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EFFECTIVENESS OF THE GROUND IMPROVEMENT ON LIQUEFACTION OBSERVED DURING THE HYOGOKEN- NAMBU EARTHQUAKE

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ABSTRACT

Many sites along Osaka Bay were liquefied during the 1995 Hyogoken-Nambu Earthquake and extensive damage to buildings, bridges, quay walls, etc were induced. However, 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. 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 600 gals of maximum surface acceleration.

KEYWORDS

Earthquake damage; Liquefaction; Sandy soil; Soil improvement; Subsoil subsidence

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 600 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.

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. 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.

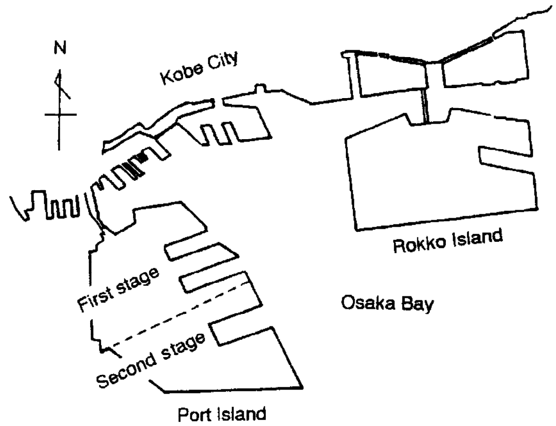


Fig.1 Location of Port and Rokko Islands

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 0.2mm to 6mm. The contents of gravel and fines are about 0 to 65% and 5% to 35%, respectively. Kobe layers are also sandy soils with much gravel, silt and clay. The mean diameter is mostly 0.01mm to 6mm. The contents of gravel and fines are mainly 15% to 65% and 10% to 55%, respectively. The fine fraction of Kobe layers is greater than that of Masa.

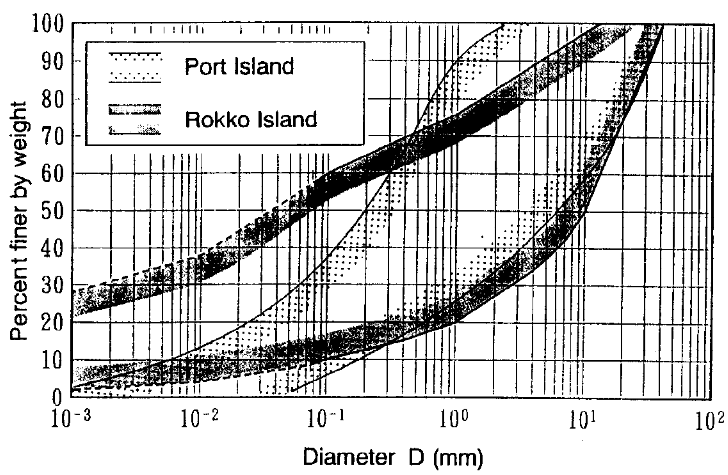


Fig.2 Grain size distribution curves for fill soil at Port and Rokko Islands

GROUND IMPROVEMENT WORKS

The depth to seabed was 10-15m before reclamation at the sites of the two islands. The seabed was comprised of an alluvial clay layer with a thickness of 10m to 20m. Figure 3 shows a simplified typical subsoil cross-section for Port Island. As shown in this figure, the reclaimed sandy soil was 15m to 20m thick. The reclaimed sandy soil was loose and the alluvial clay beneath it was very soft. Therefore, the consolidation of

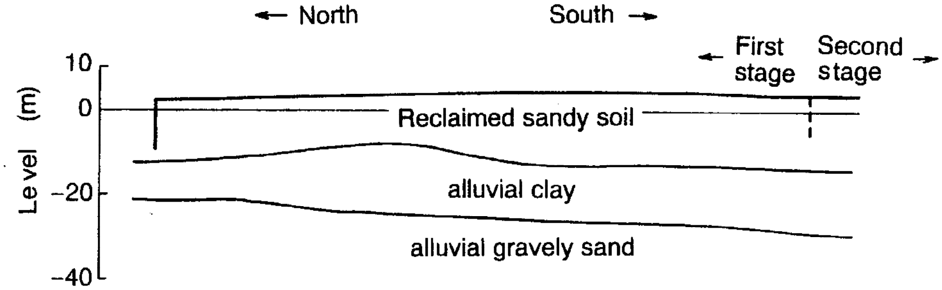


Fig.3 Simplified typical subsoil cross-section at Port Island

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 (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.

