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NEW LIQUEFACTION COUNTERMEASURE METHOD USING HDD FOR GROUND BENEATH EXISTING STRUCTURES

Hiroyasu ISHII¹, Kanji HIGAKI² and Kenichi HORIKOSHI³

ABSTRACT

A number of methods for liquefaction countermeasure work based on the principles of soil densification, solidification and shear deformation reinforcement have been developed and put into practice at various construction projects. On the other hand, there are few methods applicable to the ground beneath existing structures, even though demand for such methods is high since recent big earthquakes in Japan that damaged oil plants and other infrastructure.

This paper introduces a new liquefaction countermeasure method that the authors have developed recently, in which horizontal directional drilling method was combined with permeation grouting. Both of these conventional technologies have been specially modified to enhance work efficiency and soil improvement quality. Field tests are reported that were conducted to verify the performance of the new method. In these tests, ground that had been solidified by permeation grouting was exposed by excavation so as to observe the results directly; unconfined compressive strength tests using samples from the solidified ground demonstrated the quality of the improvement work. One project in which the new method has been adopted is also presented. This project includes a total drilling length of 4,800 m and 2,000 grouting points beneath existing oil tanks. Results of this work are given including information on drilling control and quality checks on the solidified ground while the benefits offered by the new method are explained.

Keywords: Horizontal directional drilling, permeation grouting, liquefaction

INTRODUCTION

Having recently experienced major seismic events like the Great Hanshin Earthquake, Japan's demand for seismic retrofitting of existing structures has been increasing. Among the factors leading to seismic damage, soil liquefaction has been a primary cause of structural damage, especially in coastal areas.

Various countermeasures against liquefaction, based on the principles of soil densification, solidification and shear deformation reinforcement, have been developed so far and these have been put into practice at various construction projects (Japanese Geotechnical Society (1998)). However, the number of countermeasures applicable to the ground beneath existing structures is relatively few, even though they would bring huge benefit to clients because seismic retrofitting has relatively less impact on ongoing operations than replacement of a structure.

This paper presents details of a new liquefaction countermeasure, developed by the authors and known as Ground Flex Mole method. The results of a field test conducted to verify the effectiveness of the method

¹ Senior Research Engineer, Civil Engineering Research Institute, TAISEI Corporation, e-mail: hiroyasu.ishii@askura.taisei.co.jp

² Chief Research Engineer, Civil Engineering Research Institute, TAISEI Corporation.

³ Vice-chief, TAISEI Corporation.

are summarized following an outline of its characteristics. A construction project in which the new method was applied is also described so as to demonstrate its benefits.

LIQUEFACTION COUNTERMEASURES BENEATH EXISTING OIL TANKS

The main target in developing the new method is the retrofitting of existing oil tanks. The Hazardous Materials Safety Techniques Association of Japan has already conducted an intensive study into the retrofitting of existing oil tanks, leading to the proposal of four types of liquefaction countermeasures for existing oil storage tanks. To provide background, these conventional countermeasures are summarized here. Schematic diagrams are given in Figure 1.

Groundwater lowering method

With this method, soil liquefaction is prevented by drawing down the groundwater level through continuous pumping. As shown in the figure, a cut-off wall structure is necessary to effectively lower the groundwater level. Once in unsaturated condition, the soil beneath the tank is unable to liquefy. This method is more feasible and economical when a group of tanks are seismically reinforced at the same time. It should be noted that, although liquefaction is without question prevented by this method, it does require constant pumping throughout the design life of the tank, which increases operating costs.

Chemical grouting method

This method has been the most popular method of retrofitting, since it can be implemented while the tank remains in operation. Soil strength beneath the tank is improved by grouting solidification chemicals. Generally, a liquid glass solution is used as the grouting material. The unconfined strength obtained after solidification should be typically at least 60-100 kN/m². Since the grouting material needs to permeate into ground uniformly, the ratio of fine soil in the ground should be relatively low. This chemical grouting method is the basis for the newly developed Ground Flex Mole technology described in this paper.

Sheet pile ring method

This method prevents the settlement of oil tanks by preventing excessive ground deformation. Steel sheet piles are installed around the edge of the tank as shown in the figure. Pipelines connected to the tanks need to be removed temporarily during the installation of the sheet piles, so this method cannot be implemented while a tank is in operation.

