

EFFECT OF SOIL IMPROVEMENT ON GROUND SUBSIDENCE DUE TO LIQUEFACTION

SUSUMU YASUDAⁱ⁾, KENJI ISHIHARAⁱⁱ⁾, KENJI HARADAⁱⁱⁱ⁾
and NAOTOSHI SHINKAWAⁱⁱⁱ⁾

ABSTRACT

Liquefaction occurred at many sites along Osaka Bay during the 1995 Hyogoken-Nambu earthquake (the Great Hanshin-Awaji earthquake disaster) and caused extensive damage to buildings, bridges, quay walls, etc. The authors conducted detailed site surveys at the liquefied sites and found a remarkable phenomenon. Some zones in two big artificial islands, Port Island and Rokko Island, in Kobe City, did not liquefy even though the zones surrounding the islands liquefied. Damage to buildings and ground subsidence in these zones were also less severe than the damage and subsidence in the surrounding zones. Based on a study of the soil conditions in these islands, it was found that the non-liquefied zones had been improved by several methods, including sand compaction piles, rod (vibro) compaction, sand drains and preloading, before buildings had been constructed on them. These ground improvement methods were effective in mitigating liquefaction even though the ground shaking was as extreme as more than 400 gals of maximum surface acceleration.

Key words: earthquake, earthquake damage, liquefaction, sandy soil, soil improvement, subsoil subsidence (IGC: E8)

INTRODUCTION

The 1995 Hyogoken-Nambu earthquake with a magnitude of 7.2 occurred at 5:47 A.M. on January 17, 1995. The earthquake caused liquefaction of many reclaimed land areas and alluvial plain deposits along Osaka Bay, and severe damage to buildings, bridges, tanks, buried pipelines, etc. In Kobe City, several waterfront areas and two large islands have been constructed with reclaimed land along Osaka Bay. Liquefaction occurred in almost all of the artificially reclaimed land and islands because the reclaimed soil was loose and the ground shaking was very strong, i.e., more than 400 gals of maximum surface acceleration. However, some zones in both, Port and Rokko Islands, did not liquefy and structures in these zones were not seriously damaged.

The authors identified both liquefied and non-liquefied zones on the islands by site and aerial-photo surveys, and measured ground subsidence at many locations. Soil conditions in the islands were also studied based on existing soil boring data.

Since the reclaimed soils were loose and an underlying alluvial clay layer was very soft, the subsoils in some

zones on the islands had been improved with sand compaction piles, rod (vibro) compaction, sand drains and preloading to strengthen the reclaimed soil and/or to accelerate the consolidation of the clay layer. By comparing the non-liquefied zones and the improved zones, it was demonstrated that liquefaction did not occur in the treated zones. In addition, the ground subsidence in each zone was different. The zones densified with sand compaction piles or rod (vibro) compaction did not subside even though the subsidence in the improved zone reached almost 45 cm. The subsidence in zones improved with sand drains or by preloading was almost 15 cm and 30 cm, respectively.

CONSTRUCTION OF THE TWO ISLANDS

Kobe City was built on a narrow alluvial plain facing Osaka Bay, as shown in Fig. 1. There is a mountain behind this plane named Rokko Mountain with a steep slope. Coastal areas have been reclaimed for many years to enlarge the flat land areas. One such large area was reclaimed starting in 1953. Several areas of Rokko Mountain were cut and the soil was transported as fill to the

ⁱ⁾ Professor of Civil Engineering, Tokyo Denki University, Hatoyama-cho, Hiki-gun, Saitama 350-03.

ⁱⁱ⁾ Professor of Civil Engineering, Science University of Tokyo.

ⁱⁱⁱ⁾ Senior Engineer, Fudo Construction Co., Ltd.

Manuscript was received for review on August 18, 1995.

Written discussions on this paper should be submitted before August 1, 1996 to the Japanese Geotechnical Society, Sugayama Bldg. 4 F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

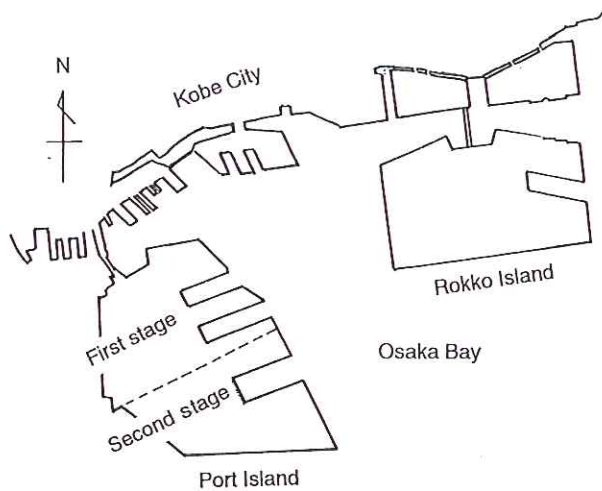


Fig. 1. Location of Port and Rokko Islands

coastal area. Seven large reclaimed land areas were thereby constructed along Osaka Bay by 1970. The construction of two large islands, Port and Rokko, started in 1966 using the same cut and fill method. The first stage reclamation of Port Island was carried out at its northern part of the island from 1966 to 1980. Rokko Island was constructed from 1972 to 1990. The second stage reclamation of Port Island started in 1986 and will be finished by 1996.

The cut and fill soil was mainly granite-origin sandy soil called Masa. The entire area of the first stage reclaimed land for Port Island and the northern area of Rokko Island were filled mainly with Masa. The southern area of Rokko Island however was filled with different soils which are mud stone-origin and tuff-origin sandy soils and were excavated from Kobe layers, because of a lack of Masa. Figure 2 shows the range of grain-size distribution curves of Masa, and the mud stone-origin and tuff-origin sandy soils, which were used as fill for both Port and Rokko Islands, respectively. Masa soil is a sandy soil with much gravel, silt and clay. The mean grain diameter is mostly 0.2 mm to 6 mm. The contents of gravel and fines are about 0 to 65% and 5% to 35%, respectively. Kobe layers are also sandy soils

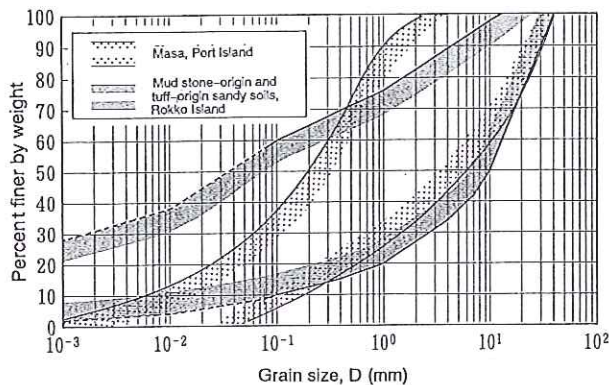


Fig. 2. Grain size distribution curves for fill soils at Port and Rokko Islands

with much gravel, silt and clay. The mean diameter is mostly 0.03 mm to 10 mm. The contents of gravel and fines are mainly 15% to 75% and 10% to 55%, respectively. The fine fraction of Kobe layers is greater than that of Masa.

