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Application of Improved Dredged Soil with Steelmaking Slag to Artificial Tidal Flat†

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Abstract:

In order to effectively use dredged soil, improved dredged soil which is mixed with steelmaking slag has been developed. Intended application areas of the improved soil are tidelands, dredging hollows and reclamation materials. Restoration method of an artificial tidal flat and development of a new artificial tideland using the improved dredged soil were studied. For the restoration method using the improved dredged soil, proposed new method was demonstrated to be effective compared with the conventional type through field construction test. For the development of new artificial tideland, proposed new structure with the improved dredged soil enables reduction in soil improvement width and increase in dredged soil quantity, and the stability of this artificial tideland was confirmed through centrifuge model test.

1. Introduction

In port facility improvement works, dredged soil is generated by dredging to maintain the necessary water depth for navigation of ships and deepening work in response to the larger size of ships, and effective utilization of this dredged soil has become an issue. JFE Steel has developed applications for a mixed soil (hereinafter, "improved dredged soil") consisting of dredged soil, which is difficult to reuse as-is due to its high content of silt and clay, and steelmaking slag[1,2]. Steelmaking slag is a byproduct of the steel manufacturing process and contains free lime in its composition. Improved dredged soil displays strength development due to the pozzolanic reaction between the silica component of the dredged soil and the free lime component of the steelmaking slag. Since the material solidifies, it is resistant to liquefaction, and the improved dredged soil also has low water permeability and other desirable properties[1,2] because dredged soil is the main raw material. Thus, the intended areas of application for this improved dredged soil include use as a material for restoration/construction of shoals and tidelands, backfill material for dredged depression and material for land reclamation. This paper reports a restoration method for artificial tidal flats and an artificial tideland structure using improved dredged soil as a widening material with the aim of application of the improved dredged soil to artificial tidelands.

2. Application of Improved Dredged Soil as Artificial Tidal Flat Restoration Method

2.1 Outline of Artificial Tidal Flat Restoration Method

In many cases, artificial tidal flats consist of dredged soil as a filling material and natural sand as a capping material on the land side of a submerged mound made of stone material. However, a decrease in area or reduction of the functions of the tidal flat due to consolidation settlement of the fill material was a problem. As a countermeasure for this problem, a restoration method in which a slurry of dredged soil is injected into the fill under high pressure to raise the level of the sunken tidal flat ground has been studied[3]. Although this method has the merits of effectively utilizing dredged soil, which is generated regularly, and not affecting the biological environment of the sand-capped surface layer, the small amount of dredged soil that could be injected from one injection point was a problem. As a method for improving the dredged soil injection effect of this restoration method, in this study, we propose a structure in which improved dredged soil is provided as a solidified layer between the dredged soil and sand-capping material[4]. **Figure 1** shows a schematic diagram of this artificial tidal flat restoration

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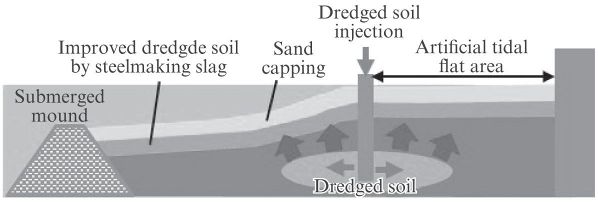

Fig. 1 Restoration method of the artificial tidal flat

method. By using the proposed structure, it is thought that that local bulging at the dredged soil injection point can be suppressed by the strong improved dredged soil, and the amount of injected dredged soil can be increased because the tidal flat ground is raised over a wider area. Therefore, an actual-scale field construction test was carried out in order to demonstrate the effect of the proposed structure on injection of dredged soil.

