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Cases Histories and Recent Development of the Sand Compaction Pile Method as a Countermeasure Against Liquefaction

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ABSTRACT

The Sand Compaction Pile (SCP) method is the most useful countermeasure against liquefaction in Japan. The investigation on the effectiveness of improved ground by the SCP method suffered from the past large-scale earthquakes (the 1993 Kushiro-Oki Earthquake, the 1994 Hokkaido Toho-Oki Earthquake, the 1995 Hyogo-ken Nambu Earthquake etc.) were conducted and found that the behavior of the compacted ground apparently differ from unimproved one. Especially less subsidence occurred on the compacted area compared with the unimproved area at Port Island and Rokko Island during even the 1995 Hyogo-ken Nambu (Kobe) earthquake.

The conventional SCP method aims to increase the bearing capacity of soft ground by reinforcing it as compacted ground, or by increasing the density of loose sandy ground, through the vibratory installation of additional sand piles. However, the use of a vibro-hammer generates noise and vibration, which may adversely affect the surrounding environment. It is therefore difficult to use this method for ground improvement work in urban areas or on sites close to existing structures. To reduce noise and vibration, the non-vibratory SCP method which is based on a rotary penetration system using a forced lifting/driving device and a rotary drive motor were developed.

This paper describes the case histories during the past large-scale earthquakes and newly development (objectives, applications etc.) of the SCP method applied as a countermeasure against liquefaction in Japan.

1. INTRODUCTION

The sand compaction pile (SCP) method is a method of improving soft ground by means of installing well-compacted sand piles in the ground. It combines such fundamental principles of ground improvement as densification and drainage. It can be applied to all soil types in Japan, from sandy to clayey soils, and it has therefore been widely used for improvement of soft ground. In sandy ground the SCP method is often used as a countermeasure against liquefaction, and the effectiveness of compaction to prevent from liquefaction has been confirmed in past intense earthquakes, showing this to be one of the most reliable improvement methods.

However, the vibro-hammer used in this method has a negative effect in the form of vibration and noise on the surrounding environment, making it difficult to utilize the method on urban sites or at locations close up to existing structures. To address this issue, a non-vibratory sand compaction pile method (non-vibratory SCP method with the commercial name 'SAVE Compozer') was therefore developed,

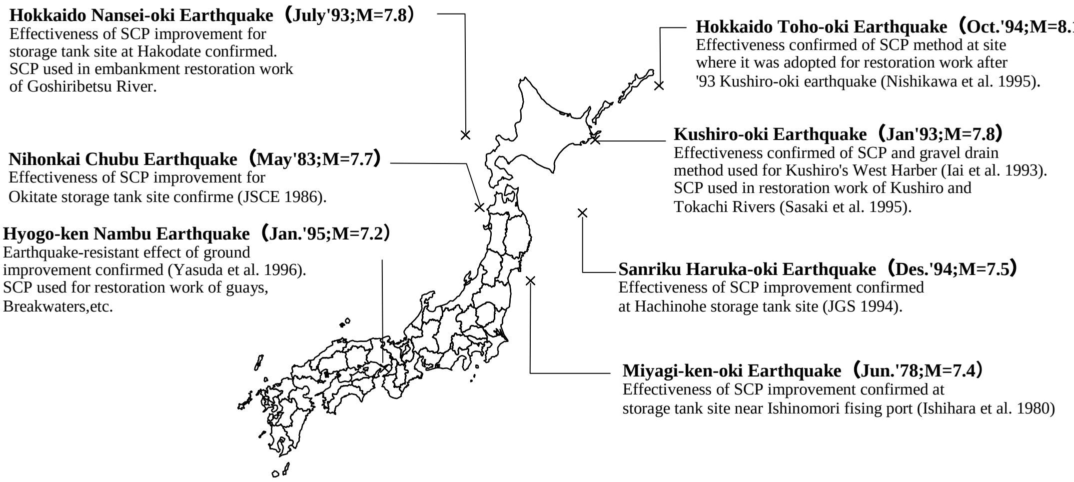


Fig. 1 Recent intense earthquakes and information gained on compaction-type ground improvement

which does not require impact or vibration for the driving device to penetrate the ground.

This paper offers some representative cases that demonstrate the difference in the degree of damage suffered through past intense earthquakes between unimproved ground and ground compacted by the SCP method. It also gives an outline of the non-vibratory sand compaction pile method as a refinement of the SCP method that has no negative effect on the surrounding environment, and reports on actual applications.

