Restoration Method of Artificial Tidal Flat by Use of Pressure Injection of Slurry Dredge Clay

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ABSTRACT: The method of uplifting the ground surface by pressure injection of slurry dredge clay is proposed to restore the settled tidal flat without influencing the creatures living on and inside it. In order to establish the method, the study was carried out to examine the effectiveness of several technologies to uplift the ground smoothly avoiding the blowout of injected soil. As a result of laboratory experiment, it turns out that prior softening of original ground horizontally and placement of uplift restraint are effective for the purpose. The applicability of the proposed method was verified in situ contributing to the future practical application of technology by a field experiment.

KEYWORDS: Consolidation settlement, Dredged soil, Clam

1. INTRODUCTION

In Japan, over 20 million m^3 of dredging is conducted each year in navigation channels and berths for construction and maintenance of ports. Conventionally, most dredged soil is dumped at landfill sites near dredging areas. However, in recent times, the residual capacities of the sites are running out, while it is difficult to construct new landfill sites owing to high construction cost and environmental protection concerns. As a result, the disposal of dredge soil is an urgent issue in the field of marine engineering.

On the other hand, artificial tidal flats are being constructed in various places to enable restoration of coastal natural environments that have already been lost. The use of dredge clayey soil as infill is a method proposed to enable the construction of artificial tidal flats without large volumes of natural sand, as reported by Furukawa (2005), Okutani *et al*. (2011) and Shiomi *et al*. (2012). This method has the advantage of not only reducing the burden on the natural environment with sand resource but also of utilizing large volumes of dredge clay as infill. In Addition, sand coverage is placed to protect the soft infill from erosive action of waves and provide favorable habitat for bivalves such as a clam. At this point, as clayey dredge soil that has been used is subject to consolidation settlement, there is concern that the tidal function will deteriorate because of the decreasing of the intertidal area.

Conventionally, the addition of sand coverage has been employed to restore settled tidal flats as reported by Yamamoto *et al*. (2006). The placement of sand from the surface for this purpose, for instance by use of hopper barges, requires little construction expenditure, but the placement of even, thinly layered sand coverage is difficult and turbidity of water often occurs during the construction. Although, there is a recently developed construction method that allows for thin-layered sand coverage with less turbidity, the habitats of organisms in the surface are destroyed during the construction, and bio-function of the tidal flat is lost. Furthermore, adding sand coverage also has the disadvantage of causing furthering of settlement due to consolidation because of the added load. Consequently, more effective methods are required for the restoration of artificial tidal flats without disturbing surface biota and promoting the settlement due to consolidation.

In this study, uplifting the tidal flat ground subject to consolidation settlement by pressure injection of slurry clay is proposed. With this method, clayey dredge soil is directly injected under pressure as infill without disturbing the surface so as not to affect the surface biota. Moreover, the magnitude of settlement due to consolidation is also low in comparison with the conventional method that involves the addition of sand coverage with high unit weight. Furthermore, this proposed method ensures the compatibility of regular maintenance dredging in ports with the construction and maintenance of artificial tidal flats. In the present study, we performed laboratory experiment to develop base technologies that enable to uplift the ground smoothly without causing the blowout of injected soil. Then, based on the laboratory experiments, a field experiment has been implemented to contribute to the future practical application of technology.

2. LABORATORY EXPERIMENT USING A LARGE TANK

There is a requirement for technologies that enable wide-range yet smooth uplifting of tidal flat ground while avoiding blowouts of injected soil and extreme local uplifts. Therefore, the present study proposes the following technologies to aid pressure injection: 1) prior softening of the original ground horizontally, 2) placing of uplift restraints on the surface, and 3) pressure injection at increased depths. The effectiveness of each technology is examined by performing tests using a large tank.

2.1 Preliminary Experiment

2.1.1 Experimental setup

A preliminary experiment was performed to examine the basic effects of technologies proposed to aid pressure injection for enabling to uplift the ground smoothly without causing the blowout of injected soil. A 2.4 m × 2.4 m × 1.2 m steel tank (with one acrylic side only) was used for the experiment corresponding to a 1/5 scale of the actual site. The characteristics of soil to be used in the experiment are summarized in Table 1. The soil was placed in the tank after its water content was adjusted to 130% (1.2 times the liquid limit w_L) with undrained shear strength of 0.5 kN/m^2 according to the similarity rule for the 1/5-scale experiment.

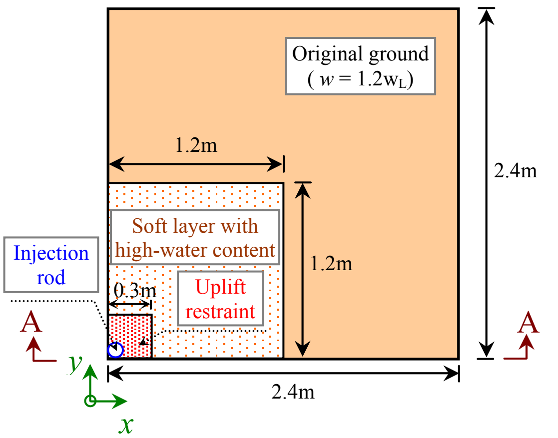
The scenarios studied are listed in Table 2. Item 1 involves the prior softening of the original ground horizontally, and it is modelled in the experiment by placing beforehand a soft layer by 0.1 m thick with high water content of 165 % (1.5 times the liquid limit) in the tank. Item 2 involves placing a board for uplift restraint on the ground surface and is modeled in the experiment by placing a 5-kg weight on the top of a wooden board (0.3 m × 0.3 m) with the loading pressure of 0.6 kN/m^2. Item 3 involves increasing the depth of the pressure-injection point. The scenarios listed in Table 2 were set up to enable these technologies to be combined. Figure 1 illustrates the experimental setup for Case 2.