GROUND IMPROVEMENT WORKS

The depth to seabed was 10–15 m before reclamation at the sites of the two islands. The seabed was comprised of an alluvial clay layer with a thickness of 10 m to 20 m. Figure 3 shows a simplified typical subsoil cross-section for Port Island. As shown in this figure, the reclaimed sandy soil was 15 m to 20 m thick. The reclaimed sandy soil was loose and the alluvial clay beneath it was very soft. Therefore, the consolidation of the soft clay had to be accelerated and the loose sandy soil had to be strengthened in zones where heavy or important structures were to be constructed. For these purposes the subsoil in some zones was improved by installing sand drains and preloading. In addition, some zones were compacted with sand compaction piles or rod (vibro) compaction. The purpose of the soil improvement, therefore, was not the mitigation of liquefaction during earthquakes. Only one zone where a tram depot was to be built in Rokko Island, was compacted by sand compaction method to prevent the occurrence of liquefaction. The *N*-value in SPT of the reclaimed sandy soil in this zone was increased from about 10 to about 18 due to the soil improvement (Nakajima et al., 1992).

Figures 4 and 5 show the zones of soil improvement in both in Port and Rokko Islands. The central areas, which are used as residential areas, were improved by installing sand drains, preloading and a combination of the two methods. High-rise apartments and office buildings are constructed in these areas. The ground for an amusement park, tanks, some structures and a tram depot were improved using sand compaction piles or rod (vibro) compaction. Most of this soil improvement work was advanced to the bottom of the alluvial soft clay.

Figure 6 shows the procedure for the sand compaction pile method. After penetrating a casing into the ground, sand is inserted into the casing. Then by withdrawing the casing, the sand is discharged into the bored hole and compacted by vibration. The surrounding subsoils are also compacted during this procedure. The diameter of the casing and the compacted sand piles was 50 cm and 70 cm for these islands. The sand compaction piles were spaced at 2.0 m to 3.0 m. In the rod (vibro) compaction method, sand was fed from outside an H-beam 45 cm