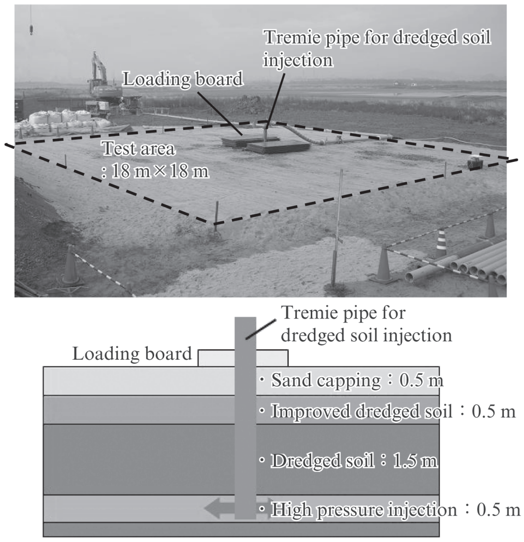

Fig. 3 Cross section of construction test

2.2 Outline of Actual–Scale Field Construction Test

2.2.1 Improved dredged soil used in test

The improved dredged soil consisted of 70 vol% dredged soil (fine grain content: 91%) from a channel at Fukuyama Port and 30 vol% steelmaking slag (particle size: 26.5 mm or less, free lime content: 4.1%). These raw materials were mixed with a backhoe. From the results of a preliminary mixing test, the flow value of the improved dredged soil was set at approximately 9 cm, considering workability immediately after mixing and early period strength development.

2.2.2 Method of field construction test

A partial model of an artificial tidal flat was constructed in a range of 18 m×18 m in a dredged soil storage yard on land. The flow of the construction test and the cross section of the test are shown in **Fig. 2** and **Fig. 3**, respectively. The dredged soil from the surface to a depth of 2.5 m was decomposed to the specified size and its moisture content was adjusted by adding water (water content: 95%) by a vehicle for work on mud equipped with a mixer, so that the strength of the experimental ground was similar to the ground of an actual tidal flat[5)] (undrained shear strength c_u=1.4–4.1 kN/m^2). A 50 cm thick layer of improved dredged soil immediately after mixing was laid on the surface of the experimental ground and allowed to cure for 3 months, after which a 50 cm thick layer of sand-capping material (granulated blast furnace slag) was laid. Next, the dredged soil around the injection position was softened in order to raise the ground gradually during dredged soil injection. Here, the ground was softened by increasing the water content to 125%, or approximately 1.2 times the liquid limit, by spraying a high pressure water jet (40 MPa) in a range of 2.5 m±0.25 m from below the ground surface, using the high pressure injection mixing method, which is utilized in the ground improvement (soil stabilization) field[6)]. High pressure injection of the dredged soil was performed by inserting a tremie pipe for dredged soil injection so that the center of the opening at the tip of the tremie pipe was positioned at a depth of 2.5 m from the crown of the sand-capping material, and then pumping the dredged soil at a pumping flow rate of 45 m^3/h using a concrete pump. In order to prevent local bulging around the tremie pipe and blowout of the pressurized dredged soil, a circular loading plate with a diameter of 3 m and steel plates (loaded weight: 20 kN/m^2) were placed at the tremie pipe insertion position. The dredged soil for injection was adjusted to approximately 1.2 times the liquid limit (water content: 125%) supposing dredging with a grab bucket. For a