Table 1 Physical properties of clay used in the experiment

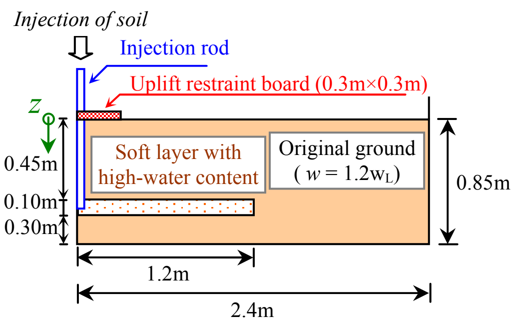
Soil particle density ρ_s:		2.62 g/cm^3
Texture	Sand:	4.5%
	Silt:	46.0%
	Clay:	49.5%
Consistency	Liquid limit w_L:	110.6%
	Plastic limit: w_P:	40.0%
	Plasticity index I_P:	70.6
Ignition loss L_i:		10.0%

Table 2 Experimental cases

	(1) Placing soft layer	(2) Placing uplift restraint	(3) Injection depth
Case1	-	-	0.50 m
Case2	Yes	Yes	0.50 m
Case3	Yes	Yes	0.65 m



(1) Plan view



(2) Cross-sectional view

Figure 1 Experimental setup for Case 2

2.1.2 Method of pressure injection of soil and measurement

The pressure-injection of soil was conducted in a corner of the tank, assuming a quarter-sized cross-section. To investigate the shape of injected soil, we used cement bentonite (CB) with the same fluidity as the supposed slurry clay (water content w = 165%, 1.5 times the liquid limit w_L) as infill material. The CB was injected by an amount of 75 L into the tank at a rate of 15 min/L.

Furthermore, to determine the uplift shape of the ground before and after pressure injection, the ground height was measured in the horizontal X and Y directions before the start and after the end of the pressure injection at 0.2-m intervals. To further determine the shape of the injected material after pressure injection, the solidified CB was removed for observation once measurements had been completed.

2.1.3 Experimental results

The uplift distribution in A–A cross-section after injection of soil in Cases 1–3 are shown in Figure 2. In the case of Case 1, the CB blew out 2 min after pressure injection had started with injected volume of approximately 10 L. The uplift height in this case includes the effect of blowout. To examine the effects of a pressure injection on the uplift of the ground, we set the significant impact height h and compared the cases.

Assuming that the shape at the point of pressure injection is spherical, the impact height h corresponds to an average uplift height of 30 %. At this point, the average uplift height is calculated by dividing the total infill volume by the significant affected area on the ground surface, which is deemed to break up at an angle of 45° from the edge of the spherical shape towards the surface. In the present experiment, the impact height h was calculated as 0.03 m.

Furthermore, we calculated the gradient from the point of the maximum uplift to the point at which the impact height h is apparent (hereafter called the uplift gradient) and the planar area where uplift over impact height h is apparent (hereafter, uplift area).

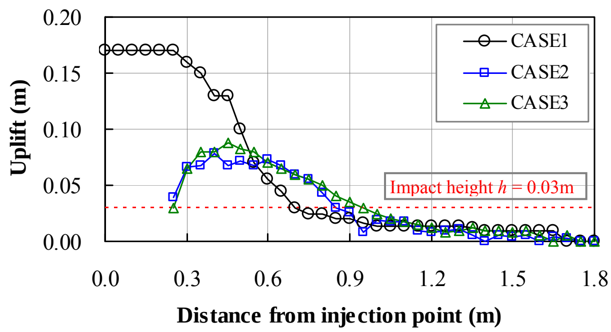


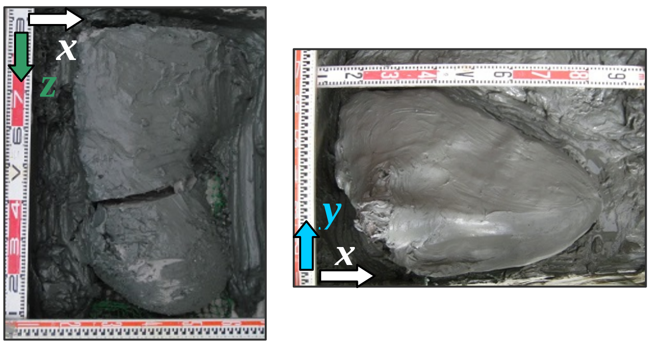
Figure 2 Uplift distribution in A–A cross-section after injection of soil

As shown in Table 3, the results showed that compared with Case 1, where plain pressure injection was applied, in Cases 2 and 3, the uplift gradient was lower and the uplift area was larger. The uplift shape was also found to be smoother in Case 3, for which the pressure injection was performed at a greater depth than in Case 2. Moreover, the CB that was removed after pressure injection had a long cylindrical shape in the vertical Z direction for Case 1, whereas had a flat shape in the horizontal X and Y directions for Case 2 (Photo 1). The flat shape in Case 2 can be considered to be due to the lateral spread of the pressure-injected CB into the layer of soft clay with high water content.

Table 3 Uplift gradient and area that appeared in the experiment

	Uplift gradient	Uplift area
Case1	31.1 %	0.33 m^2
Case2	17.2 %	0.47 m^2
Case3	11.6 %	0.53 m^2

Based on this finding, we have verified the effectiveness of the technologies used to ensure a wide-range and smooth uplifting of the ground. Specifically, prior softening of the ground was found to accelerate the lateral spread of the pressure-injected slurry clay and was highly effective in causing the ground to uplift smoothly.