2. SOME CASES WHERE THE IMPROVEMENT EFFECT OF THE SCP METHOD HAS BEEN VERIFIED IN INTENSE EARTHQUAKES

Fig. 1 shows the epicenter locations and characteristics of the 1974 Miyagiken-oki earthquake and six later large-scale earthquakes, and gives information on SCP-improved ground obtained as a result of these earthquakes. As the figure shows, there have been no reports of major disruption to structures erected on SCP-compacted ground, thus confirming in a qualitative sense the validity of compaction-type ground improvement. There follow some representative cases of ground improvement related to important structures.

2.1 Improvement effectiveness for port facility structures (The 1993 Kushiro-oki Earthquake)

Fig. 2 shows a standard section of the Kushiro West Port that was suffered by the 1993 Kushiro-oki Earthquake (Yamada et al. 1990). At this location reinforcement to resist earthquakes, which was mostly compaction by the SCP method, was implemented in the ground behind the quay walls. In areas adjacent to steel structures, the gravel drain method was adopted to avoid any negative effects of vibration or displacement from the improvement work SPT N-values in areas between sand piles in the compaction -improved areas were around 20~30. The maximum horizontal acceleration recorded at the Kushiro Port Construction Office, about 1.5 km distant from the quay walls, was 470 gal, but no damage due to the earthquake was observed, and port activities were resumed on the following day. However, in unimproved areas within the same wharf area, large cracks appeared in quay walls (approx. 10 cm wide, 20 cm level displacement) and the quays could not be used.

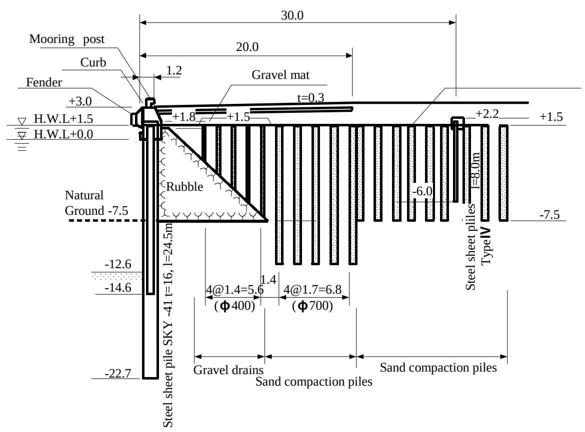


Fig. 2 Standard section of revetment

2.2 Improvement effectiveness at a storage tank facility (The 1978 Miyagiken-oki Earthquake, The 1993 Hokkaido Nansei -oki Earthquake)

The effectiveness of SCP ground improvement implemented at this storage tank facility was verified at the time of the 1978 Miyagiken-oki Earthquake, and Ishihara et al (Ishihara et al. 1980) have reported survey and reverse analysis results. In the 1993 Hokkaido Nansei-oki Earthquake a remarkable difference was observed between the areas of improved ground, including the SCP-improved tank base ground, and the adjacent unimproved areas. Fig. 3 shows the locations of sand boil marks in the improved tank base ground and the adjacent non-improved ground areas. The tanks themselves, installed on ground that had been reinforced against liquefaction using the SCP method, did not suffer damage, but evidence of sand boiling could be observed at locations at a distance from the improved section that represented approx. 1/2 of the improvement depth. Through back analysis of this of local slipping attributed to loss of strength due to a rise in excess pore water pressure at the time of the earthquake, confirmed that negligible damage had occurred in the improved ground (Shinkawa et al. 1996).

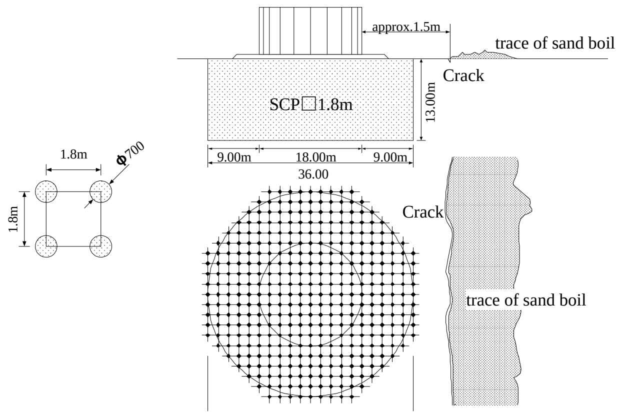


Fig. 3 Standard section and plan of storage tank facility

2.3 Improvement effectiveness at river embankments (The 1993 Kushiro-oki Earthquake)

The 1993 Kushiro-oki Earthquake caused serious damage in many parts of eastern Hokkaido. River embankments, particularly those of the Kushiro River, suffered damage that included lateral cracking, cross cracking, slope collapse and cave-ins. The Kushiro River embankment suffered intermittent collapse over a section of several hundred meters, attributed to liquefaction in the alluvial sand layer and in the embankment itself below groundwater level.

