Sand Compaction Pile Technology and its Performance in both Sandy and Clayey Grounds

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ABSTRACT

Sand Compaction Pile (SCP) technology has been developed in Japan since the 1950s and has been widely applied to various structures on both clayey and sandy grounds (as liquefaction mitigation). In this paper, various projects that verify the effectiveness of the SCP method in past intense earthquakes including the 2011 huge earthquake are discussed and the following observations are made: (1) strong sand pile with consistent diameter is possible to be installed even with using top vibrator and vertical vibration sequence; (2) SL-gauge system which has been developed in Japan is able to secure uniform diameter sand pile installation; (3) top vibrator system has many advantages, such as sand and other materials can be used, and addition of water is not necessary for installation; and (4) SCP method has also non-vibratory system using forced lifting/driving device.

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, from sandy to clayey soils, and it has therefore been widely used in Japan 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 liquefaction has been confirmed in past intense earthquakes, showing this to be one of the most reliable improvement methods.

This paper describes the outline, classification and history of SCP method and concludes by discussing its features through comparison with the stone column method, which is used worldwide as vibratory gravel pile method. The paper also demonstrates the improvement effectiveness of the SCP method for both sandy and clayey ground. Furthermore, some 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 are shown.

2. OUTLINE OF SCP METHOD

Figure 1 shows the classification and history of the SCP method, including some relevant geotechnical issues. The SCP method has both vibratory system with vibro-hammer and non-vibratory system with forced lifting/driving device. It also can be implemented both on land and off-shore using an exclusive barge. Although the vibratory SCP was developed more over 50 years ago and has been implemented in more than 380,000 km of improved ground, the vibro-hammer used has a negative effect in the form of vibration and noise on the surrounding environment, making it difficult to utilize the method in urban sites or at locations close up to existing structures. To address this issue, a non-vibratory SCP method (with the commercial name 'SAVE Compozer') was therefore developed, which does not require impact or vibration on the driving device to penetrate the ground. The implementation volume of the non-vibratory SCP has reached more over 7,000 km to date.

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 as shown in Figure 2. 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 Figure 3, is discussed below and is identical to that adopted in the conventional SCP method. A 400~500 mm diameter casing pipe is used to create well compacted sand piles of 700 mm diameter and as a result, the surrounding ground is densified.

(1) Set the casing pipe to the predetermined place.

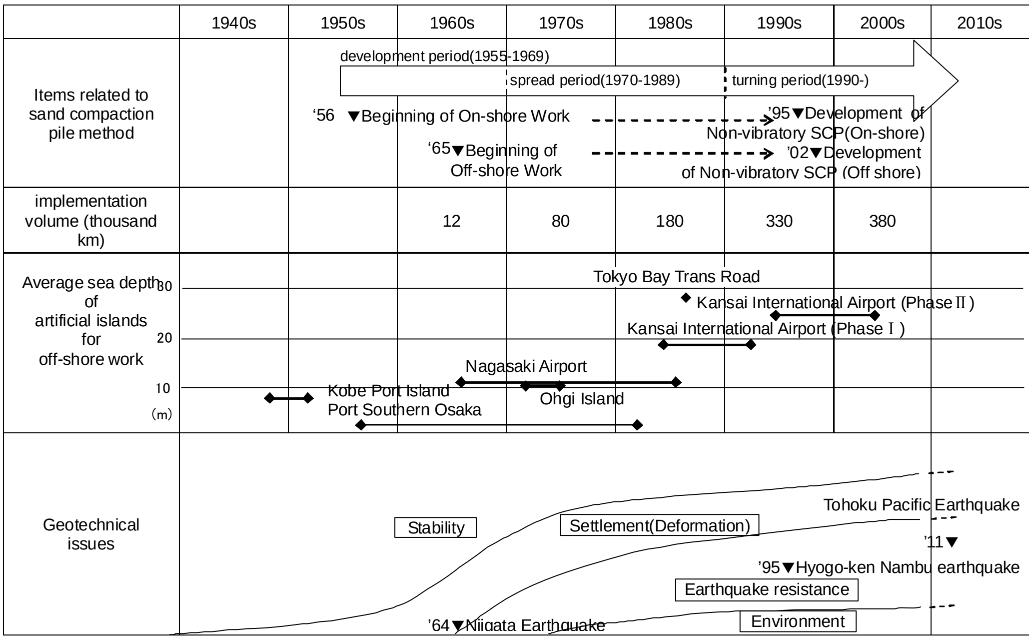

Figure 1: Geotechnical issues and history of SCP method

(2) By operating the forced lifting/driving device, install the casing pipe into the ground while rotating.
(3) After the casing pipe reached the required depth, feed sand through the upper hopper.
(4) By drawing up the casing pipe, the sand in the casing pipe is pressed out to the void by compressed air.
(5) Extract the casing while compacting the pressed out sand pile to enlarge it.
(6) Form the sand pile to the ground surface by repeating the above procedure.