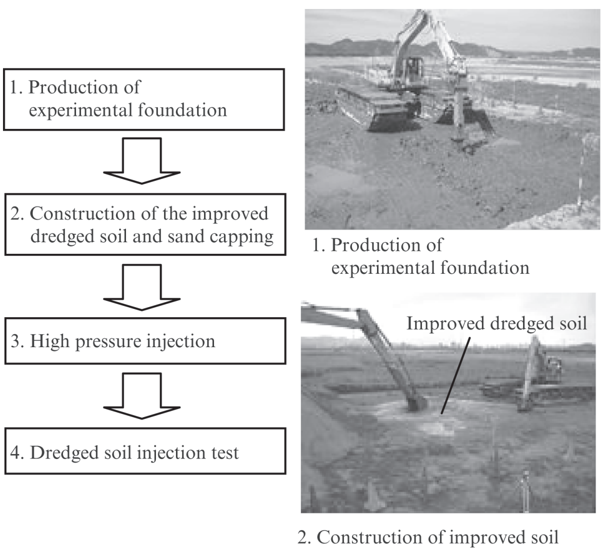

Fig. 2 Construction test flow

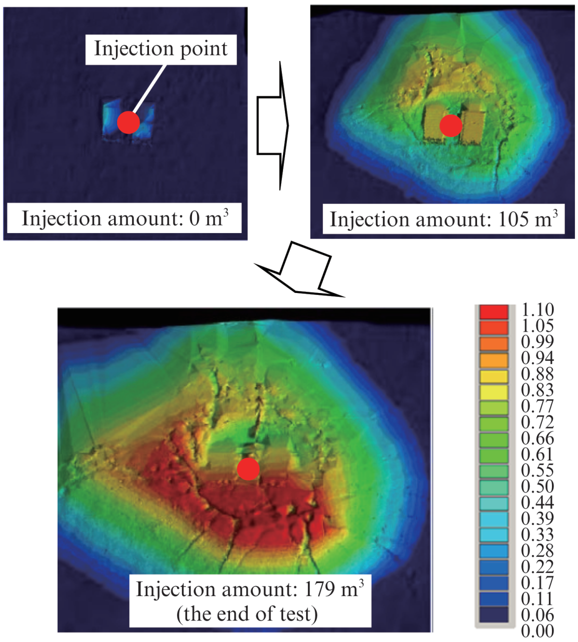

Fig. 4 Result of the ground level measurement

drilling investigation after the test, cement slurry (cement addition amount: 60 kg/m^3) was added to the dredged soil. After injection of the dredged soil, the ground surface profile was measured with a 3D scanner.

2.3 Results of Field Construction Test

2.3.1 Quality of improved dredged soil

To confirm the quality of the improved dredged soil used in this test, a strength test was performed using samples taken immediately after backhoe mixing. As a result, the coefficient of variation of uniaxial compressive strength after curing for 28 days was 0.15 (number of samples: 24, mean value: 174 kN/m^2, standard deviation: 26.5 kN/m^2). Since this is less than the set point used in the cement mixing soil stabilization method[7], the mixing quality is considered to be satisfactory. Furthermore, the results of a strength test of core samples taken from the improved dredged soil laid in the test area confirmed that the uniaxial compressive strength of the core samples was on the same level as that of the samples taken immediately after backhoe mixing. The uniaxial compressive strength of the improved dredged soil of the test area in the high pressure injection test was 223 kN/m^2.

2.3.2 Results of high pressure dredged soil injection test

As the injection pressure measured during dredged soil injection was approximately 0.1–0.2 MPa, stable injection of the dredged soil was possible. The change over time in the amount of ground level rise measured by the 3D scanner is shown in **Fig. 4**, and the condition

Photo 1 Situation of the protuberance in the ground level

of protuberance of the ground level after the end of the test is shown in **Photo 1**. After the start of the test, the ground level began to rise when dredged soil injection reached 50 m^3, and after injection of 105 m^3, a circular protuberance centering on the injection position and cracks in the sand-capping material occurred. Following this, leakage of the dredged soil from the cracks was observed when injection reached 179 m^3, and this was judged to be the limit of injection in the construction test. The maximum ground level rise at this time was 1.26 m.

On the other hand, the results of a test[3] by the same construction method, but without laying a layer of dredged soil improved with steelmaking slag, showed a dredged soil injection limit of 86 m^3 and a maximum ground level rise of 0.66 m. Based on this, the artificial tidal flat structure using the improved dredged soil as a solidified layer between the dredged soil and the sand-capping material is an effective method for enhancing the dredged soil injection effect. Under the injection conditions in this experiment, the amount of dredged soil injection per injection point could be increased to approximately 2 times that with the conventional method.

2.4 Study of Injection by Numerical Analysis

2.4.1 Analysis method

In order to verify the applicability of numerical analysis to this construction method, an FEM analysis of this construction test was performed under the condition of axial symmetry, using static ground deformation analysis program. The analysis model is shown in **Fig. 5**. The lower edge was assumed to be the horizontal/vertical displacement fixed boundary, and as in the actual construction test, a loading plate with a diameter of 3 m and a surcharge pressure of 20 kN/m^2 was set on the top surface of the sand-capping layer. The analysis constants are shown in **Table 1**. All of the ground was assumed to be a linear elastic body. The deformation moduli of the decomposed dredged soil layer and the high pressure injection layer were calculated by