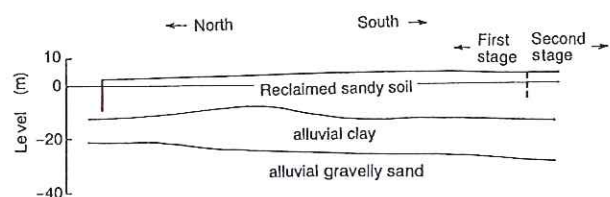


Fig. 3. Simplified typical subsoil cross-section at Port Island

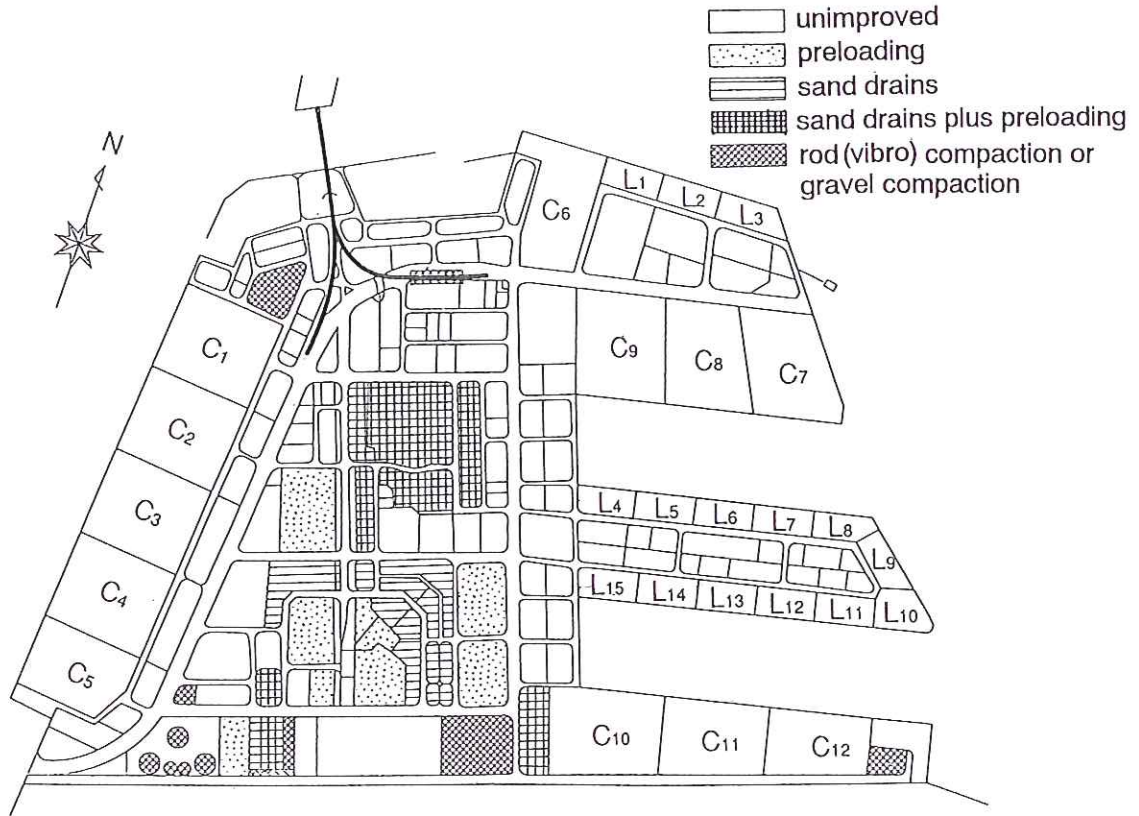
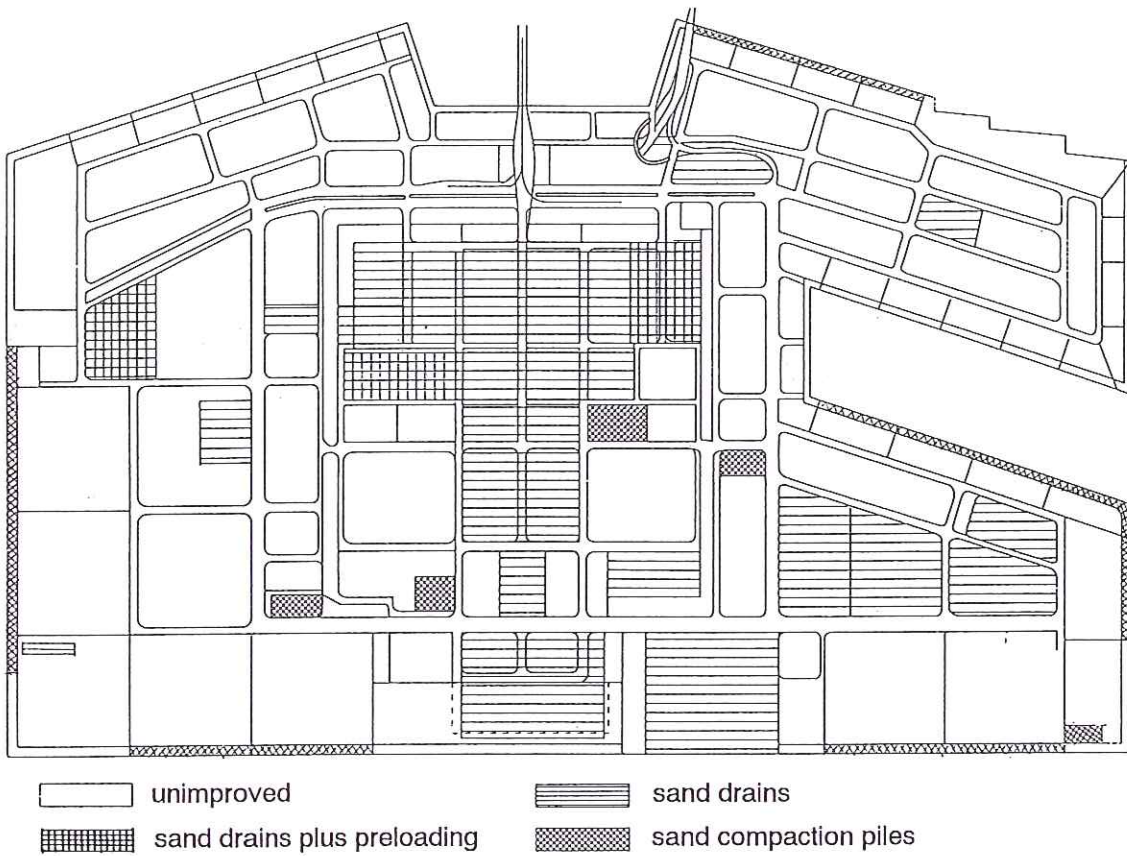
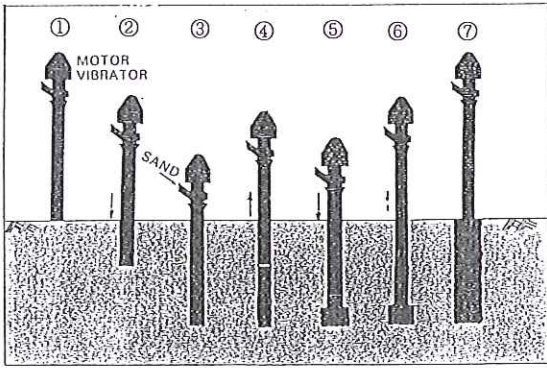


Fig. 4. Improvement zones in Port Island (quoted and modified from Watanabe (1981))



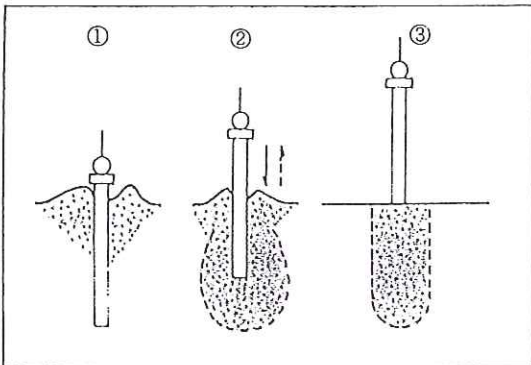
Note: Extent of zones treated by preloading may be inaccurate in size

Fig. 5. Improvement zones in Rokko Island



- ① Set the casing at the specified location.
- ② Actuate the vibrator for the casing to penetrate below the ground surface.
- ③ Penetrate to the specified depth, then placed sand into the casing through a hopper.
- ④ Withdraw the casing to the specified level; the sand in the casing is discharged into the bored hole with compressed air.
- ⑤ Insert the casing into the hole; the sand is compacted by vibration.
- ⑥ Place sand into the casing while withdrawing the casing to a specified level.
- ⑦ By repeating this procedure, the sand compaction pile is completed up to the ground surface.

Fig. 6. Sand compaction pile procedure

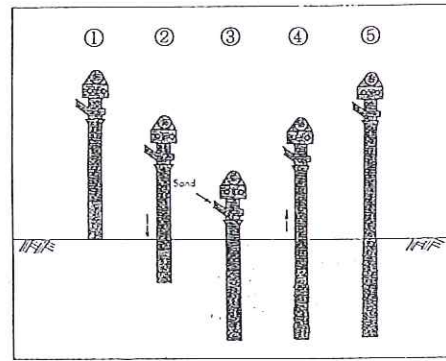


- ① Actuate the vibrator for the rod to penetrate the subsoil.
- ② By repeating the penetration and extraction process, a compaction force is transmitted to the adjacent subsoils.
- ③ Extract the rod completely to the ground surface.

Fig. 7. Rod compaction procedure

wide, as shown in Fig. 7. The rod (vibro) compaction locations were spaced at 1.5 m to 2.4 m. Sand compaction piles can compact more densely than rod (vibro) compaction.