Table 1 compares the features between the SCP method and the stone column method. The main point of difference is the location of vibrator and this gives the SCP method an increase in penetration ability and can penetrate without water.

Recordings of vibration associated with the vibratory methods (vibratory SCP method and stone column method) and non-vibratory SCP method are shown in Figure 4. As clearly seen from the figure, vibrations are greatly reduced in the non-vibratory method compared with the vibratory methods, making it suitable for applications in urban areas and close to existing structures.

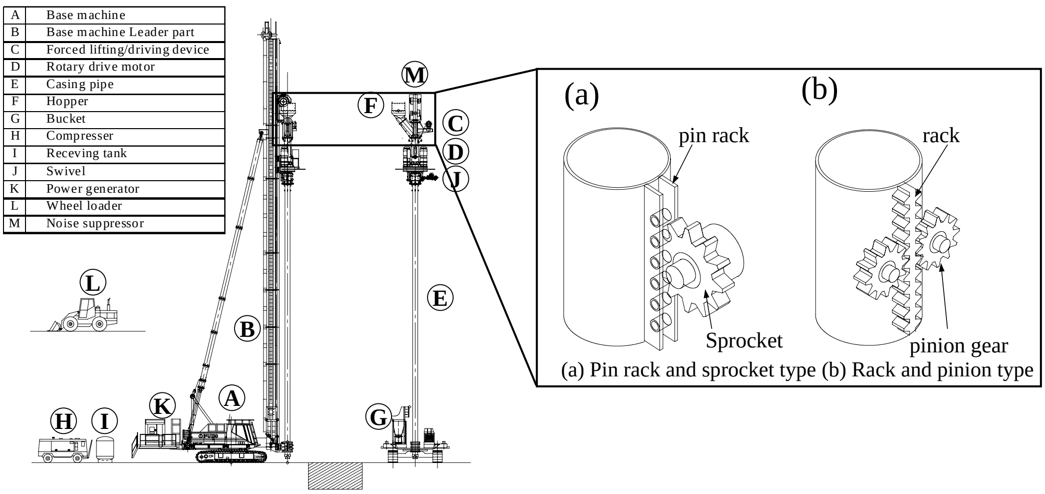

Figure 2: Non-vibratory SCP equipment and main components of forced lifting/driving device

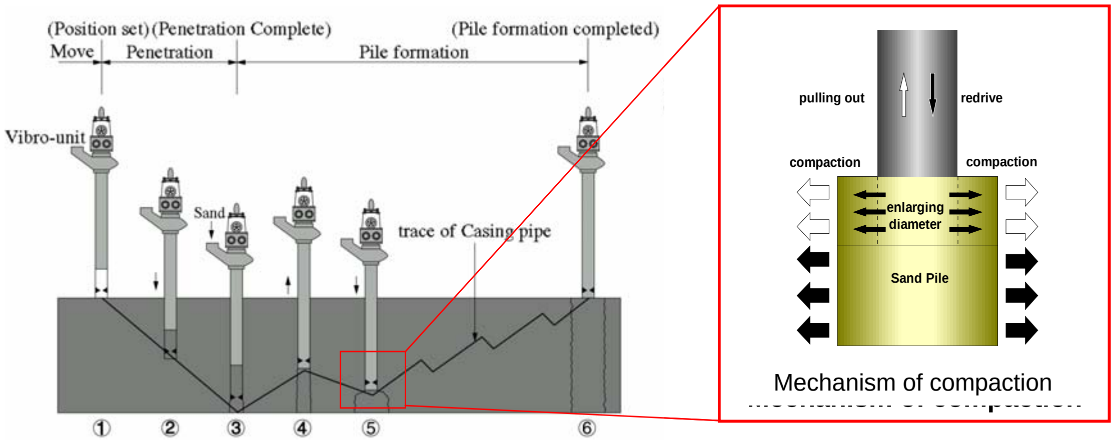

Figure 3: Operating procedure of non-vibratory SCP method

Table 1: Comparison between SCP method and stone column method

	Sand Compaction Pile method	Stone Column method (dry-bottom feed)
Location of vibrator	Upper part	lower part
Vibration direction	vertical	horizontal
Supply way of material	lower part	lower part
Use of air/water	air no water	air/water
Infilling material	sand/gravel	gravel only
Quality control	sand/gravel volume	Intensify of electric current