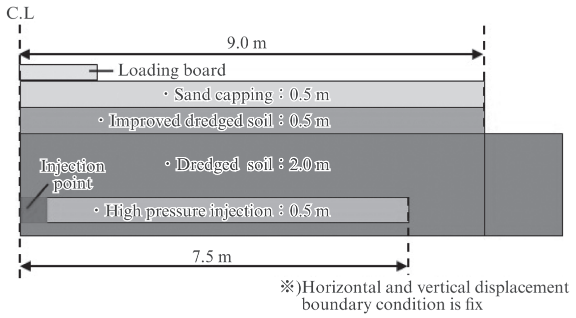

Fig. 5 Analysis model

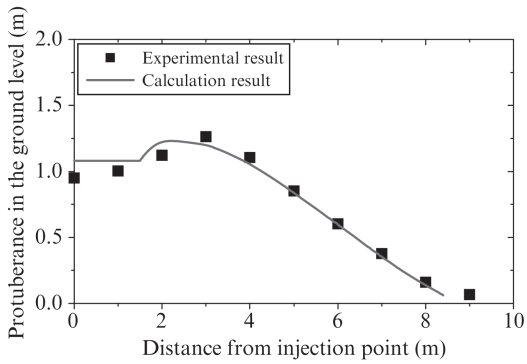

Fig. 6 Comparison between calculation and measurement

Table 1 Analysis constants

	Cohesion of soil (kN/m^2)	Internal friction angle (°)	Deformation modulus (kN/m^2)
Sand capping (granulated slag)	0	35	1.0×10^4
Improved dredged soil	111	0	6.68×10^4
Dredged soil	–	–	5.30×10^2
High pressure injection	–	–	2.00×10^2

converting the cone penetration resistance q_c obtained from an electric static cone penetration test to undrained shear strength by using Eqs. (1) and (2). The deformation modulus of the improved dredged soil was calculated from the 91 day uniaxial compressive strength of the samples by using Eq. (3). Injection of the dredged soil in the analysis was expressed in the analysis by applying internal pressure to cause bulging of the ground elements, with the ground elements at the injection position closed at the undrained boundary. The applied pressure was adjusted so that the volumetric increment before/after injection was equal to the amount of injected dredged soil.

$$c_u=q_c/20 \quad (1)$$

$$E=200\ c_u \quad (2)$$

$$E=300\ q_u \quad (3)$$

2.4.2 Results of analysis

Figure 6 shows a comparison of the analysis results of ground protuberance and the measured values obtained in the construction test. Although the position of maximum protuberance varies slightly, the amount of maximum protuberance and the protuberance profile are in good agreement. Thus, application of FEM analysis to this construction method is considered possible.

3. Structure of Artificial Tideland using Improved Dredged Soil as Widening Material

3.1 Outline of Artificial Tideland Structure using Improved Dredged Soil

Although development of new artificial tideland has been carried out by using dredged soil, in cases where the sea bottom ground is weak clay soil, soil stabilization by Sand Compaction Piles (hereinafter, “SCP”) or other appropriate methods is necessary in the foundation ground for the earth-retaining submerged mound. Because the cost of this foundation improvement occupies a large percentage of the total construction cost, reduction of the cost of foundation improvement has become an issue. Therefore, artificial tideland development combining the use of improved dredged soil as a widening material for the submerged mound was proposed[8]. A schematic diagram of the artificial tideland structure in this study is shown in **Fig. 7**. This artificial tideland structure has the following three features. First, because the improved dredged soil used as the widening material is lighter in weight than the submerged unit weight of the conventional stone material (10 kN/m^3) and also has large adhesive force, it is possible to reduce the ground improvement width. Second, the flowability of the improved dredged soil is lower than that of simple dredged soil. Taking advantage of this feature, it is possible to use a larger amount of dredged soil as fill than in the conventional