(1) Case 1　　(2) Case 2

Photo 1 Shape of injected soil after solidification in the ground

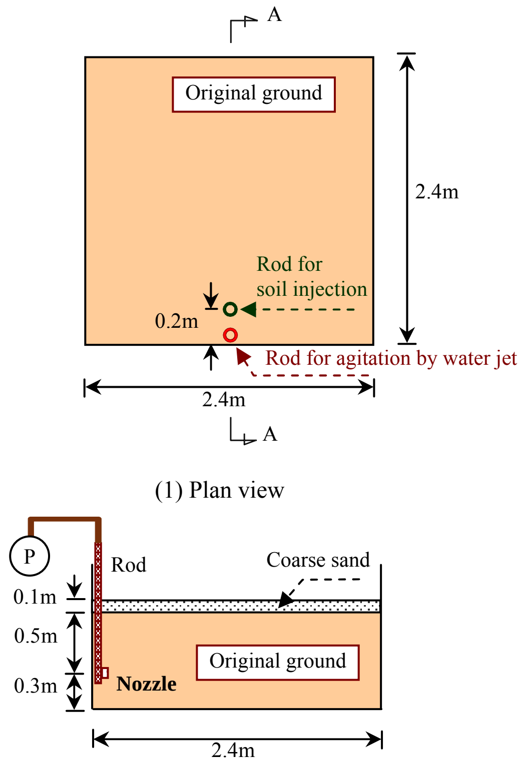
2.2 Pressure-injection experiment introducing a practical technology for soil softening

2.2.1 Summary

Prior softening of the original ground horizontally was verified to accelerate lateral spread of the pressure-injected clay. To soften the original ground, the present study proposes the application of an agitation technology by use of high-pressure water jet, which is widely applied in the field of jet grouting method for soil improvement. To examine its effectiveness, we simulated the application of the proposed method in the large tank as mentioned in previous section and performed a pressure injection test after agitating the ground by a high-pressure water jet.

Figure 3 illustrates the tank and placement of the injection pipe. A tidal flat was simulated by placing a layer of coarse sand with 0.1 m thick on the surface of a 0.5 m-thick clay body, water content of which was adjusted to 130 % as in the preliminary experiment described in the previous section. To agitate and soften the original ground, the pump output pressure for the water jet was set to 3.0 MN/m^2 in the experiment. Considering the water volume of 13 L, which is required to create the soft clay layer equivalent to the high water-content clay layer of w = 165 % mentioned in the previous section, the jet-agitation period was set to 35 s based on the discharge rate of 22 L/min. As in the preliminary experiment, cement bentonite was used as infill material, which had the same fluidity as supposed slurry clay of water content w = 165%. The material was injected 75 L in total at a rate of 15 L/min.

The ground height was measured at 0.2-m intervals in the horizontal X and Y directions to determine the ground uplift shape before the start of the experiment, after prior agitation of the original ground, and after the completion of pressure injection of slurry soil.



(1) Plan view

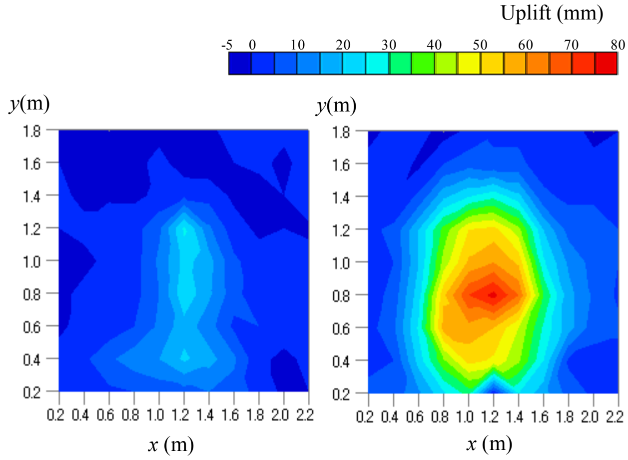
(2) Cross-sectional view in A-A section

Figure 3 Experimental setup for soil-injection experiment

2.2.2 Experimental results

The spatial distributions of uplift of the ground surface and the sectional changes in the uplift at each stage are shown in Figure 4 and Figure 5 respectively. The maximum ground uplift after high-pressure jet agitation was 26 mm, which was small compared with the height after pressure injection of soil (77 mm). In addition, it is confirmed that the uplift gradient of the ground height after pressure injection was approximately 2.1%.

Furthermore, visual observation of the injected soil shape after the experiment verified the lateral spread of the clay in the vicinity of the pressure-injection depth as shown in Photo 2. This may be because of the fact that the clay had been softened over a wide area by agitation with a high-pressure water jet, thus allowing the pressure injected slurry clay to spread horizontally.



(1) After discharge of water jet　　(2) After injection of soil

Figure 4 Spatial distribution of uplift of ground surface

Based on this result, we found that the application of the technology to agitate and soften the ground using a high-pressure water jet is effective, and by applying this technology in advance, smooth ground uplift can be achieved by pressure injection of slurry clay, while avoiding its blow out to the ground surface during the injection process.