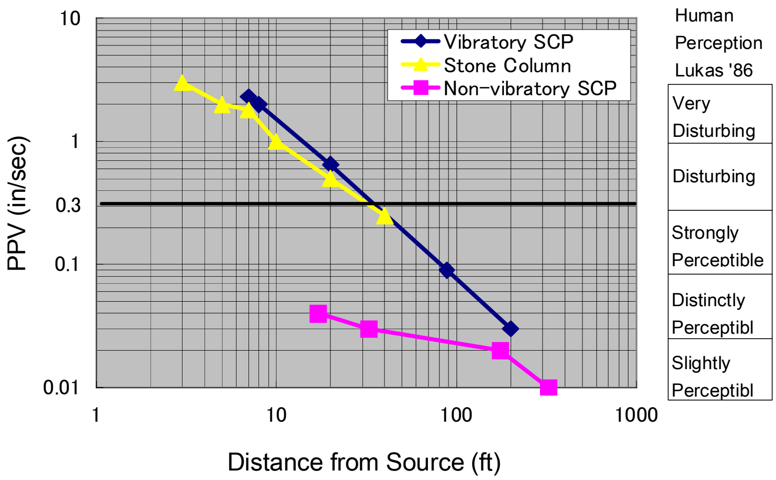

Figure 4: Decrease over distance of vibration of vibratory and non-vibratory SCP methods

To summarize, the features of the SCP method are as follows:

(1) Strong sand pile with consistent diameter is possible to be installed even with using top vibrator and vertical vibration sequence.

(2) SL-gauge system which has been developed in Japan is able to secure uniform diameter sand pile installation.

(3) Top vibrator system has lot of advantages, such as sand and other material can be used, and addition of water is not necessary during installation.

(4) SCP method has also a non-vibratory system using forced lifting/driving device.

3. IMPROVEMENT EFFCTIVENESS BY SCP METHOD

3.1. Improvement effectiveness for clayey ground

An example of application to embankment on clayey ground is discussed. Figure 5 indicates the cross-section of the embankment with the SCP improvement specification and soil boring log. From the properties of the area, the top 5 meters consist of peat layer with natural water content of w_n = 400 - 1000%. Figure 6 shows the construction process along with the amount of settlement in the central portion of the embankment over time. In the figure, the unconfined compressive strengths q_u are also plotted. The embankments were completed up to 8m in height with no failure in the SCP section. The unconfined compressive strength increased as the settlement progressed.

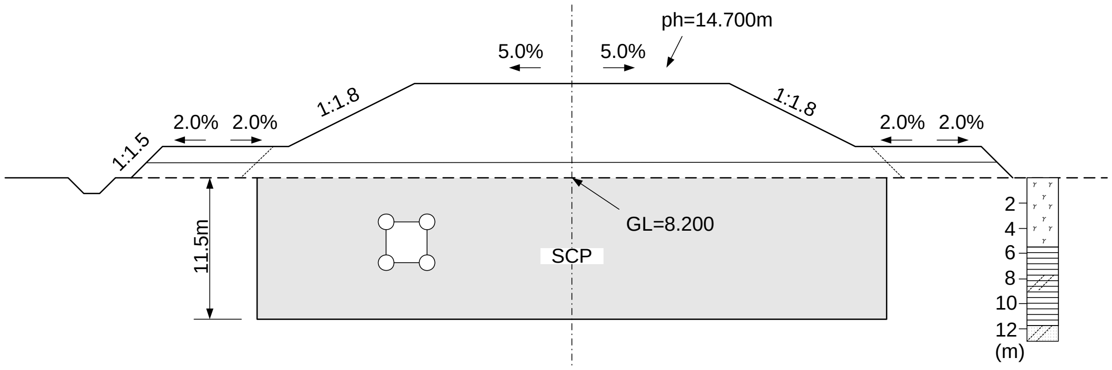

Figure 5: Cross-section of embankment

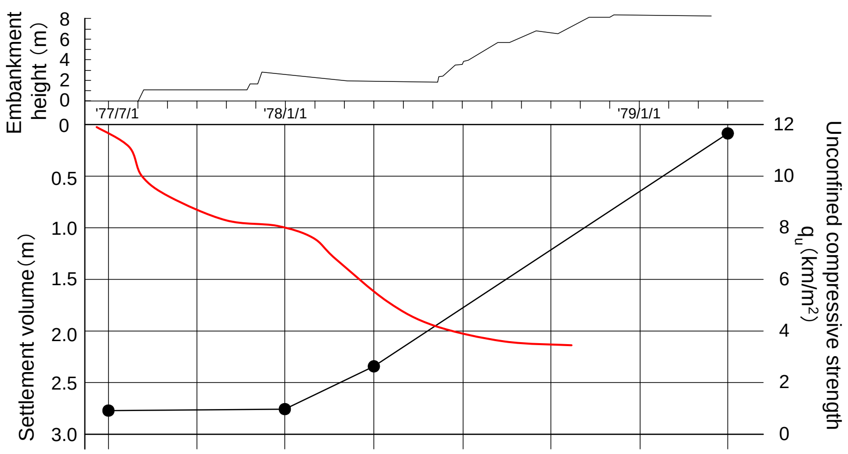

Figure 6: Elapsed time of consolidation settlement and unconfined compressive strength

3.2. Improvement effectiveness for sandy ground

Next, an example of application for sandy ground is shown. To illustrate the increase in density of sand, typical SPT N-values obtained from sites improved by both vibratory SCP and non-vibratory SCP procedures are shown in Figure 7(a) while examples of CPT q_c values from vibratory SCP–improved ground are illustrated in Figure 7(b). It is observed that penetration resistances obtained between sand piles installed increased as the piles pushed and displaced the adjacent ground.