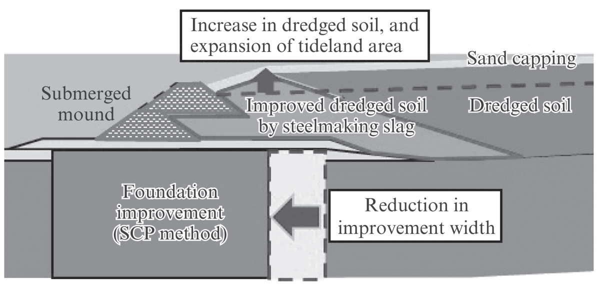

Fig. 7 Artificial tideland structure using improved dredged soil

method, by creating a slope in the improved dredged soil used as the widening material and increasing the height at the back side of the submerged mound. Third, because the height of the crown position behind the submerged mound is higher due to this increase in the height of the improved dredged soil, the slope of the sand-capping material is more moderate. As a result, in comparison with the conventional method, expansion of the tideland area becomes possible, and improved stability of the sand-capping material against waves can be expected.

On the other hand, because the width of ground improvement is reduced and the amount of dredged soil behind the submerged mound is increased with this artificial tideland structure, it may be thought that stability is a problem. Conventionally, the stability of artificial tideland structures is evaluated by using a circular slip analysis. However, in structures in which improved soil such as cement-solidification treated soil is used partially, the appropriateness of stability evaluation by circular slip analysis is sometimes an issue[9]. Therefore, a centrifuge model experiment was performed to verify the stability of the artificial tideland structure using improved dredged soil by comparison with the conventional structure, and to clarify the applicability of the circular slip method.

3.2 Outline of Centrifuge Model Experiment

3.2.1 Experimental cross sections

To set the experimental cross sections, a circular slip analysis was performed using the ground conditions in **Table 2**, assuming an artificial tideland constructed in waters with a water depth of 9 m, and the ground improvement width was obtained. Here, the improved ground was assumed to be a composite ground of clay soil and piles, using the SCP construction method with a replacement area ratio of 25%. The obtained artificial tideland cross sections are shown in **Fig. 8**. Under the conditions of this study, the ground improvement width in case improved dredged soil was used was 21.0 m, enabling a reduction of 30% in comparison with the improvement width of 29.4 m with the conventional structure. Use of dredged soil as the filling material was increased by approximately 20%. As the experimental cross section, an experimental range (actual scale) of 48 m in width, centering on the submerged mound, and 23 m in height was assumed as the object of the two cross sections in Fig. 8.

3.2.2 Production of model ground

In the experiment, a 1/80 scale model of the model ground was made in a sample container (width 60 cm×height 40 cm×depth 20 cm). The experimental procedure is shown in **Fig. 9**. The material used for the foundation ground was kaolin clay (MC clay and AX kaolin mixed at a dry weight ratio of 1: 1). A supporting sand layer (No. 5 Iide silica sand, thickness: 4 cm) was provided in the bottom layer of the sample container to function as a water permeable layer during consolidation. Next, kaolin clay with a water content adjusted to 120% was charged into the container. Since the object of this experiment was normally consolidated clay ground, self-weight consolidation was performed in a centrifugal acceleration field of 80 g (g: acceleration of gravity) after introducing the kaolin

Table 2 Condition of experiment

Item		Unit	Design	Experiment
Foundation ground	Unit weight below water level	kN/m^3	4.5	6.5
	Cohesion of soil	kN/m^2	2.0×z (ground level, z = 0)	2.6×z (ground level, z = 0)
Improvement SCP method	Replacement area ratio	%	25	25
	Unit weight below water level	kN/m^3	10.0	10.0
	Internal friction angle	°	30	35
Submerged mound	Unit weight below water level	kN/m^3	10.0	10.0
	Internal friction angle	°	40	40
Improved dredged soil	Unit weight below water level	kN/m^3	6.2	6.2
	Cohesion of soil	kN/m^2	80	80
Dredged soil	Unit weight below water level	kN/m^3	5.4	4.0
Sand capping	Unit weight below water level	kN/m^3	10.0	10.0