Figure 8 shows the sand drain method procedure. The sand placed in the casing is only discharged into the bore hole, and not compacted. Therefore, the sand piles and surrounding subsoil are not compacted in general. The diameter of the casing was 50 cm and the sand drain spacing was 2.0 m to 3.5 m. For preloading, surcharge mounds of 6 m to 10 m in height were placed on the



- ① Set the casing at the specified location.
- ② Actuate the vibrator for the casing to penetrate the ground.
- ③ Penetrate to the specified depth, then place sand in the pipe through a hopper.
- ④ Inject compressed air into the casing; extract the casing while discharging the sand from the lower end.
- ⑤ Extract the casing completely to the ground surface.

Fig. 8. Sand drain procedure

ground surface, then removed after consolidation of the alluvial clay layer. During this process, reclaimed sandy soil might be also densified slightly due to over-consolidation.

DENSIFICATION OF RECLAIMED SANDY SOIL DUE TO IMPROVEMENT WORKS

The authors collected data on soil borings made before and after the soil improvement. Figures 9 to 11 show a comparison of *N*-values in SPT of reclaimed sandy soils before and after treatment by rod (vibro) compaction, sand drains plus preloading and sand drains, respectively. Broken lines and solid lines show the *N*-values in SPT before and after the treatment at the same site, respectively. As shown in these figures, *N*-values in SPT increased after the soil was improved. Some large *N*-values in SPT (more than 30) must be neglected in the comparison because it is estimated that some large cobbles existed at these depths. Ground water was encountered usually 4 m to 6 m below the ground surface on both islands. The *N*-values in SPT of uncompacted soils below the ground water table were mostly 10 or less. Figure 12 compares *N*-values in SPT in untreated zones with those in zones treated with sand drains and sand compaction piles, including other published data (Nakajima et al., 1992). Based on Figs. 9 to 12, the *N*-values in SPT of soil treated and untreated subsoils are summarized in Table 1. *N*-values in

Table 1. Average SPT *N*-values in treated and untreated subsoils

Method	Port Island	Rokko Island
Untreated	8 to 15	8 to 10
Preloading	—	—
Sand drains	25	14 to 17
Sand drains plus preloading	25	—
Rod (vibro) compaction	18 to 31	—
Sand compaction piles	—	18

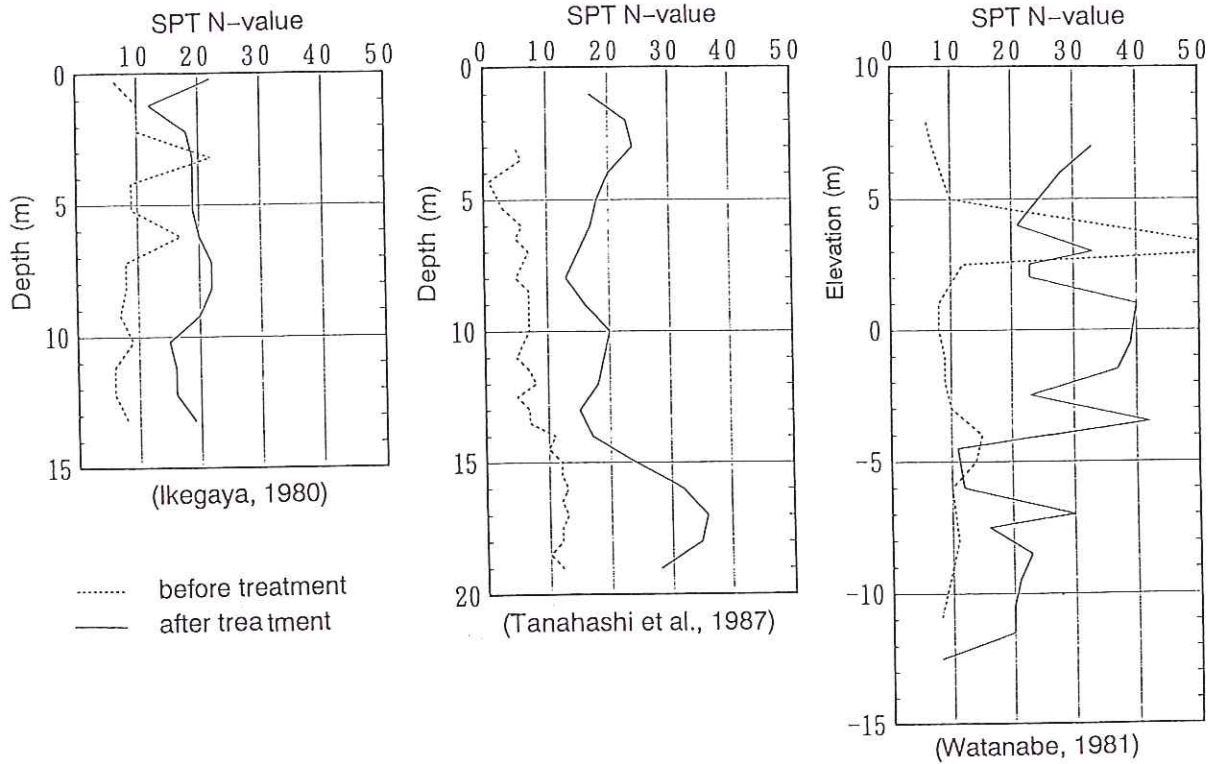


Fig. 9. Increase in *N*-value due to treatment using rod (vibro) compaction method