In the restoration work, the SCP method was adopted for the first time for foundation ground improvement in the restoration of river embankments. Fig. 4 shows a standard section (Sasaki et al. 1993). One year nine months after the restoration work was completed the Hokkaido-Toho-oki Earthquake occurred, and again the region suffered massive seismic impact. In the locations where the SCP method had been used there was no damage, but cracking recurred at locations where the

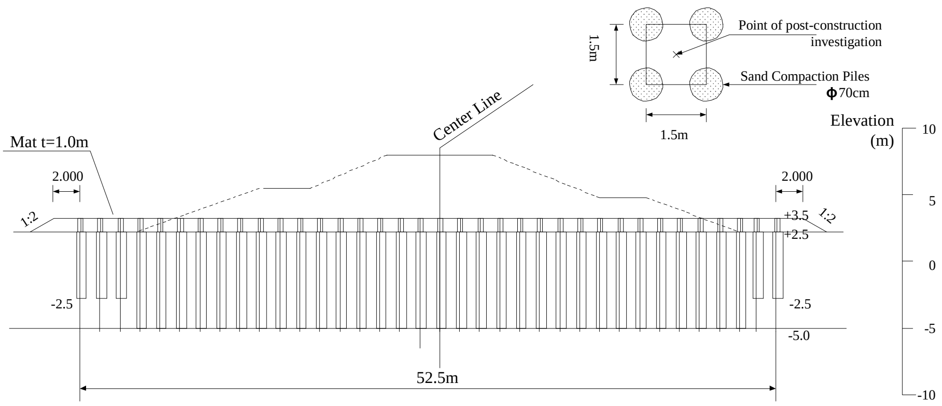


Fig. 4 Standard section of river embankment

embankment had been restored after the Kushiro-oki Earthquake only by compact-tmping because the cracking at that time had been light.

2.4 Improvement Effectiveness for Buildings (The 1995 Hyogoken Nambu Earthquake)

Large scale liquefaction occurred in the two man-made islands, Port Island and Rokko Island, in the Kobe Port area as a result of the 1995 Hyogoken Nambu Earthquake. For structures in both islands, various types of ground improvement had been undertaken as measures to prevent from consolidation settlement in the alluvial clay layer due to excess weight, and to increase the bearing capacity of the landfill soil layer. In the improved sections there was little damage caused by settlement etc. compared with the unimproved areas. Recordings of post-earthquake settlement were made in the areas of ground improvement in both islands. These settlement recordings were of the relative displacement between buildings and the ground surrounding them, and the results of settlement recordings for various ground improvement methods are shown in Fig. 5. From the figure, 40 to 50 cm of settlement can be seen to have occurred in the unimproved areas, and 15 to 18 cm in areas improved with sand drains, but in the areas improved by compaction methods, including SCP, settlement was negligible (Yasuda et al. 1996).

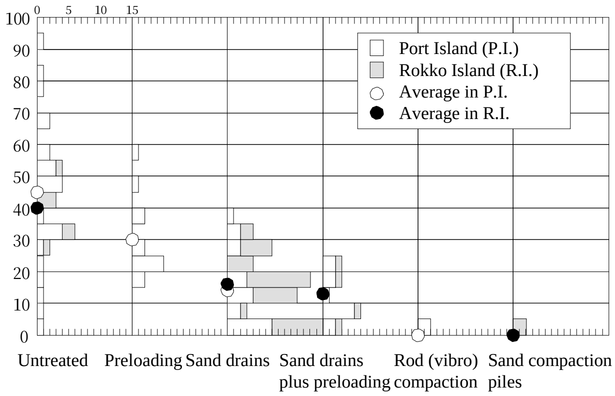


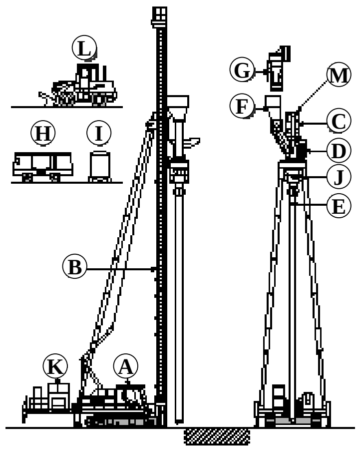
Fig. 5 Relative settlement and methods of ground

