence on the footing slab needs to be evaluated. This is a future subject.

As discussed, the following factors showing that the lateral pile resistance increases with increase in curing period can be understood from this digging test.

(1) Solidification of the subsurface ground improvement and the improvement of ground around the pile at the extreme surface of the earth

(2) Solidification of the improvement of ground around pile which was improved by mixed slag and the effect of compaction by the expandability of mixed slag

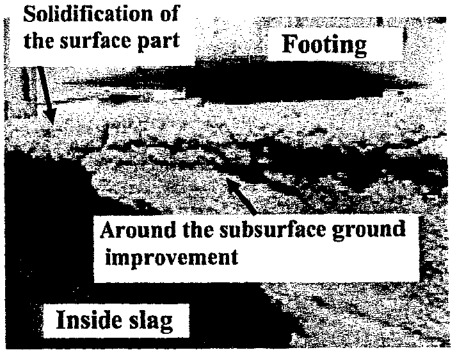


Photo. 2: Form of subsurface ground improvement part

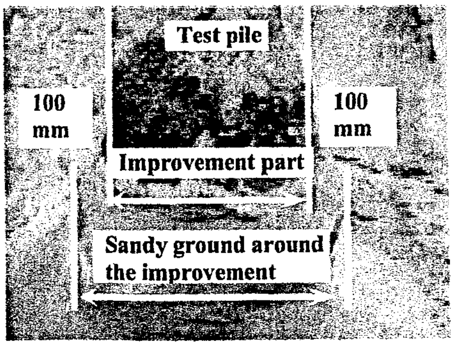


Photo. 3: Form of the improvement part (mixed slag)

Table 8 :Crack position of piles

Case		Crack number	Crack occurrence depth(mm)		
Case1		3	660	980	1260
Case2		3	620	920	1190
Case3		3	760	990	1340
Case4		3	540	730	940
Case5	Front pile	1	-50		
	Rear pile	1	-100		
Case6	Front pile	0	It can't be confirmed.		
	Rear pile	1	-50		

CONCLUSION

We examined methods of increasing lateral pile resistance by improving the ground around pile foundations by using iron and steel slag. The following were confirmed from the results of lateral load tests.

(1) Iron and steel slag as an improvement material around piles is effective in increasing lateral resistance.

(2) Lateral pile resistance in ground improved by iron and steel slag increases with time as the physical and mechanical characteristics improve. The coefficient of sub-grade reaction increase by about 1.7 times for improvement of ground around a pile, about 2.6 times at subsurface ground improvement by curing for twelve months. Accordingly, the use of slag as an improvement material enables reduction in cost if such a lateral pile resistance at the completion of building structures can be used during design.

(3) A pile provided with subsurface ground improvement can achieve large lateral resistance due to the stiffness of slag in the elastic range, and it doesn't decrease rapidly after the subsurface ground improvement part becomes plastic.

(4) In this test, the ground improvement around the surface of the earth was improved by steelmaking slag in which expansion is restrained in consideration of the application to the actual pile foundation. When using mixed slag with larger potential hydraulic property than steel making slag, greater lateral pile resistance can be expected.

ACKNOWLEDGMENT

The authors are grateful to HIROHATA WORKS NIPPON STEEL CORPORATION's, Mr. Michishita for providing us with the test site, and other project participants. They also express their gratitude to the members of a committee of JAPAN ASSOCIATION FOR BUILDING RESEARCH PROMOTION "A practical use to pile foundations of iron and steel slag" (Chairman of a committee: a professor emeritus of Tokyo Institute of Technology. Hideaki. Kishida).

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