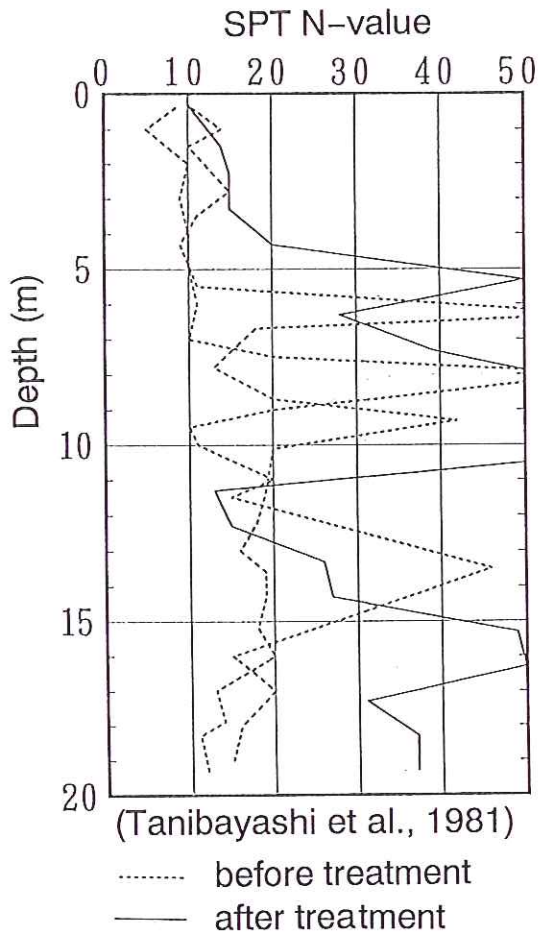


Fig. 10. Increase in *N*-value due to treatment with sand drains plus preloading

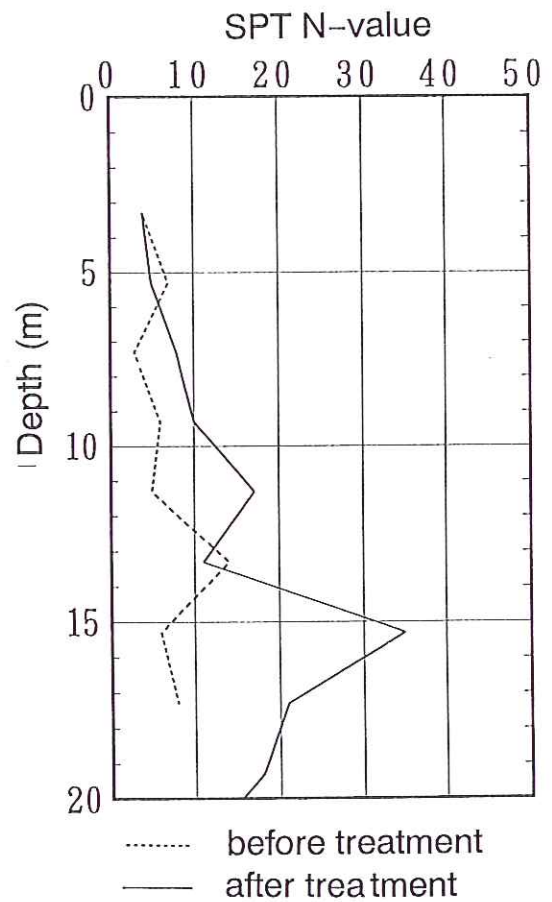


Fig. 11. Increase in *N*-value due to treatment by the sand drain method

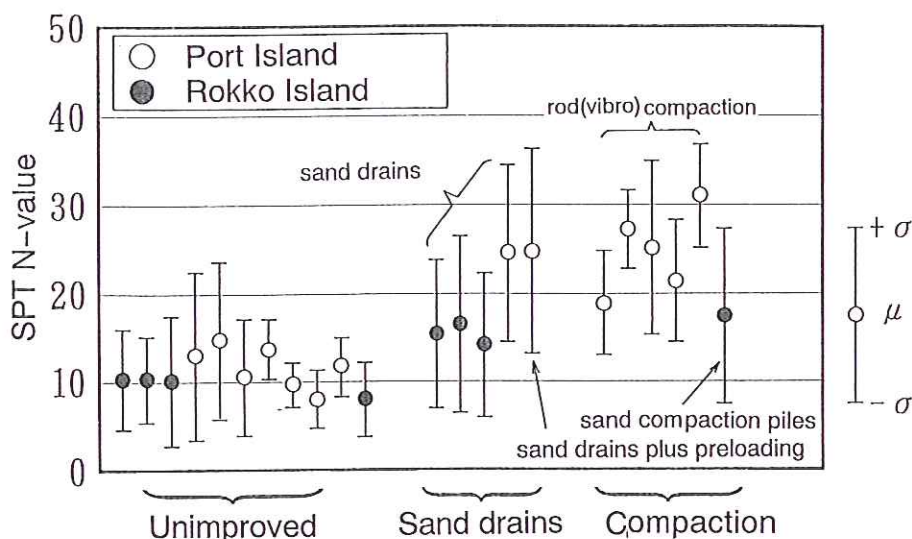


Fig. 12. Comparison of SPT N -values before and after improvement

SPT on Rokko Island were smaller than those on Port Island. This may be due to the difference in grain size as shown in Fig. 2.

As mentioned before, the sand drain method does not normally densify the subsoil. N -values in SPT for reclaimed sandy soils increased in both islands, however, as shown in Figs. 10 and 11. This densification of the reclaimed soils must have been induced by the special construction conditions. Since the reclaimed sandy soil is 15 m to 20 m thick and contains much gravels in both islands, strong vibration force and a long time were necessary to advance the casing down to the alluvial clay layer. The length of sand drains was as long as 30 m. In addition, since a hard waste material had been dumped into the seabed in some places, extra vibration was necessary to penetrate the casing through this hard material. Reclaimed sandy soils therefore were densified in both islands even though they were treated by the sand drain method.