Moreover, results of cases where various instruments (e.g., pressuremeters and dilatometers) were used to measure the lateral stresses before and after implementation of both vibratory and non-vibratory SCP methods are presented in Figure 8. In the figure, the relation between the lateral stress ratio, K_C, and replacement ratio, a_s, are plotted 1 month and 2 years after the SCP operation. Note that the data points corresponding to improvement ratio a_s=0 refer to the condition prior to the implementation of SCP method. It can be observed that substantial increase in K_C–values is observed 2 years after implementation, with larger increase in K_C values occurring at higher a_s.

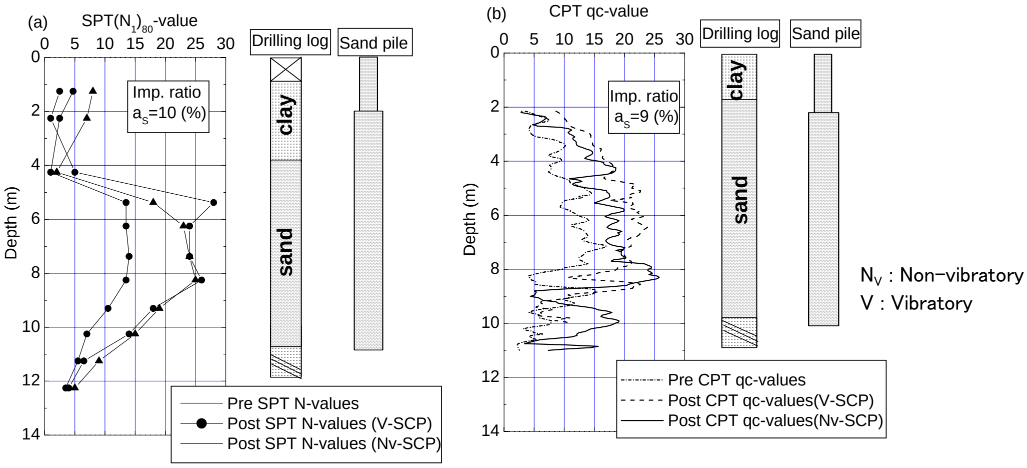

Figure 7: Examples of increased penetration resistances in grounds improved by SCP method in terms of: (a) SPT N–values; and (b) CPT q_c–values

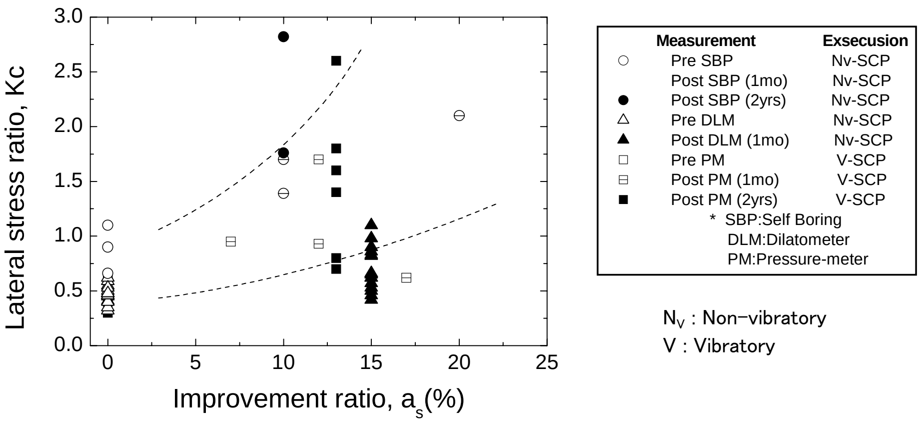

Figure 8: Example of results showing increase in K_C–values due to SCP implementation

4. CASES WHERE IMPROVEMENT EFFECT OF SCP METHOD HAS BEEN VERIFIED IN INTENSE EARTHQUAKES

Figure 9 shows the epicenter locations and characteristics of the 1974 Miyagiken-oki earthquake and seven other large-scale earthquakes which occurred later, including the 2011 Tohoku Pacific earthquake, and gives information on the performance of SCP-improved ground as a result of these earthquakes. As the figure shows, there has been no report of major disruption to structures erected on SCP-compacted ground, thus confirming in a qualitative sense the validity of compaction-type ground improvement. The following are some representative cases of ground improvement performance related to important structures.