3. DEVELOPMENT OF NON-VIBRATORY SAND COMPACTION PILE METHOD AS A REFINEMENT OF THE CONVENTIONAL SCP METHOD

As described above, in many cases the SCP method has been verified as an effective countermeasure against liquefaction. But its drawback has been the noise and vibration caused by the use of a vibro-hammer, thus creating a demand for an SCP method that would have no adverse influence on the surrounding environment. To meet this demand a non-vibratory sand compaction pile method (Tsuboi at al 1998) was developed. An outline of this method and its applications are given below.

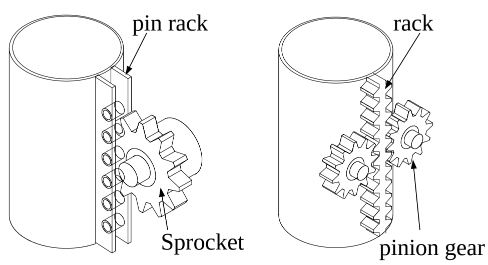
3.1 Equipment, Operating Procedure and Monitoring System

The equipment used for the non-vibratory sand compaction pile method is shown in Fig. 6. In the conventional SCP method



A	Base machine
B	Base machine Leader part
C	Forced lifting/driving device
D	Rotary drive motor
E	Casing pipe
F	Hopper
G	Bucket
H	Compresser
I	Receving tank
J	Swivel
K	Power generator
L	Wheel loader
M	Noise suppressor

Fig. 6 Non-vibratory SCP equipment



(a) Pin rack and sprocket type (b) Rack and pinion type

Fig. 7 Main components of forced lifting/driving device

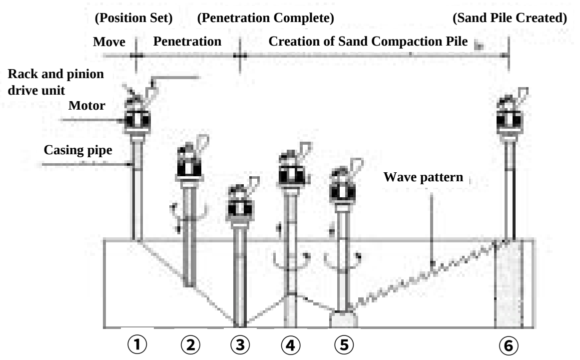


Fig. 8 Operating procedure of non-vibratory SCP method

(Vibratory SCP method), the vibromotive force of a vibro -hammer is used for ground penetration of the casing pipe, and a winding wire is used to withdraw it. In the non-vibratory sand compaction pile method a vibro-hammer is not used, and both penetration and withdrawal are achieved by means of a forced lifting/driving device, shown in Fig. 7, that rotates the casing pipe.

The equipment consists mainly of an SCP driving device used as a base machine, and a forced lifting/driving device with a rotary drive motor or hydraulic-powered geared motor to rotate the casing pipe. Two types of forced lifting/driving device are used: the pin rack-sprocket type and the rack-pinion type. In both cases, the necessary reaction force for the forced lifting/driving device comes from the total equipment weight, and the sprocket or pinion gear is rotated by a hydraulic motor. The operating procedure for the non-vibratory SCP method, shown in Fig. 8, is identical to that of the conventional SCP method. A 400~500 mm diameter casing pipe is used to create well compacted sand piles of 700 mm diameter, and the surrounding ground is densified as a result.

Fig. 9 shows the non-vibratory SCP monitoring system. During implementation, a micro-computer installed in the driving device uses depth meter recordings of the depth of the casing pipe and sand level meter recordings of the sand level within the casing pipe to provide fully automatic control of the sand amount and level of compacting in order to produce sand piles of the required diameter. At the end of the work-day, that day's implementation data can be processed at the site office to produce an implementation record for monitoring purposes.