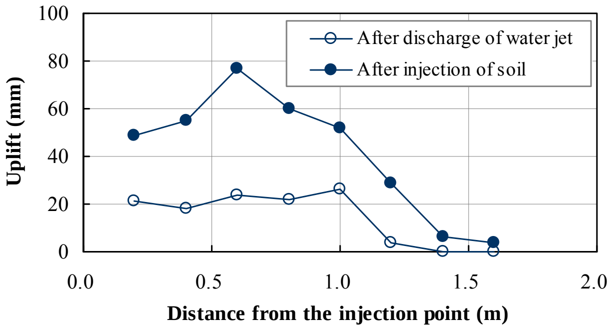


Figure 5 Sectional changes in uplift of ground surface

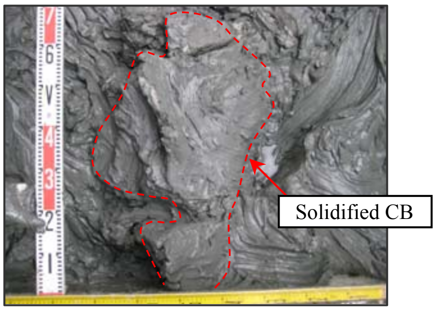


Photo 2 Shape of injected soil after solidification in the ground

3. FIELD EXPERIMENT

In the laboratory experiments, the effectiveness of the technologies proposed to aid pressure injection of soil was confirmed. Then, a field experiment was implemented to verify the applicability of the proposed method in situ and to contribute to the future practical application of technology.

3.1 Construction of Experimental Area

The test location was a landfill area for depositing the clayey dredge soil generated within the immediate vicinity port. Here we constructed an 18 m × 18 m area simulating an artificial tidal flat and performed a pressure-injection experiment. Figure 6 shows the plan and cross-sectional view of the site, and Figure 7 shows the procedure of the experiment.

The characteristics of clayey dredge soil in the site are summarized in Table 4. A number of years had passed since dredge clay was deposited in the area to be used for the experiment, and consolidation was advanced. Exposed to direct sunlight, the surface layer had dried and cracks appeared. Therefore, to ensure that it had a similar level of shear strength as that of the actual artificial tidal flat (undrained shear strength c_u = 1.5–4.0 kN/m^2 referring to Ueno *et al.*, 2012), water was added to the ground.

Table 4 Physical properties of clay in the ground

Soil particle density ρ_s:		2.62 g/cm^3
Texture	Sand:	8.8%
	Silt:	30.0%
	Clay:	61.2%
Consistency	Liquid limit w_L:	106.0%
	Plastic limit: w_P:	31.6%
	Plasticity index I_P:	74.4
Ignition loss L_i:		9.8%

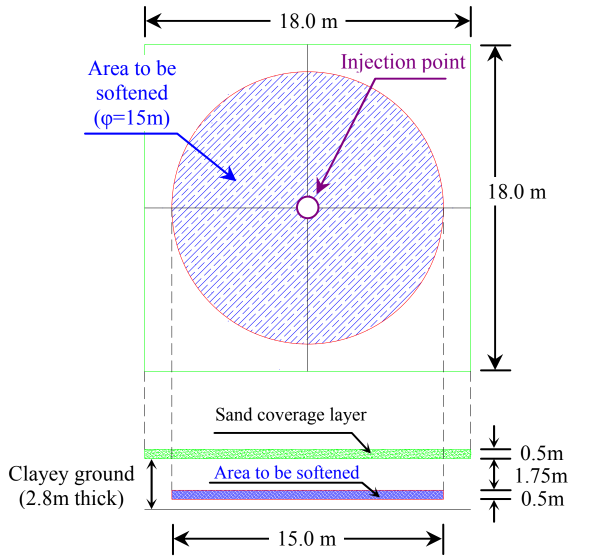


Figure 6 Plan and cross-sectional view of experimental site

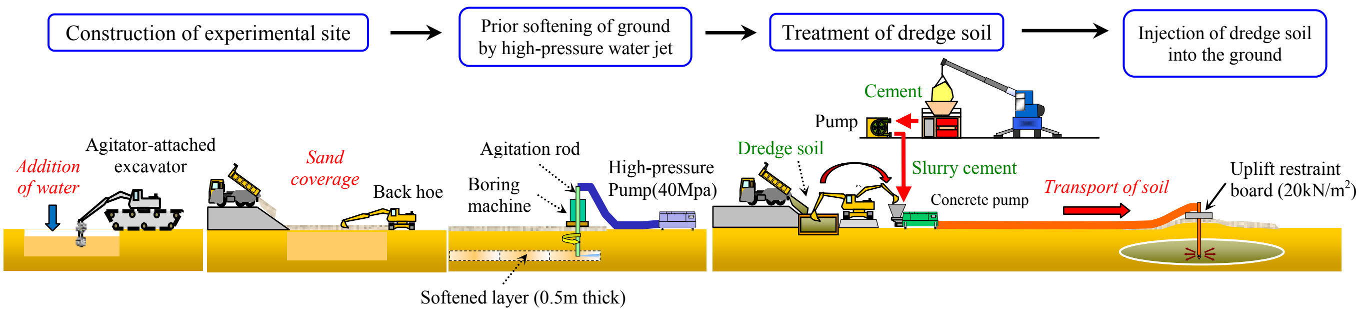


Figure 7 Procedure of field experiment

The experimental ground was mixed uniformly using a mud excavator with an agitator while water was being added to the ground. Photo 3 shows the agitator to be attached to the excavator, and Photo. 4 shows the situation that the ground is being mixed by agitator-attached excavator with addition of water.

Photo 3 Agitator to be attached to mud excavator

Photo 4 Situation that the ground is being mixed by agitator-attached excavator with addition of water

The water content of the ground measured with a RI (radio isotope) density/moisture gauge was 98.8 % after the addition of the water. The measured water content is converted to undrained shear strength c_u by use of the following formula proposed by Tsuchida *et al*. (1999).

$$c_u = 1.4 / (w / w_L)^5 \quad (1)$$

Based on the liquid limit w_L of 106 %, undrained shear strength c_u is estimated at 1.99 kN/m^2; this value was considered to be the designated ground strength. In addition, a 50-cm layer of granulated steel slag (particle density $\rho_s = 2.75$g/cm^3 and median particle size D_{50} = 0.5 mm) was placed on the adjusted ground imitating the sand coverage of artificial tidal flat.