4.1. Improvement effectiveness in port facility structures (1993 Kushiro-oki Earthquake)

Figure 10 shows a standard section of the Kushiro West Port that was affcted by the 1993 Kushiro-oki Earthquake (Yamada et al. 1990). At this location, countermeasures to resist earthquakes, mostly compaction by the vibratory SCP method, were implemented in the ground behind the quay walls. In areas adjacent to steel structures, 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, located about 1.5 km from the quay walls, was 470 gal but no damage due to the earthquake was observed, and port activities resumed the day following the earthquke. However, in unimproved grounds within the same wharf area, large cracks appeared in quay walls (approx. 10 cm wide, 20 cm vertical offset) and the quays could not be used.

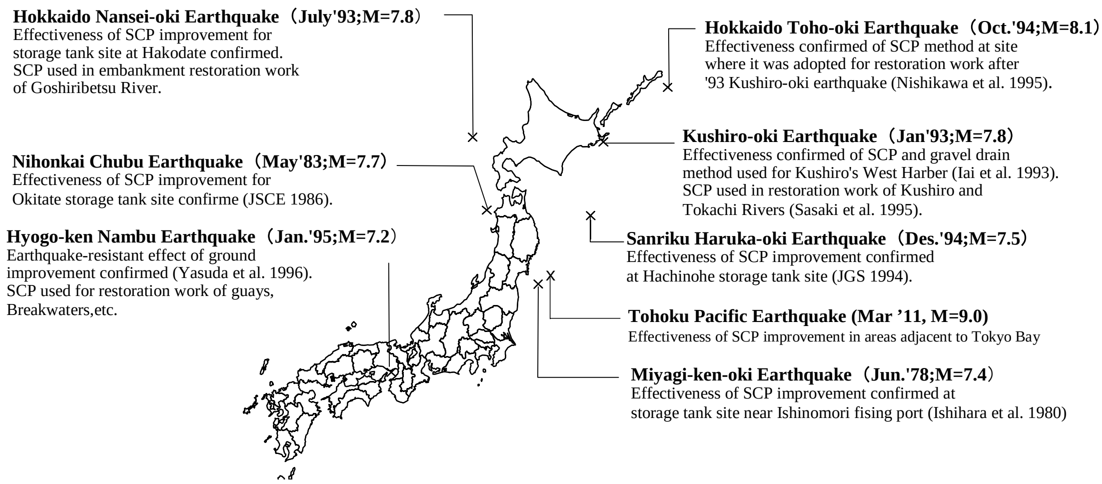

Figure 9: Recent intense earthquakes and information gained on ground improvement performance

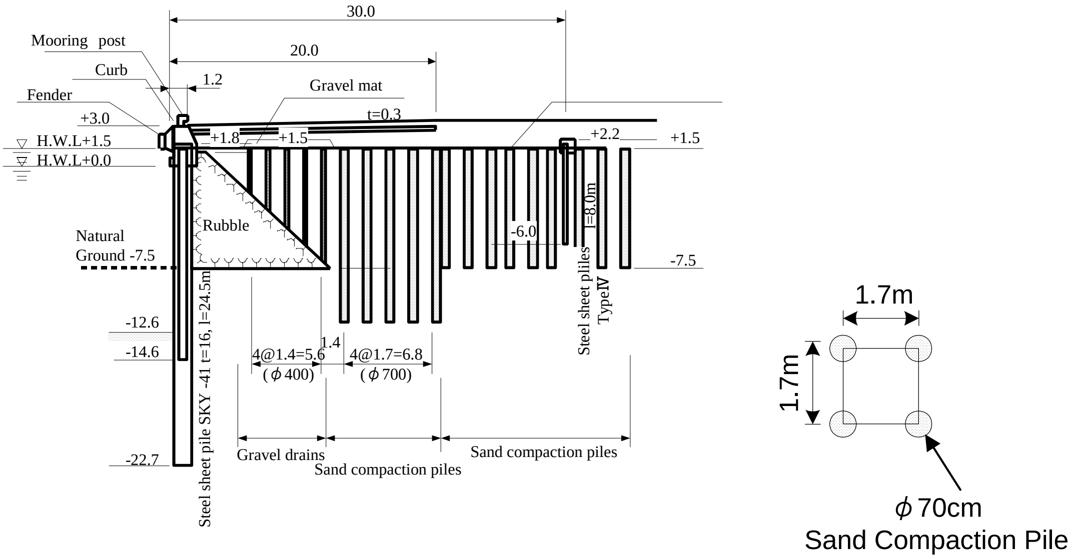

Figure 10: Standard section of revetment

4.2. Improvement effectiveness in river embankments (1993 Kushiro-oki Earthquake)

The 1993 Kushiro-oki Earthquake caused serious damage to many parts of eastern Hokkaido. River embankments, particularly those along the Kushiro River, suffered damage that included lateral cracking, cross cracking, slope collapse and cave-ins. The Kushiro River embankments 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, vibratory SCP method was adopted for the first time for foundation ground improvement in the restoration of river embankments. Figure 11 shows a standard section (Sasaki et al. 1993). One year and 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 re-occurred at locations where the embankment had been restored after the Kushiro-oki Earthquake only by compact-tamping because the cracking at that time had been light.