ZONES OF LIQUEFACTION AND GROUND SUBSIDENCE IN BOTH ISLANDS CAUSED BY THE EARTHQUAKE

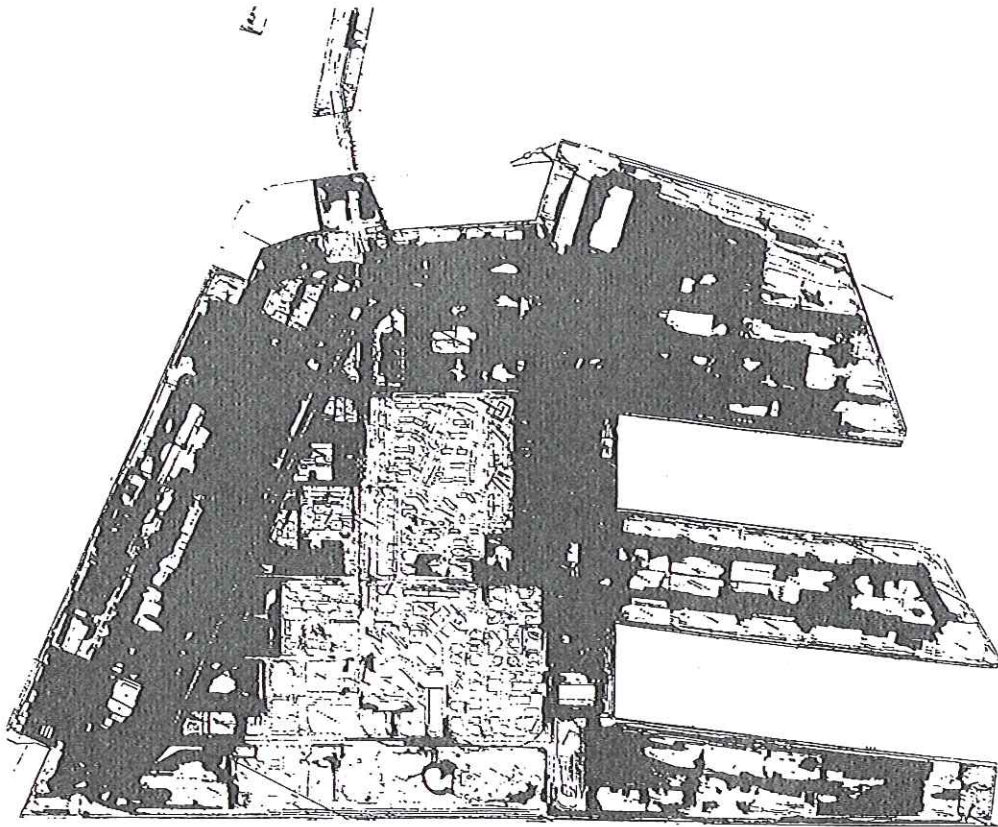
Figures 13 and 14 show the zones where sand and water were ejected, judging from aerial-photographs taken one to four days after the 1995 Hyogoken-Nambu earthquake (Association for the Development of Earthquake Prediction, 1995). By comparing Figures 4 and 5 which show the improved zones, it was determined that no sand and water were ejected in the zones treated with sand compaction piles, rod (vibro) compaction, sand drains plus preloading and sand drains. Sand and water were ejected at a few locations in the zone treated by preloading only.

Sand and water were not observed at the southern area of Rokko Island even though the ground was not treated.

As mentioned before, the reclaimed soils at the southern part of Rokko Island were of mud stone-origin and tuff-origin sandy soils, which contain much fine particles, as shown in Fig. 2. The reclaimed soils at the southern part of Rokko Island therefore might not be sensitive to liquefaction. Future study on their sensitivity to liquefaction is necessary.

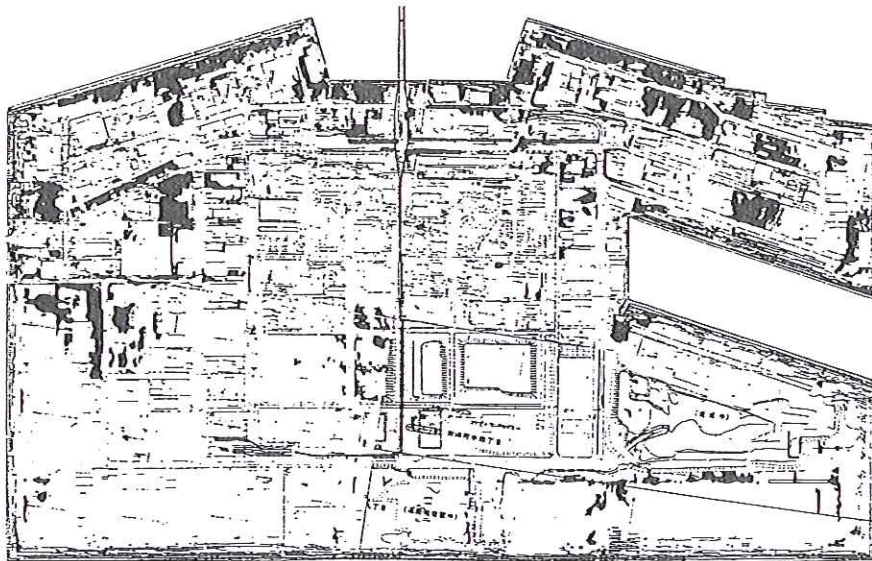
Large ground subsidence, of up to several tens of centimeters, was observed in the zones where sand and water were ejected. No subsidence and no damage to structures were observed however in the zones densified with sand compaction piles and rod (vibro) compaction, and only slight subsidence was observed in the zones treated by other methods. The authors measured the ground subsidence at many sites. Many buildings and bridges for railways and roads were supported by pile foundations on both islands. Differential settlement could be measured around the structures. Figures 15 and 16 show the contours of the ground subsidence thus measured. Figure 17 compares the measured ground subsidence in each zone treated by different methods. The average subsidence in the untreated zones was almost 40 cm to 45 cm. Subsidence decreased with the degree of compaction. The average subsidence in zones treated by preloading, sand drains, sand drains plus preloading, rod (vibro) compaction and sand compaction piles was about 30 cm, 15 cm, 12 cm, 0 cm and 0 cm, respectively. The order of decreasing subsidence is the same as the order of increase in N -values in SPT, mentioned before.

Usually the volume of liquefied soil decreases by several percent due to ejection of pore water, according to laboratory tests (Ishihara et al., 1992). As the reclaimed Masa was loose and ground shaking during the earthquake was very strong, it can be estimated that liquefaction occurred from the ground water level to the bottom of the reclaimed layer in untreated zones. Assuming the thickness of the liquefied layer was 10 m to 15 m and the



● Zones where sand and water were ejected

Fig. 13. Zones where sand and water were ejected on Port Island from the 1995 Hyogoken-Nambu earthquake (quoted from Association for the Development of Earthquake Prediction)



● Zones where sand and water were ejected

Fig. 14. Zones where sand and water were ejected on Rokko Island from the 1995 Hyogoken-Nambu earthquake (quoted from Association for the Development of Earthquake Prediction)