3.2 Pre-agitation of ground by use of water jet

Horizontal softening of the ground prior to injection of soil is confirmed to be highly effective in the lateral spread of soil to be injected later, leading to the smooth uplifting of the ground. The ground is effectively agitated and softened by use of high-pressure water jet as confirmed in the laboratory experiment.

In the field experiment, high-pressure water jet is discharged in a total of 61 spots, each supposed to have an agitation diameter of 1.8 m in the whole area with diameter of 15m as shown in Figure 6. Agitation rod was penetrated through the ground down to a depth of 2.75 m using a boring machine, and then the ground was agitated and softened with a high-pressure water jet of 40 MN/m^2 during lifting it up to a depth of 2.25 m.

Photo 5 shows the situation of discharging high-pressure water jet into the air. The target water content was set to 125%, which is about the same as that for the injected dredge soil, and to achieve this target, water jet were discharged for 3.5 min at a rate of 80 L/min.

After the high-pressure jet was discharged, the water content in the target layer measured by use of a RI (radio isotope) density/moisture gauge was 126%, which is about the same as the target value. The softened state of the ground due to the high-pressure jet was verified. Based on the vertical distribution of the cone penetration resistance q_c in the central part of the test area shown in Figure 8, it was confirmed that high-pressure jet discharge successfully induced ground softening in accordance with the design.

Photo 5 Situation of discharging water jet into the air

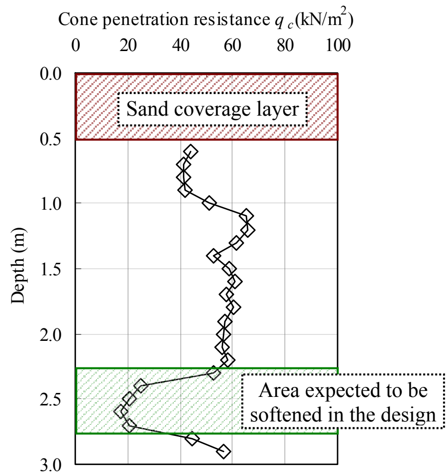


Figure 8 Vertical distribution of cone penetration resistance

3.3 Pressure injection of slurry dredge soil

Assuming the use of soil dredged with a grab bucket, the soil to be injected under pressure was adjusted to 1.2 w_L (w = 125%). Moreover, to enable the examination of the shape of the injected soil inside the ground after a certain time lapse, the solidifying agent of cement was added to the pressure-injected soil. The solidified shape of the injected soil can then be determined after a certain period of time. Considering that the fluidity of soil after adding the cement must be the same as that for the dredge soil adjusted to $w = 1.2w_L$, and furthermore that the difference of strength or stiffness between the solidified soil after injection and the original ground can be confirmed, the added cement volume was set to 60 kg/m^3.

Photo 6 shows the case where the slurry dredge soil is injected under pump pressure. The soil to be injected, for which water content had been adjusted in advance, was transported to the site, and inserted into a concrete pump with a backhoe. Cement slurry was added at the same time, and the soil was transferred by the concrete pump at 45 m^3 per hour. The soil with added cement slurry was injected into the ground through a tremie pipe that had been placed in the ground beforehand. The tremie pipe was placed with the discharge end at a depth of 2.5 m from the ground surface. An iron plate with a 3-m diameter was placed on top with a loading pressure of 20 kN/m^2 to avoid extreme local uplift and blowout of the pressure-injected soil around the injection point.

When the dredge soil was injected under pressure, the shape of the uplift was measured using a 3D laser scanner. Moreover, a surface wave method was applied to determine the shape of the pressure-injected dredge soil inside the ground after its solidification.

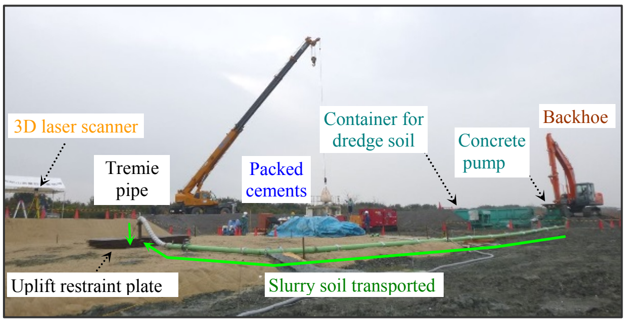


Photo 6 Situation where slurry soil is injected into the ground under pump pressure

3.4 Experimental results

3.4.1 Ground surface uplift shape

The uplift shape of the ground surface was measured continuously at 10-min intervals using a 3D laser scanner during the pressure injection of slurry dredge soil. Figure 9 shows the changes of surface uplift distribution through soil injection. At the top of the image, the area can be seen to gradually start to uplift, spread to the lower side, and then be entirely uplifted. The maximum uplift of 0.66 m is observed at the bottom of the image. If we consider the area affected by pressure injection to be 15-m diameter area where ground was prior softened, the uplift gradient is estimated at 11.6 %. This is consistent with the results obtained by the laboratory experiment, and the ground surface can be confirmed to have uplifted smoothly in the entire area.

In other words, the effectiveness of the technologies proposed to aid the pressure injection of soil, which consists of placing uplift restraints and prior softening of the ground through high-pressure water jet, were verified in a field as well as in a laboratory.