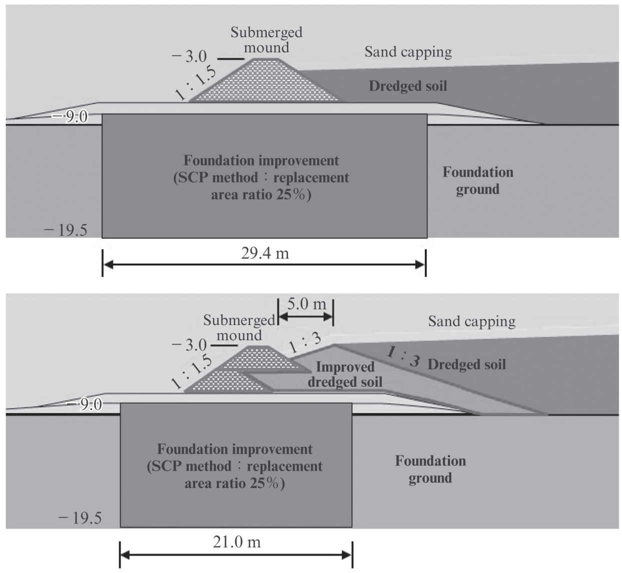

Fig. 8 Cross section of models

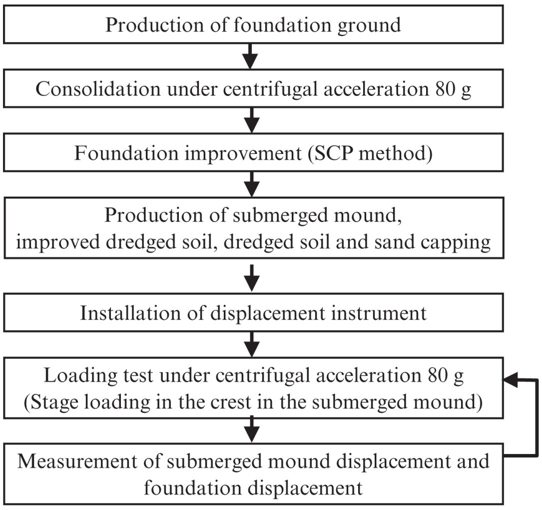

Fig. 9 Experimental test flow

clay, and a degree of consolidation of 95% or more was confirmed by the $\sqrt{t}$ method. According to the results of the cone penetration test, the strength increment of the foundation ground in the depth direction was 2.6×z kN/m^2 (z: earth covering thickness from ground surface). As the SCP (or sand piles), cylindrical acrylic pipes (inner diameter: 21 mm) were filled with No. 5 Iide silica sand, compacted to a relative density of 85% and frozen. After self-weight consolidation of the foundation ground was completed, holes (diameter: 21 cm) were drilled at the positions of SCP pile driving, and the frozen SCP (or sand piles) were driven. The improved dredged soil was prepared by mixing 20 vol% of steelmaking slag with a particle size of 1.0 mm or less in Kasaoka clay (fine grain content: 91%, moisture weight percentage: 225%). To obtain the strength during the experiment (adhesive force: 80 kN/m^2), 96 kg/m^3 of ordinary Portland cement was added. The weight per unit volume of the improved dredged soil used in the experiment was 16.2 kN/m^3. In the submerged mound, No. 7 crushed stone (size: approximately 2.0–9.5 mm) was used, and the slope-face gradient was set to 1: 1.5. As the dredged soil filling material, Kasaoka clay was used; this was same material as the dredged soil used in the improved dredged soil. The water content of the Kasaoka clay was adjusted to a unit weight of 14 kN/m^3.

3.2.3 Experimental method

The prepared model ground was loaded on the centrifuge model test device, and the experiment was performed in a centrifugal acceleration field of 80 g. The ground conditions are shown in the experimental value column of Table 2. Because the purpose of this experiment was to verify the stability of the proposed structure, the experiment was performed with the proposed structure and a conventional structure prepared under