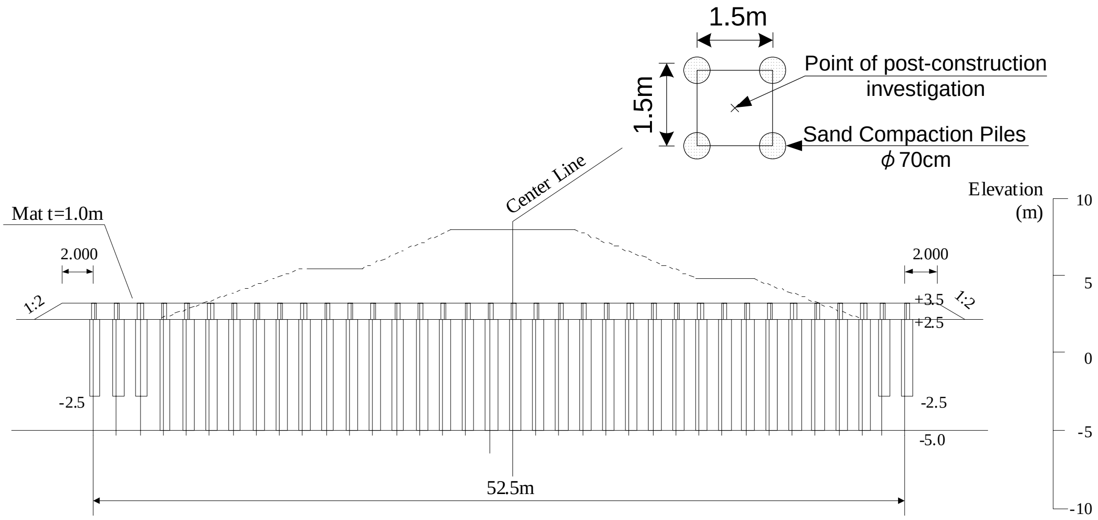

Figure 11: Standard section of river embankment

4.3. Improvement effectiveness in a storage tank facility (1993 Hokkaido Nansei -oki Earthquake)

In the 1993 Hokkaido Nansei-oki Earthquake a remarkable difference was observed between the areas of improved ground, including the vibratory SCP-improved tank base ground, and the adjacent unimproved areas. Figure 12 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 improved against liquefaction using the SCP method, did not suffer damage, but evidence of sand boiling could be observed at a distance of approximately 1/2 of the improvement depth from the improved section.

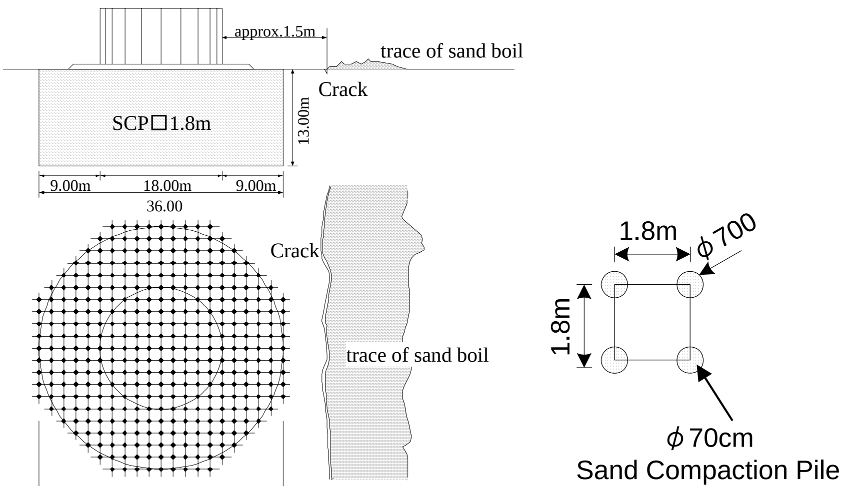

Figure 12: Standard section and plan of storage tank facility

4.4. Improvement effectiveness in buildings (1995 Hyogo-ken 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 Kobe Earthquake. For structures in both islands, various types of ground improvement were undertaken as measures to accelerate 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. as compared with the damage in unimproved areas. Figure 13 shows the measured post-earthquake settlements of the buildings with pile foundations in the areas of improved grounds. In both islands, 40-50 cm settlement occurred in the unimproved areas, but in the areas improved by compaction methods, including SCP, the settlement was negligible (Yasuda et al. 1996).