Gravel Drain Method

This method prevents liquefaction by accelerating pore water dissipation during and after an earthquake. Gravel columns are installed circumferentially around the outside edge of the tank as shown in the figure. However, the applicability of the method is limited since there is a possibility that pore water cannot be dissipated as quickly as it is generated during and after a strong earthquake.

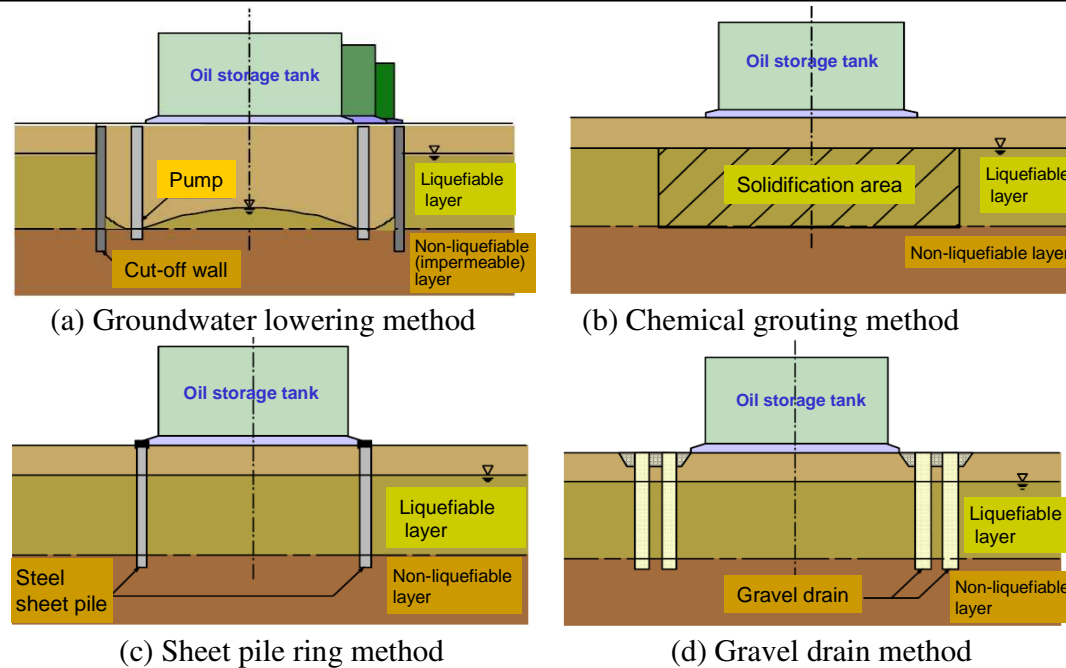


Figure 1. Methods approved for tank retrofitting

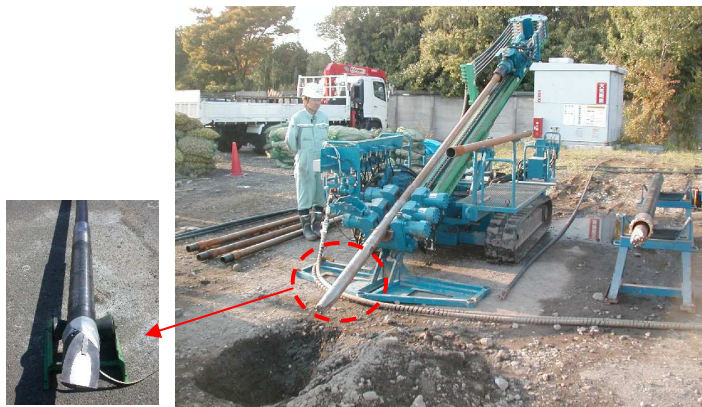
DEVELOPMENT OF NEW METHOD

As noted above, solidification by chemical grouting can allow retrofitting to go ahead while the tank operation; this has made the method the most popular countermeasure against liquefaction. However in the conventional chemical grouting method, holes are drilled diagonally from surrounding ground. With this approach, it is difficult to reinforce the ground immediately beneath the central area of the storage tank. The other method, in which the holes are drilled perpendicularly into the wall of a vertical shaft constructed near the tank, occupies spaces near the tanks, so it might interfere with tank operations (see Figure 2). The new chemical grouting technology described here was developed to solve these issues. The main characteristics of the new method are as follows:

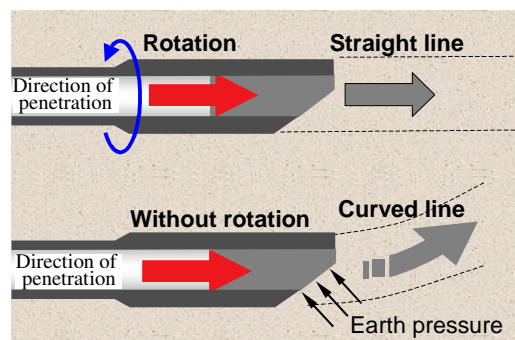
- Horizontal Directional Drilling (HDD) devices are used; these have already been used for lifeline pipe installation without the need to excavate trenches. HDD devices enable the drilling direction to be changed at any point in the ground. As shown in Figure 3, the tip of the boring rod is tapered. When straight-line drilling is required, the drilling rod is rotated as it is forced into the soil, whereas the rod is forced forward without rotation to drill curves. Note that the drilling system has a percussion system that enables the rod to proceed even in hard ground.
- A double boring head system is used for the first time, as indicated in Figure 3. This system was designed so that Ground Flex Mole can be used for various purposes other than permeation grouting, such as soil decontamination and cement grouting. As illustrated in Figure 4, after the HDD completes its work, the inner head is extracted back along the boring rod. Then an inner system, such as a grouting pipe or other device depending on objective of the work, is pushed into the boring rod. Finally, the boring rod is extracted, leaving the inner system in place.
- An inner system known as ‘self-packer system’ was developed to simplify grouting and minimize the diameter of the grout pipe (Ishii et al. (2009)). The pressure of the chemical grouting material itself inflates the packers, unlike conventional packer methods in which an independent air or water supply system is used for inflation.



Figure 2. Conventional horizontal grouting from a vertical shaft

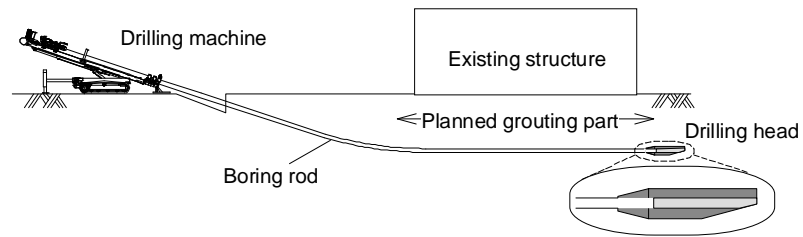


(a) Drilling machine

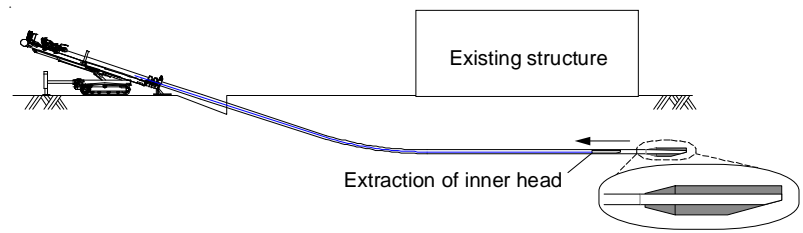


(b) Principle of directional drilling

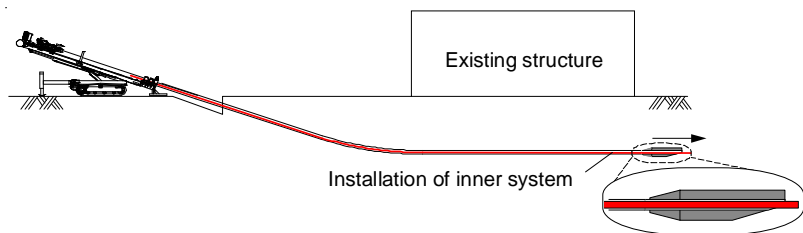
Figure 3. Horizontal directional drilling device