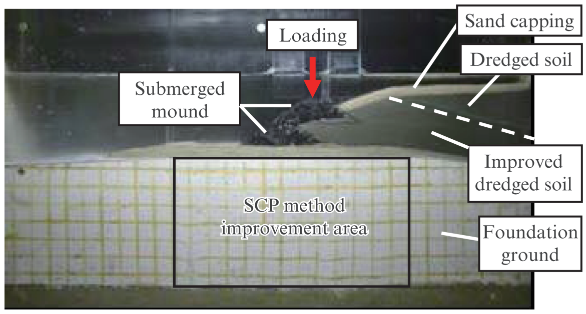

Photo 2 Centrifuge model test

the same ground conditions, and the deformation behavior of the two structures was compared. The condition of the centrifuge model test is shown in **Photo 2**. In this experiment, deformation of the submerged mound was caused by loading a weight at the crown position of the submerged mound as the driving force in the circular slip analysis. The loading weight was set in six steps from 0 to 347 kN/m^2 (actual scale), and was increased step by step. The amount of settlement of the submerged mound crown was measured at each load. In addition, the amount of deformation of the improved part was measured by image processing of the grid-shaped colored sand (yellow) of the foundation ground part.

3.3 Experimental Results

3.3.1 Deformation behavior of proposed structure

With the proposed structure, the occurrence of a crack in the improved dredged soil of the bottom part (upper level) of the submerged mound could be seen when the load on the mound crown reached 139 kN/m^2. If the load dispersion of the crushed stone (submerged mound) is considered, it can be thought that a total of 159 kN/m^2 acts on the improved dredged soil at this time. This total is the sum of the load of 139 kN/m^2 on the crown of the submerged mound and the self-weight of the mound (submerged unit weight of 10 kN/m^3×height of 2 m). Thus, cracks occurred when the loading action was similar to the uniaxial compressive strength of 160 kN/m^2, which was a condition of this experiment. Subsequently, at loading of 204 kN/m^2, enlargement of the crack width could be seen, but no large deformation of the foundation ground or settlement of the submerged mound due to crack growth was observed. The deformation of the proposed structure at loading of 278 kN/m^2 is shown in **Photo 3**. Focusing on the colored sand (yellow) laid in the improved foundation part, the colored sand (vertical lines) positioned on the ocean side of the center of the submerged mound deformed toward the ocean side, but deformation was not observed on the land side of the submerged mound center. This deformation