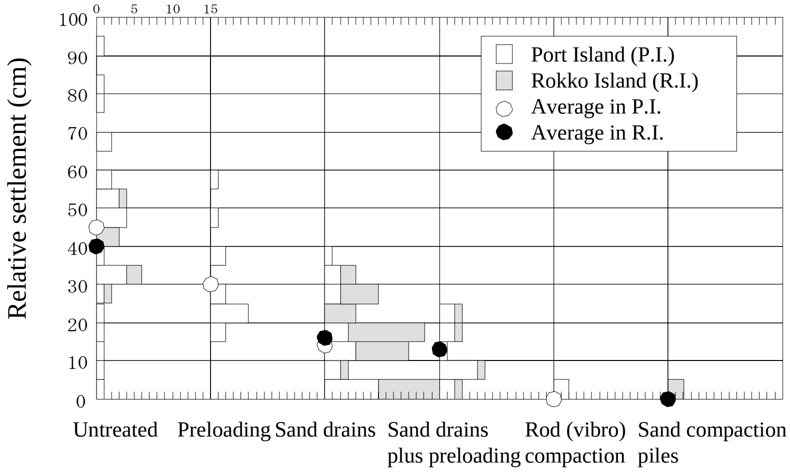

Figure 13: Relative settlement and methods of ground improvement (buildings with pile foundation)

During the 1995 Hyogoken Nambu earthquake, six cases of subsidence measurement of buildings on spread foundations located in the man-made islands were conducted before and after the earthquake (Kakurai et al. 1996). Figure 14 shows the cross-sections of these buildings. The foundation ground beneath buildings a~e were improved by compaction, while no improvement was implemented under building f. Also indicated in each figure are the total bearing load from each of the building, the amount of absolute settlement measured and the improvement ratio. As shown in the figure, the settlement following the earthquake of building f with unimproved foundation ground was about 20cm whereas the amount of settlement in buildings a~e was in the order of several centimeters, depending on the extent of improvement.

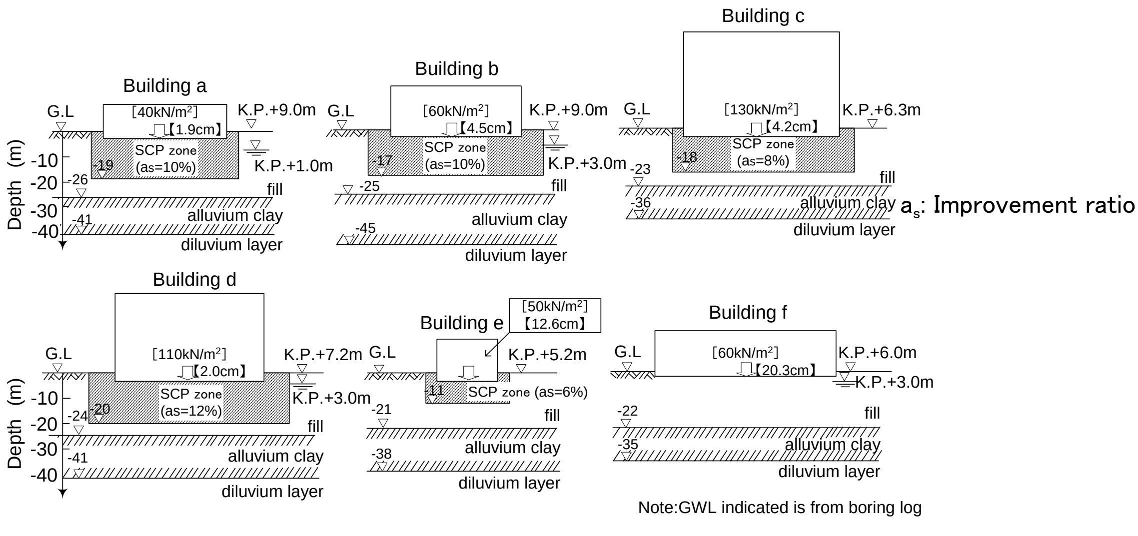

Figure 14: Absolute settlement and SCP improved area (Buildings on spread foundation)

4.5. Improvement effectiveness in buildings (2001 Tohoku Pacific Earthquake)

Following the 11 March 2011 Tohoku Pacific Earthquake (M_w 9.0), liquefaction was observed in many areas adjacent to Tokyo Bay, about 390 km from the epicentre, as shown in Figure 15. Manholes were uplifted, grounds settled, and buildings and bridges were damaged as a result of liquefaction.