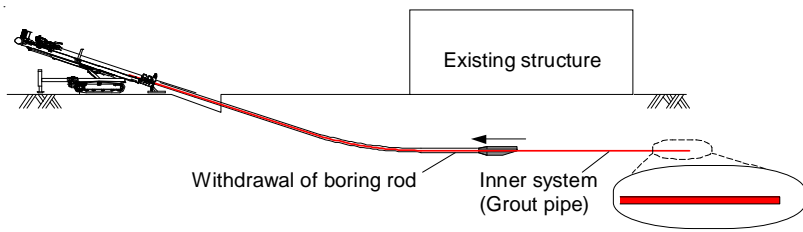
(a) Horizontal directional drilling



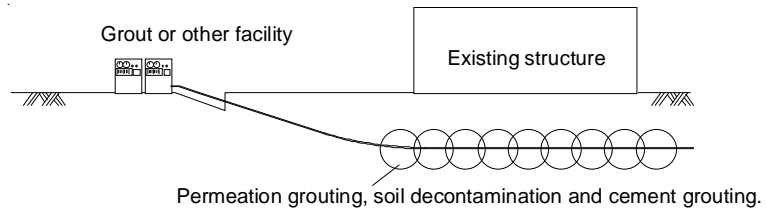
(b) Extraction of inner head



(c) Installation of inner system



(d) Withdrawal of boring rod



(e) Permeation grouting, soil decontamination or cement grouting

Figure 4. Ground Flex Mole workflow

FIELD TESTS

General plan

A field test was conducted at Tateyama, Chiba prefecture, to assess the performance of the new ground improvement method. The test covered all the process involved in implementing soil improvement by this method: drilling, inserting the grout pipes and permeation grouting.

The ground at the test site comprised clayey sand with a fine content of 11-31 % and an approximate STP N -value of 20. The drilling machine was placed at a horizontal distance of 40 m from the planned grouting point as illustrated in Figure 5.

Directional drilling was successfully completed; the percussion system worked effectively when the drill head met large cobbles during the earlier stages of drilling work. The grout pipe was then inserted into the ground after the inner part of the double head system was pulled out. Once it was in place, the boring rod was extracted.

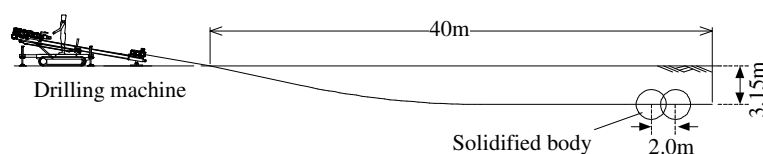


Figure 5. Sectional view of field test

Permeation grouting

Prior to grouting, an examination was carried out to determine the relationship between injection pressure and injection rate. This would enable the grouting injection rate to be controlled so as to avoid fracturing. The results, shown in Figure 6, indicated that injection rate increases almost linearly with pressure up to 10L/minute and then suddenly decrease beyond 14L/minute, suggesting that the fracturing occurred. Based on this finding, a controlled injection rate of 10L/minute was chosen for each grouting point.

The amount of grout to be injected was determined such that each grouting point would solidify 8m^3 of ground. An undisturbed soil sample taken in advance showed that the void ratio of the ground was 58%, so 4,640L of grout was to be injected per grouting point.

Seven days after injection, the ground was excavated to allow visual observation of the solidified ground. Solidification was found to have extended further in horizontal direction than planned, as illustrated in Figure 7. This was thought to be mainly attributable to variations in void ratio in the grouted area; the established void ratio of 58% was found to be relatively large as compared with post-excavation tests carried out at other investigation points.