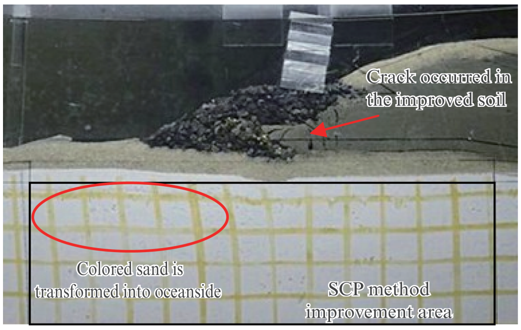

Photo 3 Situation of loading 278 kN/m^2

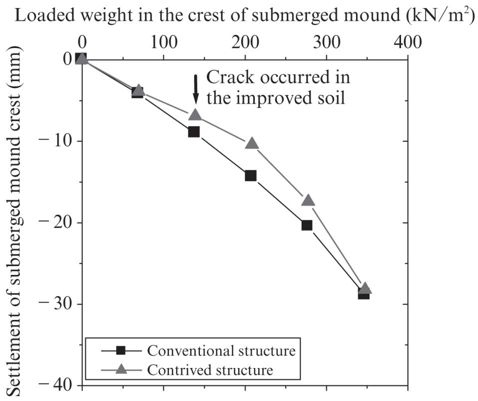

Fig. 10 Comparison of the submerged mound settlement

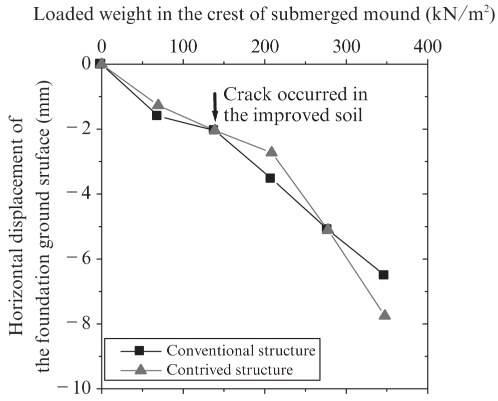

Fig. 11 Comparison of the horizontal displacement

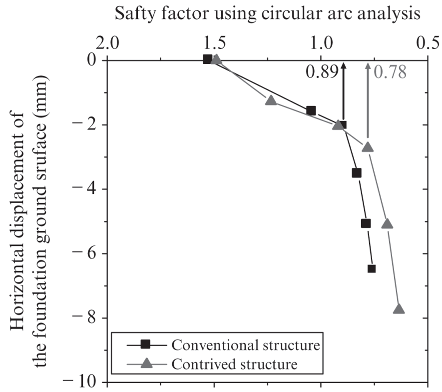

Fig. 12 Comparison of the safety factor

affected the foundation ground to a somewhat deeper position than the slip line in the results of the circular slip analysis.

3.3.2 Comparison of displacement between proposed structure and conventional structure

A comparison of the settlement of the submerged mound under various loaded weights is shown in **Fig. 10**. For settlement, which shown on the *y*-axis, the end point of the centrifuge experiment at a loaded weight of 0 kN/m^2 was defined as the standard value (zero). In these results, the settlement of the proposed structure was smaller than that of the conventional structure at the same loaded weight. In the case of the proposed structure, the slope was more moderate than that of the conventional structure up to the load of 204 kN/m^2, and no sudden changes in settlement could be seen even after the crack occurred (load: 139 kN/^{2}) in the improved dredged soil. The slope became steeper when the load exceeded 204 kN/m^2, and the amount of settlement was similar to that of the conventional structure. **Figure 11** shows a comparison of the horizontal displacement of the ground surface of the foot of the slope of the submerged crest (ocean side). With the conventional structure, the slope became steep when the load exceeded 139 kN/m^2, and horizontal displacement increased. On the other hand, the horizontal displacement of the proposed structure was similar to that of the conventional structure up to the load of 204 kN/m^2, and when the load exceeded 204 kN/m^2, the slope became steep and horizontal displacement increased. Thus, from the results of the comparison of the displacement of the proposed structure and the conventional structure under the same loaded weight, it is thought that the stability of the proposed structure is similar to that of the conventional structure.

3.3.3 Comparison with circular slip analysis results

Stability evaluation by circular slip analysis is used in the existing design method. To study its applicability to the proposed structure, a comparison of the proposed structure and the conventional structure was performed. **Figure 12** shows the comparison of the horizontal displacement of the ground surface of the foot of the slope of the submerged mound (ocean side) and the safety factors obtained by the circular slip analysis. The horizontal displacement of the conventional structure increased rapidly when the safety factor was less than 0.9. On the other hand, the horizontal displacement of the proposed structure was approximately the same as that of the conventional structure until around a safety factor of 0.8, and displacement increased rapidly when the safety factor was less than 0.8. Although a similar comparison of the settlement of the crown of the submerged mound was also carried out, the tendency was the same. From the results of this comparison, the safety factor at the inflection point, where the displacement of the proposed structure begins to increase rapidly, is 1.0 or less, and is lower than that of the conventional structure. From this, it is thought that the evaluation will tend toward the conservative side if the existing stability evaluation technique by circular slip analysis is applied to the proposed structure.

4. Conclusion

As use technologies for dredged soil improved with steelmaking slag, an artificial tidal flat restoration method and an artificial tideland structure using the improved dredged soil as a widening material were studied. In the artificial tidal flat restoration method, a structure in which improved dredged soil is provided as an intermediate layer between the dredged soil used as fill and the sand-capping material was proposed, and an actual-scale field construction test demonstrated that an increase of approximately two times in the dredged soil injection effect is possible by the proposed method. In the study of the artificial tideland structure, a structure which makes it possible to reduce the width of ground improvement and increase the amount of dredged soil used was proposed, and a centrifuge model experiment was performed, confirming that the overall stability of the proposed structure is similar to that of the conventional structure. In recent years, efforts to improve the environment in coastal regions have been promoted, including restoration of shoals and tidal flats, backfilling of dredging depression, etc. Because the materials used in this improved dredged soil are byproduct materials, namely, steelmaking slag and dredged soil, the proposed methods contribute to effective utilization of recycled resources. The authors hope to contribute to building a society with low environmental loads in which sustainable development is possible by popularization of these technologies.

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