Furthermore, considering that the ultimate injected soil volume is 85.6 m^3 and the diameter of the area affected by the pressure injection is 15 m in this experiment, it is estimated that approximately 4,800 m^3 of dredge soil can be injected in the ground for 1 ha of artificial tidal flat through approximately 56 pressure injection spots.

3.4.2 Internal shape of pressure-injected dredge soil

A surface wave method, called multi-channel analysis of surface waves (MASW) (Park et al., 1999; Hayashi and Suzuki, 2004), was applied to determine the shape of the pressure-injected dredge soil inside the ground. MASW is a seismic method for geophysical site investigations, in which the internal sedimentary stratigraphy of the ground is explored revealing the distribution of S-wave velocity. Watabe and Sassa (2008) reported that the S-wave velocity is effective in determining the sedimentary structure of tidal flat soil.

Figure 10 shows lines for survey by the surface wave method. After the pressure injection of dredge soil, the survey was performed at 4.5-m intervals for 3 vertical and 3 horizontal survey lines, i.e., 6 in total. The shape of the pressure-injected dredge soil in the ground is estimated from the S-wave velocity distribution. Figure 11 shows the S-wave velocity distribution for the central horizontal survey line. Cement was added beforehand to the injected soil, and the S-wave velocity for that solidified part was clearly reflected. To estimate the pressure-injection area, it is important to determine the boundary between the pressure-injected soil and the original clay that was softened by high-pressure water jet. The unconfined compressive strength q_u of the softened original clay is estimated at approximately 2 kN/m^2 from the cone penetration resistance q_c in the water-jet discharged layer (Figure 8). Moreover, prior laboratory mixing tests showed that unconfined compressive strength q_u of the pressure-injected dredge soil with added cement was 434 kN/m^2.

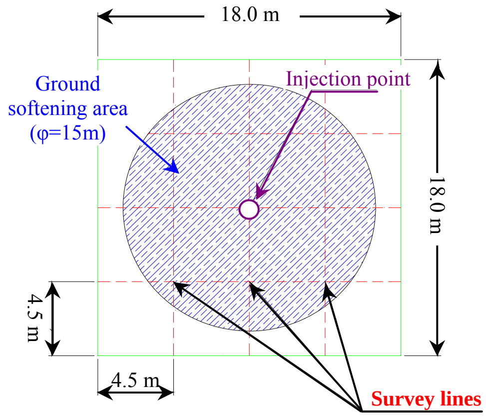
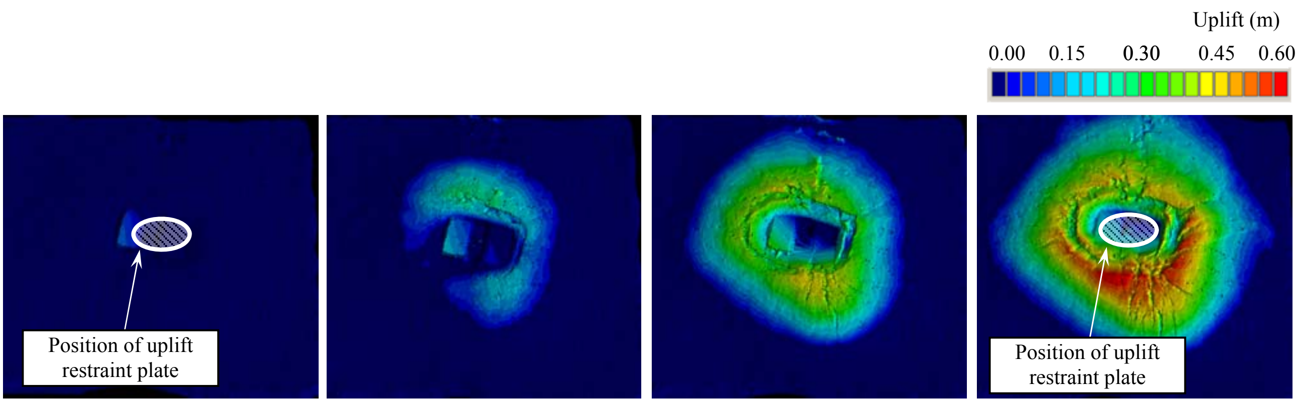


Figure 10 Lines for the survey by a surface wave method



(1) Initial state (2) State of 12 m^3 injected (3) State of 40 m^3 injected (4) Final state of 85.6 m^3 injected

Figure 9 Changes of surface uplift distribution through soil injection

If the good mixing degree is attained, the field strength in on-land construction is estimated to be about 0.7 times the strength obtained in a laboratory test in the reference of Kitazume and Terashi (2013), namely 304 kN/m^2. Based on these two conditions, the strength manifested at the boundary is considered to average around q_u = 153 kN/m^2. Kulkarni *et al.* (2010) proposed the following empirical equation the correlation between the S-wave velocity V_s in cohesive soil and unconfined compressive strength q_u.

$$q_u = 1.0 \times 10^{-3} \times V_s^{\ 2.5} \tag{2}$$

Assuming that the unconfined compressive strength q_u is 153 kN/m^2 at the boundary between the solidified dredge soil and the original clay softened by the high-pressure water jet, the corresponding S-wave velocity V_s is estimated at 176 m/s by use of Eq. (2); thus allowing us to estimate the pressure-injection area to be the area within the broken line in Figure 11. Furthermore, the pressure-injection area is elliptical, and it is verified that the injected soil spread laterally because the original ground was softened horizontally by the high-pressure water jet prior to the injection of soil.