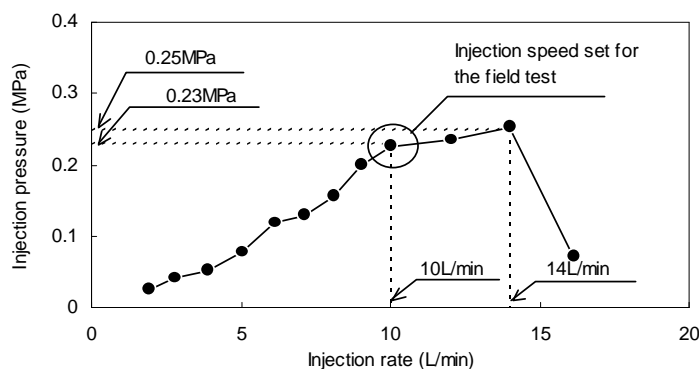


Figure 6. Change in injection pressure with injection rate



Figure 7. Exposed solidified ground sliced at GL-2.5m

Properties of solidified ground

The relationship between unconfined compressive strength and cyclic loading strength is well established in the Technical Manual on the Permeation Grouting Method (2008). Based on this the effectiveness of permeation grouting is often judged based on measurements of unconfined compressive strength for reasons of simplicity and economics. In this case, block samples were collected from the solidified region and a number of specimens were prepared for unconfined compressive strength tests. Results ranged from 125 to 351kN/m², which exceeds the conventional strength requirement of 100kN/m² for preventing liquefaction. The unconfined compressive strength of the specimens, normalized by the compressive strength at the actual point of injection, is plotted in Figure 8 against distance from the injection point. This plot includes data obtained from other injection tests conducted by authors using the same chemical grout, but in different ground. Strength decreases linearly with the same gradient despite different levels of strength. The Technical Manual on the Permeation Grouting Method (2008) cited above recommends that the job mix strength should have a strength two or three times the design strength; the applicability of this specification is backed up by this plot, in which normalized strength is approximately 0.5 at usual permeation distance of 1-1.5 m.

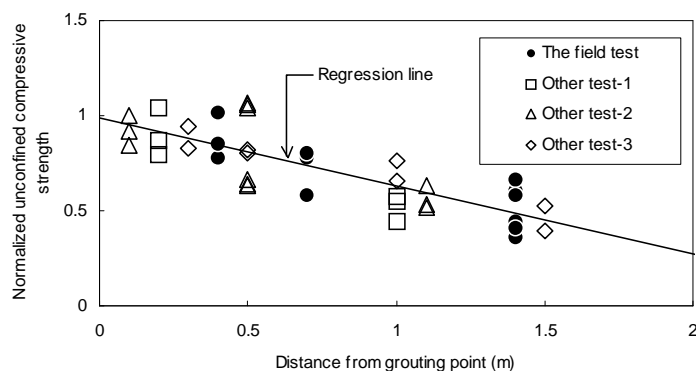


Figure 8. Variation in improved strength with distance from grouting point

APPLICATION TO EXISTING OIL TANKS

General plan

The new ground improvement technology was used to reinforce the ground beneath some existing oil storage tanks in western Japan as a countermeasure against liquefaction. Preliminary soil investigations showed that two 8,000 kL tanks and three 2,000 kL tanks were in need of reinforcement in accordance with the Technical Manual on the Permeation Grouting Method (2008). A loose sand layer at a depth of 2-4 m was targeted for improvement. A plan view and a cross section of the ground improvement work are illustrated in Figure 9 and Figure 10, respectively.

Prior to this application of Ground Flex Mole technology, conventional horizontal grouting had been applied to other tanks at the site, using temporary vertical shafts. This is the work shown previously in Figure 2. A relatively large vertical shaft is required for this kind of operation, and the site road around the tanks had to be closed for more than two months. In contrast, for the Ground Flex Mole work, drilling machine was positioned outside the oil dike and the existing site road, so their functionality could be maintained. Further, the fire authorities allowed work to proceed under tanks that were up to 60% filled with oil. This makes clear the advantages of the new method in terms of safety, work period, and cost, as well as adaptability to site constraints.

Execution and results

During improvement work, the maximum allowable ground movement and the maximum allowable inclination were set at 17 mm and 1/430, respectively. Ground movement was observed periodically using fluid-pressure settlement gauges. Since the oil tanks were 60% full during the work period, a real-time warning system was employed for safety. Observations indicated that the maximum ground movement was at most about 7.4 mm at the final stage, while inclination was negligible. These data show that grouting caused almost no displacement of the surrounding soil.

Directional drilling work took about three months using two machines and was carried out with minimal impact on the site owner's operation (Figure 11). The comparison of planned and actual borehole paths is shown in Figure 12. The somewhat large deviation from the planned paths was attributed to the existence of cobbles and concrete blocks in the reclaimed ground of the site. Percussion drilling was effective, so the drilling was completed without changing the original paths.