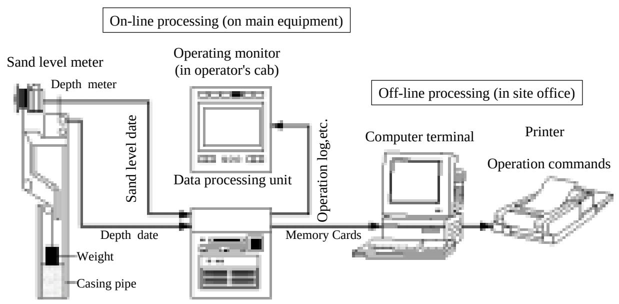


Fig. 9 Implementation monitoring system (non-vibratory SCP)

3.2 Confirmation Noise and Vibration Reduction and Improvement Effect.

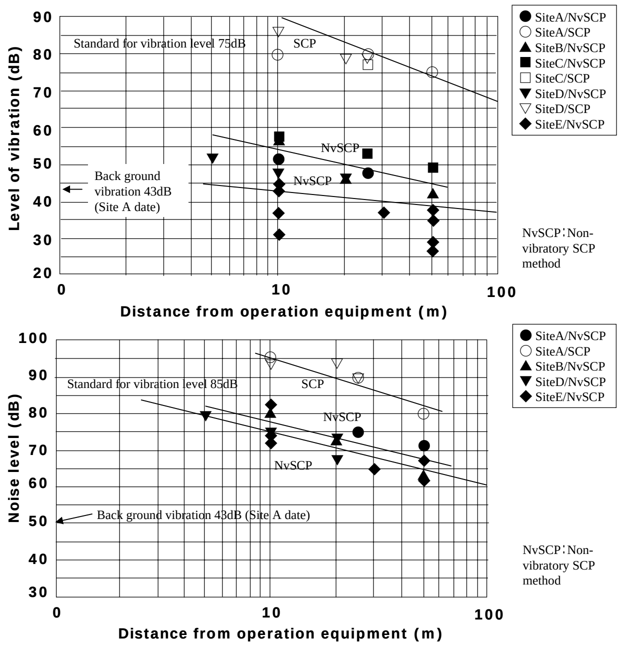


Fig. 10 Decrease over distance of noise and vibration with non-vibratory SCP method

Recordings of noise and vibration associated with the conventional SCP and non-vibratory SCP methods made at five sites, A to E, are shown in Fig. 10. As is clear from the figure, both noise and vibration are greatly reduced in the non-vibratory method compared with the conventional SCP method, making it suitable for applications in urban areas and close up to existing structures.

The results of standard penetration tests carried out before and after a test implementation are shown to confirm the densification effect of the non-vibratory SCP method compared with the conventional SCP method. SCP N-values after improvement were compared for the two methods employed at field test of differing improvement ratios, as shown in Fig. 11. Fig. 12 shows a depth distribution of SPT N-values for different improvement ratios on the same ground, together with a soil boring log and distribution of fines content. The depth distribution of before and after improvement SCP N-values shows results for ground with improvement ratios of 10 % on the left and 20% on the right. The top layer of clay soil of a thickness of approx. 4 m was excluded from the improvement. In the sand layer 4 m to 12 m in depth, which had a fines content of about 20%, for the 10% improvement ratio ground, SPT N-values before improvement of 10~15 increased to 20~25 after improvement, and were the same for the non-vibratory SCP method (●, ▲) and the vibratory SCP method (■, ◆). In the area of 20% improvement ratio the SPT N-values after improvement show an increase to 20~30, and as with the 10% improvement ratio ground, they are almost the same for both the non-vibratory and the conventional SCP methods.

3.3 Application to a Coastal Embankment

In this case the non-vibratory SCP method was used for a sea wall embankment as a countermeasure against liquefaction. After removal of the existing revetment, an SCP method was selected for compaction to provide stability for the new

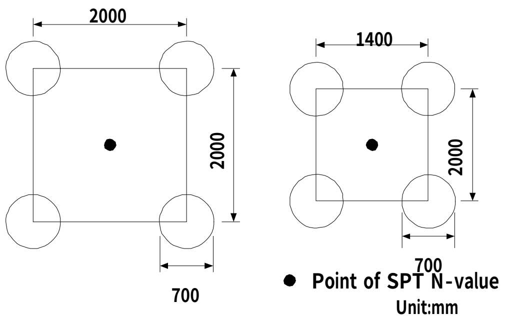


Fig. 11 Improvement specifications

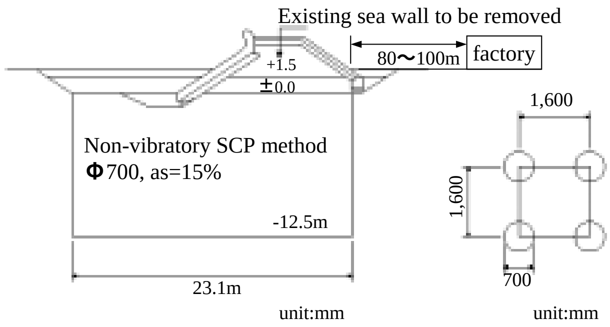


Fig. 13 Standard section and improvement specifications

revetment in the event of an earthquake. As shown in Fig. 13, it was feared that vibration could cause problems for buildings close to a section 80~100 m from the implementation area and so the non-vibratory SCP method was adopted.