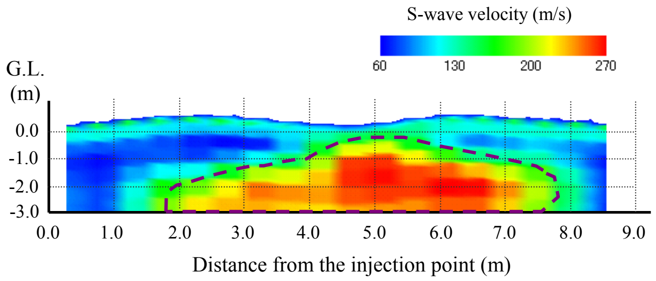


Figure 11 S-wave velocity distribution for the central horizontal survey line

The pressure-injected volume can be calculated on the basis of the pressure-injection area estimated from the S-wave velocity distribution. By mapping both ends of the cross-sectional pressure-injection area estimated from the S-wave velocity to the entire planar area on all 6 survey lines, the range of pressure-injection area is considered to spread with the plane area of 116 m^2, as shown in Figure 12. As the average thickness of the pressure-injection area is 0.8 m for the 6 survey lines, its volume is estimated at 92.8 m^3. Since the actual volume of pressure-injection of soil is 85.6 m^3, the pressure-injection area estimated from the S-wave velocity distribution by the surface wave survey can be considered to be valid.

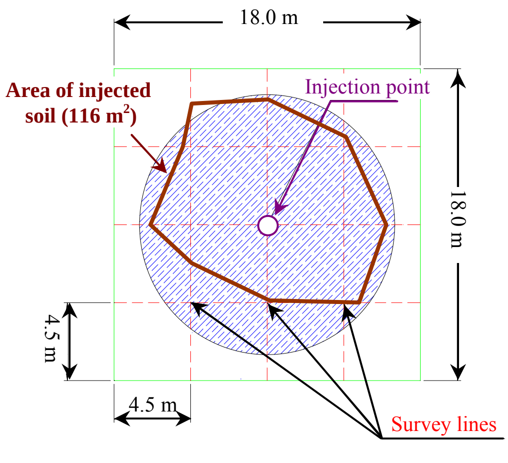


Figure 12 Planar range of pressure-injected soil considered to be spread

4. REPRODUCING THE PRESSURE-INJECTION METHOD THROUGH ANALYSIS

4.1 Overview of analysis

A reproduction analysis was performed by an axisymmetric finite element method (FEM) for a field pressure-injection experiment, using a conventional ground deformation analysis program. The soil parameters used in the analysis are listed in Table 5. The clayey ground was modeled as a linear elastic body, in which modulus of elasticity E_s was calculated on the basis of the cone resistance q_c obtained in the field experiment. At this point, cone resistance q_c was converted to undrained shear stress c_u by use of conventional empirical equation of Eq.(3) referring to Mayne and Kemper (1988), and modulus of elasticity was calculated by use of Eq. (4) in the reference of Bowles (1997) assuming that the soil is in the state of normal or under-consolidation.

$$c_u = \frac{q_c - \sigma_0}{N_k} \tag{3}$$

where σ_0 is total vertical stress and N_k is bearing capacity factor (= 15 for electric cone).

$$E_s = 200 c_u \tag{4}$$

Table 5 Soil parameters used in the FEM analysis

	Undrained shear strength c_u (kN/m^2)	Modulus of elasticity E_s (kN/m^2)
Sand coverage layer	-	1.0×10^3
Clayey ground	2.25	4.5×10^2
Softened layer by water jet	9.38	2.0×10^2

Figure 13 shows the domain of FEM analysis, which was performed in an axisymmetric condition fixing the displacements at the lateral and bottom boundaries. Regarding the proposed technologies to aid pressure-injection of soil, the uplift restraint was placed at the top of the surface layer (at a position 2.5 m above the pressure-injection point). The uplift restraint was set in the same manner as in the experiment, namely with a diameter of 3 m and loading pressure of 20 kN/m^2. The softened state of the original ground by high-pressure water jet was expressed by setting the proper values of modulus of elasticity on the basis the cone penetration resistance q_c for the layer using Eq. (3) and (4).

The pressure injection of dredge soil in the analysis is represented by expanding the soil elements around the pressure-injection point 2.5 m below the surface the internal area with imposing pressure after enclosing the elements with undrained boundaries. The area to be expanded is shown as the area hatched in red in Figure 13. The imposed pressure was adjusted so that the total expansion volume of soil elements due to pressure can be equal to the actual volume of injected soil.

Moreover, to verify the effectiveness of the technologies proposed to aid pressure-injection of soil, an analysis was also conducted for the scenario without an uplift restraint or ground softening.

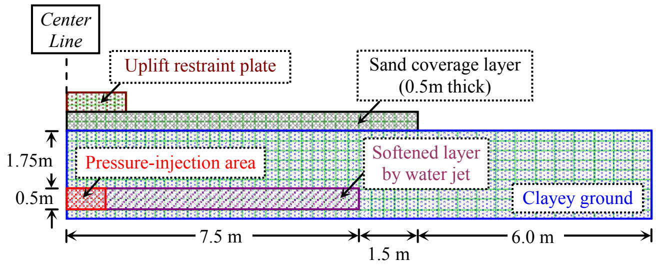


Figure 13 Domain of axisymmetric FEM analysis

4.2 Results of analysis

Figure14 shows the distribution of vertical displacement on the ground surface in comparison of measured data with analyzed results. The uplift was restrained directly above the pressure-injection point, and the uplift shape was smooth for the actual experimental results and for the case where the proposed technologies were employed. In contrast, this trend could not appear for the case where the proposed technologies were not used. lthough a difference of approximately 1.3 m can be seen where the uplift is the greatest, but the uplift level of 0.64 m is consistent with the measured value of 0.66 m. Based on this result, we verified that the pressure-injection method can be reproduced through FEM analysis. Furthermore, the effectiveness of the proposed technologies to aid pressure-injection was also verified through the FEM analysis.