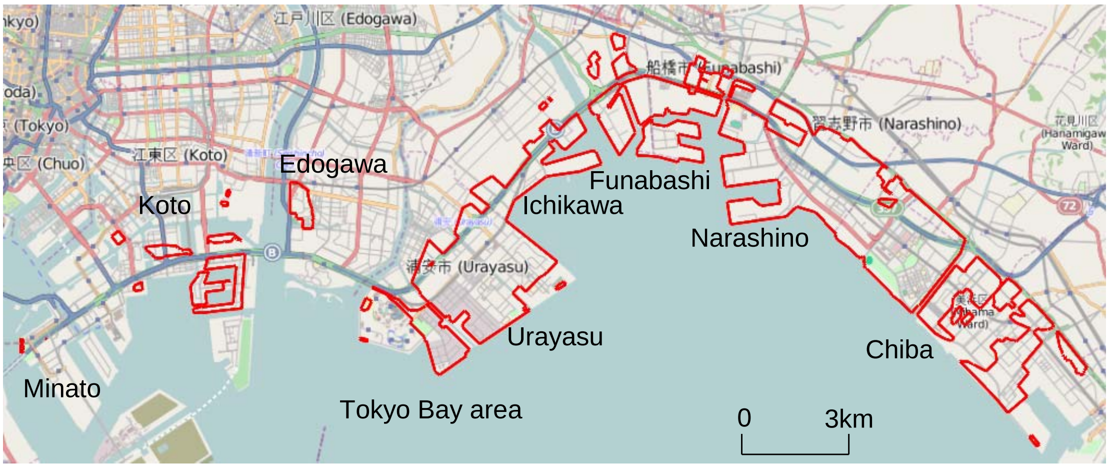

Figure 15: Liquefied zones along Tokyo Bay (Ishikawa et al, 2011)

A medical center building is located in reclaimed land along the Tokyo Bay as shown in Figure 16. The building is 5 stories high and supported by piles. After the liquefaction assessment, it was judged that there is a high potential for liquefaction and consequently, non-vibratory SCP was adopted at this site as a countermeasure against liquefaction. The imrovement specification is square arrangement with pitch of 1.5m (a_s=16.7%) and the length of the pile is 12m. In the surrounding area of the improved site, gravel instead of sand was used to dissipate the excess water pressure from liquefied area. The effectiveness of this method was verified for a building in Rokko Island during the 1995 Hyogo-ken Nambu Earthquake. As shown in Photo 1, although liquefaction-induced damage was observed outside the improved area, no damage was observed within the improved area.

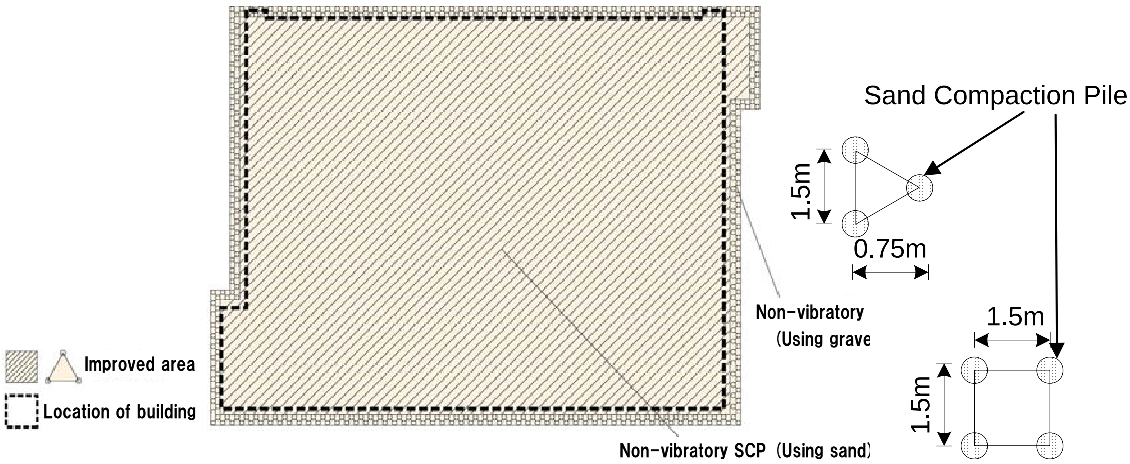

Figure 16: Plan view of the SCP improved area of the building

5. CONCLUDING REMARKS

This paper highlighted the features of the SCP method and its improvement effectiveness though investigation of the implementation and performance of improved grounds during actual large earthquakes in Japan.

There was no damage on the improved area during the 2011 Tohoku Pacific Earthquake. This showed that the improved ground by SCP method is effective not only against intense earthquakes such as the 1995 Hyogo-ken Nambu Earthquake but also against earthquakes having long duration time. A qualitative understanding of these factors and analyses should be undertaken in future studies.

Photo 1: Successful ground improvement in Tatsumi area

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