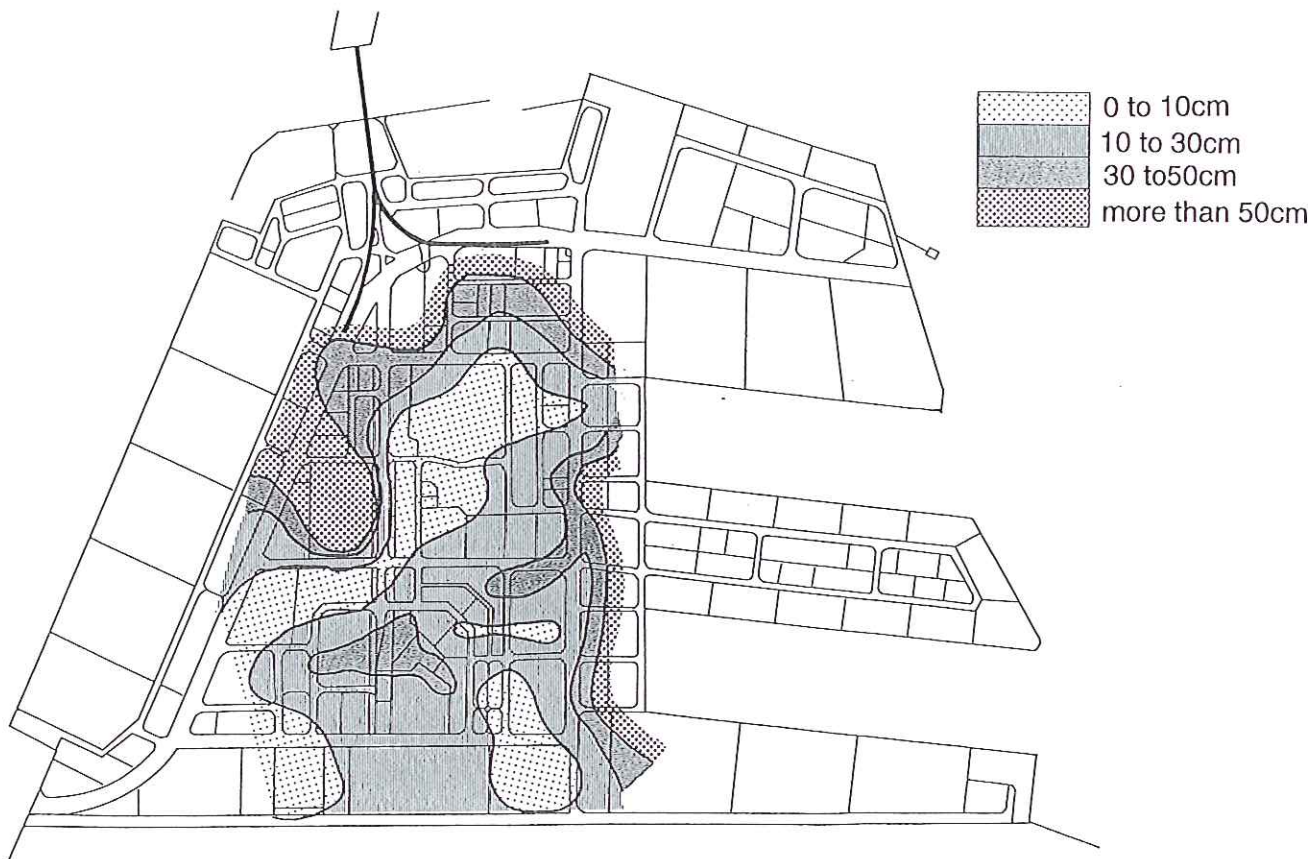


Fig. 15. Contour lines of ground subsidence on Port Island

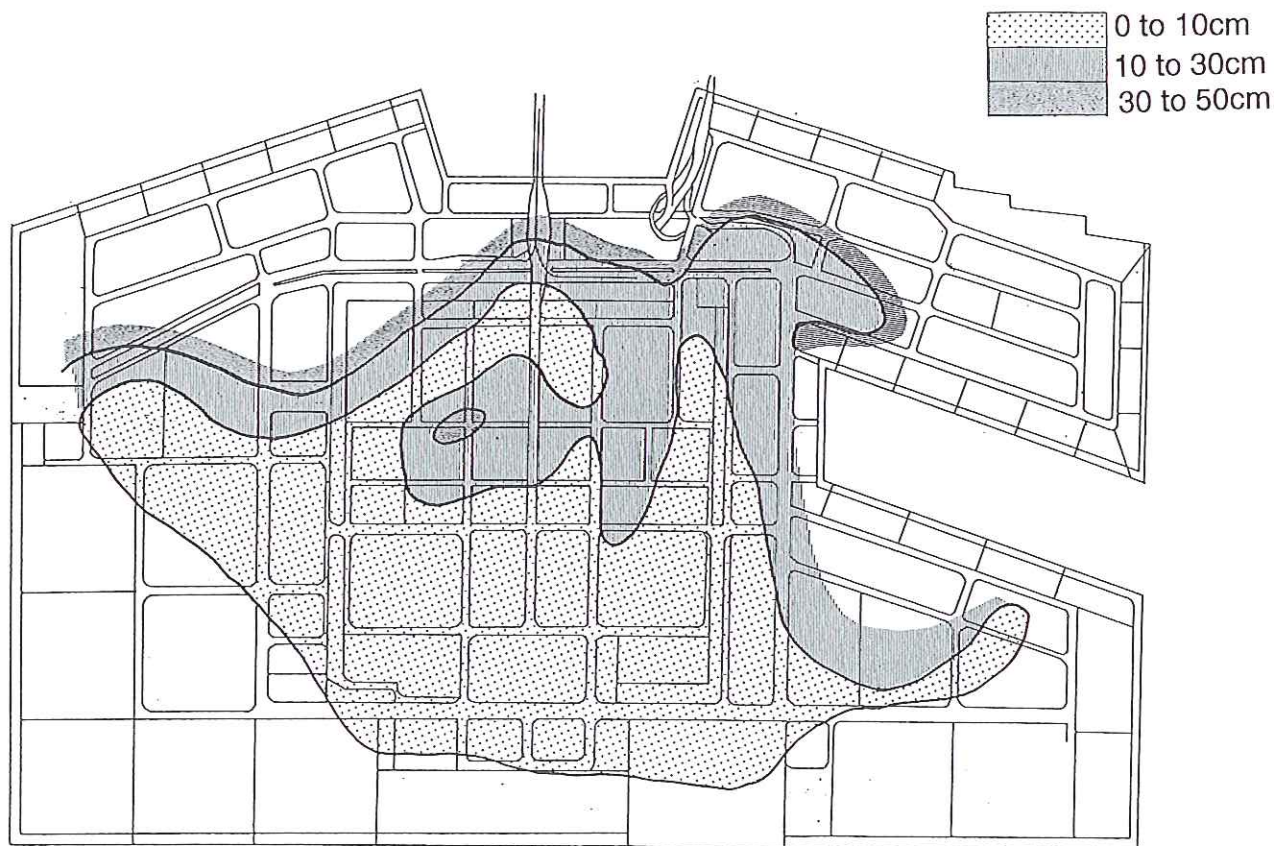


Fig. 16. Contour lines of ground subsidence on Rokko Island

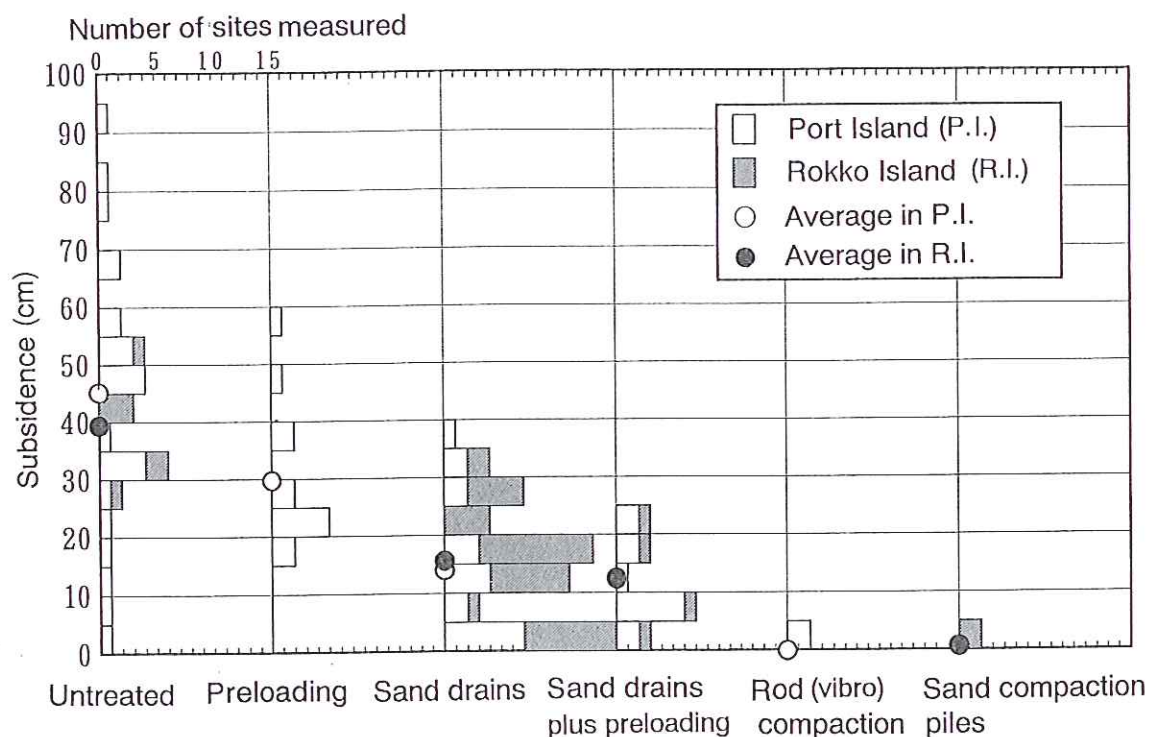


Fig. 17. Comparison of ground subsidence in zones treated with different methods

subsidence was 45 cm, the volume change can therefore be estimated to be 3 to 5%. This value coincides fairly well with the values obtained from the laboratory tests mentioned above. The reclaimed soils in the zones compacted by sand compaction or rod (vibro) compaction were not liquefied, because no evidence of subsidence, ejection of water or damage to structures was observed. The reclaimed soils in the zones treated by other methods might have liquefied at some depths. Detailed study is necessary to estimate the depths of liquefaction by obtaining sand samples, laboratory tests and response analyses. It must be stressed, however, that the compacted subsoils did not liquefy even though very strong shaking, of 400 gal or more, hit the site. Data on the unliquefied soil is important for the development of methods to predict liquefaction.

CONCLUSIONS

Subsoil conditions of two reclaimed island in Kobe City which were liquefied and not liquefied by the 1995 Hyogoken-Nambu earthquake, were investigated, and the following conclusions were drawn:

1. The subsoil treated with sand compaction piles or rod (vibro) compaction did not liquefy and subside, even though the earthquake shaking was very strong.
2. The untreated subsoil subsided almost 45 cm due to liquefaction and caused damage to structures.