After the ground improvement work, SPT N-values in the standard section and improvement specifications on ground between piles in the improved area, and SPT N-values, were plotted against fines content to confirm the improvement effect, as shown in Fig. 14. With the increase in fines content the SPT N-value before and after improvement become relatively smaller, but the improvement effect can be seen in the increase in N values.

4. CONCLUSION

This report gives cases that verify the effectiveness of the SCP method in past intense earthquakes. For a non-vibratory SPT method that was developed as an SCP method that avoids affecting the surrounding environment, it describes the operating procedure, reports on the level of vibration and noise affecting the surrounding environment and the improvement effect of the method, and gives a case of its application.

Studies on the characteristics of ground improved by compaction through SCP methods such as this are currently making rapid progress in Japan. (Yamamoto et al. 1997) As Fig. 5 shows, the effectiveness of compacted improved ground suppressing deformation was verified on the man-made islands in Kobe struck by the 1995 Hyogo-ken Nambu Earthquake, and these studies are examining how this ground was able to resist violent earthquake conditions. The authors guess that the cause,

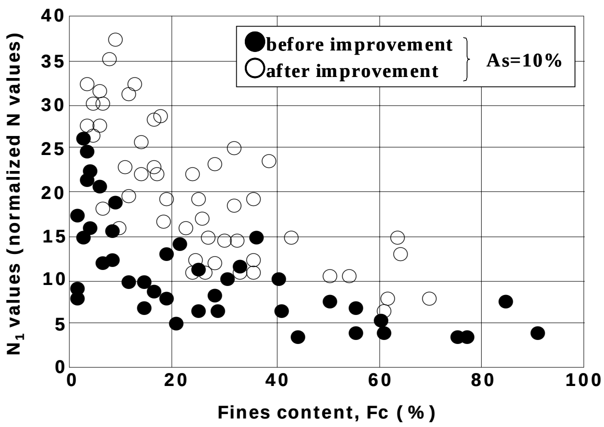


Fig. 14 Relation between SPT N-values and fines content before and after improvement and fines content

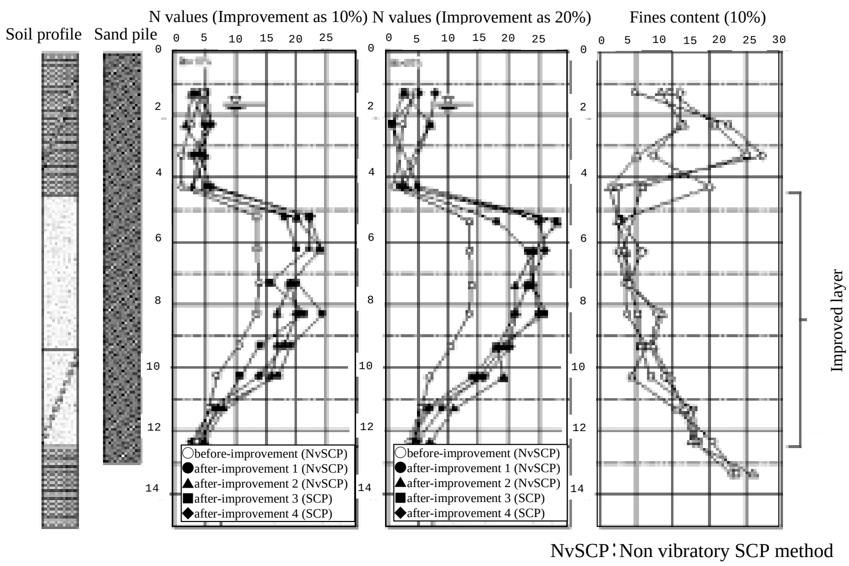


Fig. 12 Comparison of improvement results (improvement ratios of 10% and 20%)

quite apart from the effectiveness of the increase in density, lies in the increase in the coefficient of earth pressure at rest, a phenomenon peculiar to compaction improved ground, and the composite ground created by the installation of sand piles. The authors plan to undertake further study for a qualitative understanding of these causes.

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