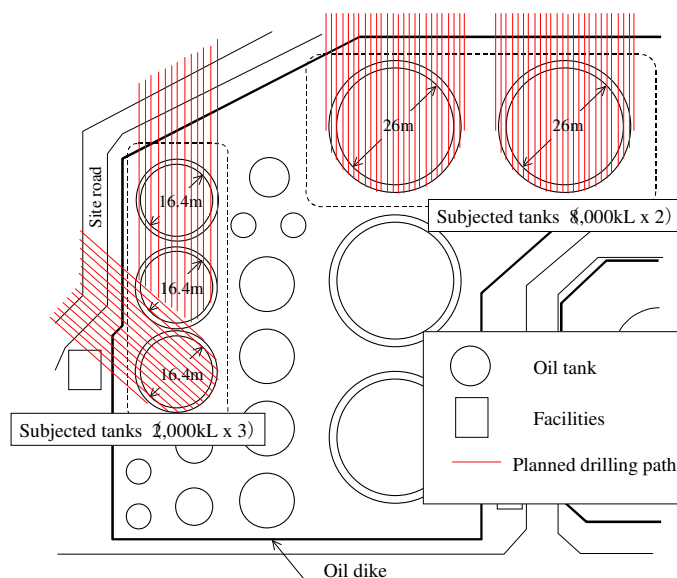
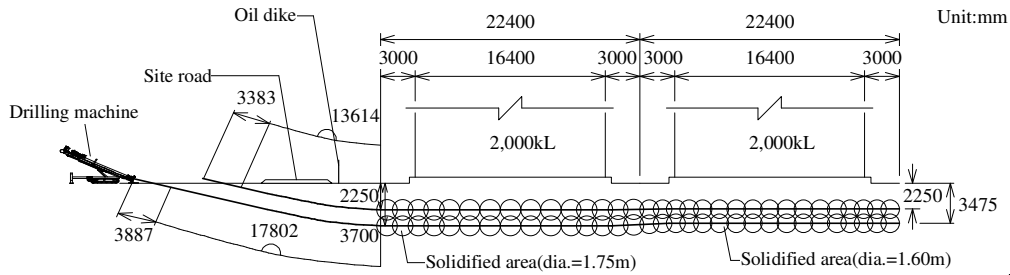
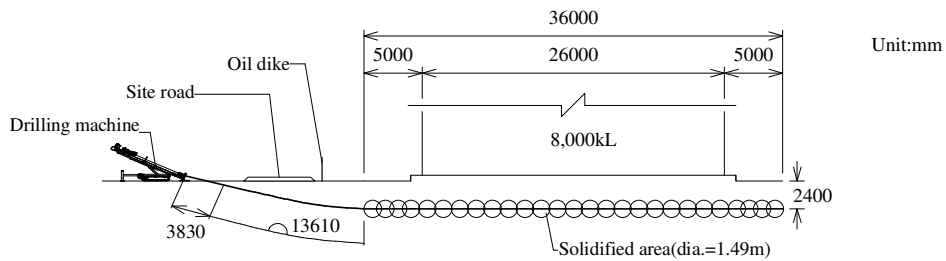


Figure 9. General view of the project

Permeation grouting took about five months following the drilling work. Unconfined compressive strengths were checked using core samples collected from the improved ground. The measured strengths for individual tanks were well above the requirement of 60 kN/m^2 after 28 days of curing.



(a) For tanks with capacity 2,000 kL



(b) For tanks with capacity 8,000 kL

Figure 10. Cross section of the ground improvement beneath existing oil tanks



(a) Directional drilling towards ground beneath tank



(b) Installed grouting pipes

Figure 11. Work beside the tanks

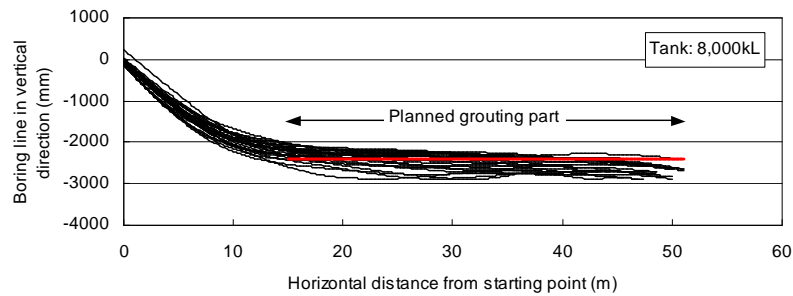


Figure 12. Planned and actual drilling paths

SUMMARY AND CONCLUSIONS

A new method of implementing liquefaction countermeasures for ground beneath existing structures, known as Ground Flex Mole technology, has been developed. Details of this soil improvement method are presented along with an operational test.

A case study is also described, in which the effectiveness of the new method is demonstrated, particularly with respect to safety, and work period, as well as adaptability to site constraints.

Although the work has successfully established this new method, it still costs more than conventional methods. Enhancing drilling speed and injection rate with some technical improvements are possible measures to reduce the cost. The authors hope to continue their efforts to improve performance and provide even greater benefit to site owners.

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