3. Soil improvement with sand drains or preloading decreased the liquefaction and ground surface subsidence.

ACKNOWLEDGMENTS

The authors would like to acknowledge the help of Mr. H. Tsuboi and Y. Takahashi of Fudo Construction Co., Ltd., who made the site survey and collected data for the soil borings.

REFERENCES

- 1) Association for the Development of Earthquake Prediction (1995): "Liquefied sites by the 1995 Hyogoken-Nambu earthquake," in press (in Japanese).
- 2) Ikegaya, M. (1980): "Examples of ground improvement with sand drain piles," *Journal of Japan Sewage Work Association*, Vol. 17, No. 190, pp. 30-39 (in Japanese).
- 3) Ishihara, K. and Yoshimine, M. (1992): "Evaluation of settlements in sand deposits following liquefaction during earthquakes," *Soils and Foundations*, Vol. 32, No. 1, pp. 173-188.
- 4) Nakajima, M., Fukui, M. and Tanimoto, K. (1992): "Foundations of a tram depot for a new tram system in Rokko Island," *The Foundation Engineering and Equipment*, Vol. 20, No. 5, pp. 73-79 (in Japanese).
- 5) Tanahashi, H., Fukui, M., Uchida, N. and Kawamura, M. (1987): "Measurement of settlement of buildings with various type pile foundations in reclaimed land," *Proceeding of Annual Meeting in Kinki Branch of Architectural Institution of Japan*, pp. 229-232 (in Japanese).
- 6) Tanibayashi, K. and Kobori, T. (1981): "Ground improvement works and pile load tests at the site of high-rise buildings in reclaimed lands," *The Foundation Engineering and Equipment*, Vol. 9, No. 1, pp. 100-110 (in Japanese).
- 7) Watanabe, K., (1981): "Development of Kobe Port Island and foundations of structures in the island," *The Foundation Engineering and Equipment*, Vol. 9, No. 1, pp. 83-91 (in Japanese).