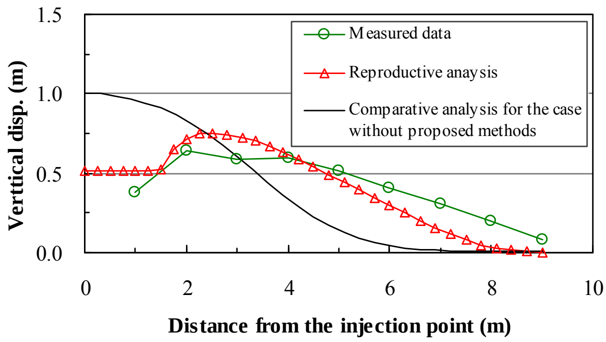


Figure 14 Distribution of vertical displacement on the ground surface obtained by measurement and analysis

5. PROPOSITION OF CONSTRUCTION METHOD

A practical construction method, in which the technologies of prior softening of original ground by water jet and pressure injection of slurry clay are realized, is also proposed for the restoration of settled tidal flat. Figure 15 shows the proposed construction sequence. In particular, a crane-boarded barge with shallow draft is used for the dedicated works considering the practical applicability of technologies on a tidal flat. The barge is used while water depth is desirably kept over its draft in a tidal cycle.

Pressure injection of soil is implemented at the depth of 2.5 m – 3.0 m after softening the original ground horizontally with 0.5 – 1.0 m thick. Target volume of soil in each injection is 200 m^3 while target area of prior softening of original ground is 12.6m^2 per one spot, which is equivalent of 4 m-diameter circle. In the proposed sequence of construction, the soil injection work is implemented after a number of ground agitation works expanding planar area of softened ground.

For softening of original ground, an agitation technology by use of high-pressure pump, boring machine and agitation rod is applied, which is widely used in the field of jet grouting method for soil improvement. At first, the rod is penetrated down to a certain depth using a boring machine, and then the ground is agitated and softened with a high-pressure water jet of 20 – 40 MN/m^2 during lifting it up by 0.5 – 1.0m. This agitation work is continuously implemented as far as softened area can be desirably expanded.

The dredge soil to be injected is transported to the site by a soil carrier barge. According to the stiffness of the soil, it may be adjusted in the barge by addition of water considering the suitability for injection under pressure. After transported, it is inserted into a concrete pump with a backhoe. The soil is injected by pressure into the ground after inserting a tremie pipe and placing an iron plate of 3-m diameter with a loading pressure of 20 kN/m^2 as an uplift restraint.

6. CONCLUSION

In the present study, uplifting the tidal flat ground subject to consolidation settlement by pressure injection of slurry clay is proposed, and a laboratory experiment was conducted to develop base technologies that enable to uplift the ground smoothly without causing the blowout of injected soil. Then, a field experiment was implemented to verify the applicability of the technologies in situ and to contribute to the future practical application of technologies.

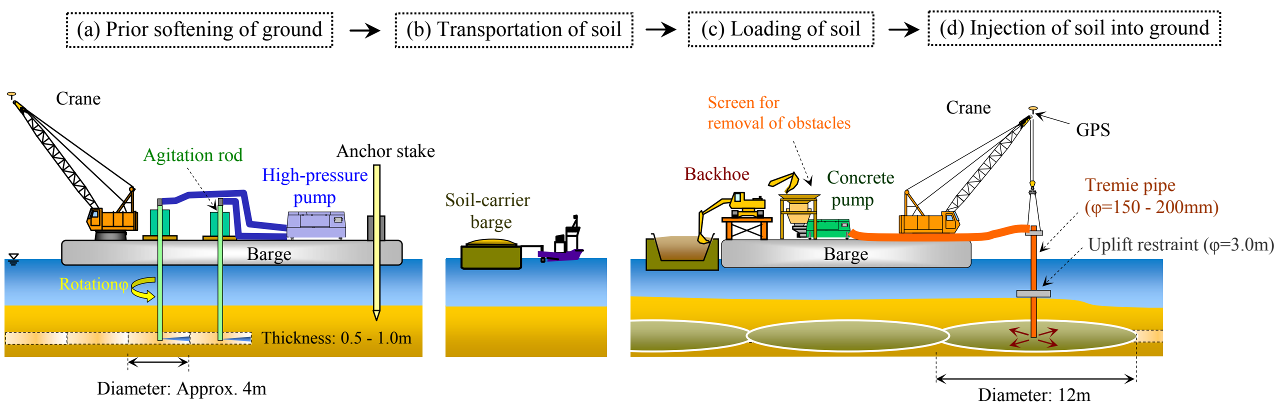


Figure 15 Construction sequence for restoration of tidal flat

Furthermore, the reproducibility of pressure-injection by an axisymmetric FEM analysis has been verified.

The use of the pressure-injection method enables to realize the following interlinked system of construction: 1) construction of artificial tidal flat (offshore submerged embankments, placement of infill such as dredge soil, creation of shallows and finishing through sand coverage), 2) decrease of intertidal area due to consolidation settlement, 3) application of pressure-injection method, 4) restoration of intertidal area through ground uplift.

It is concluded that artificial tidal flats can be constructed using dredge soil generated either in single large volumes by berth dredging or continuously by maintenance dredging.

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