The authors collected data on soil borings made before and after the soil improvement. Figures 6 to 8 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. Ground water was encountered usually 4m to 6m 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 9 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 Fig.6 to Fig.8, the N-values in SPT of soil treated and untreated subsoils are summarized in Table 1. N-

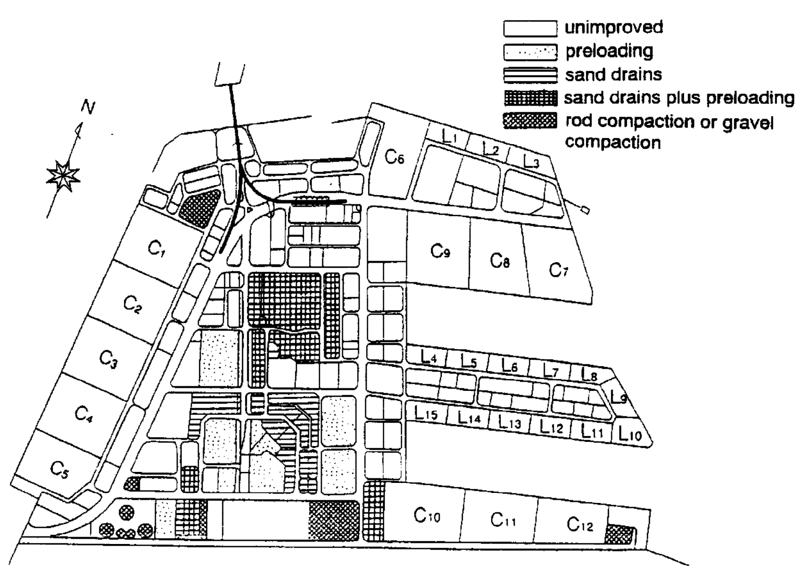


Fig.4 Improvement zones in Port Island

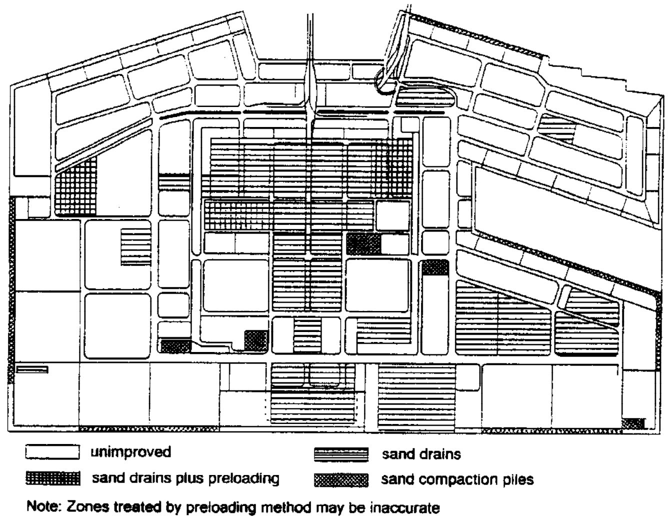
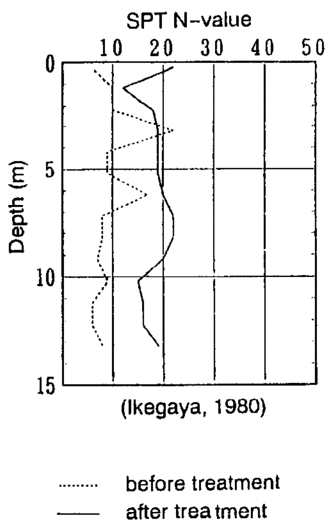
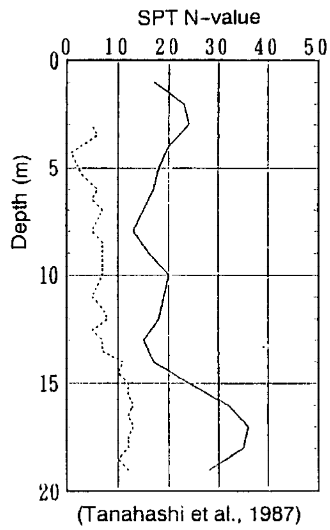


Fig.5 Improvement zones in Rokko Island





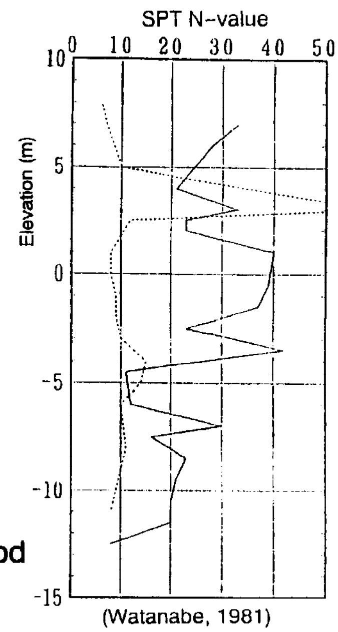


Fig.6 Increase in N-value due to treatment using rod compaction method

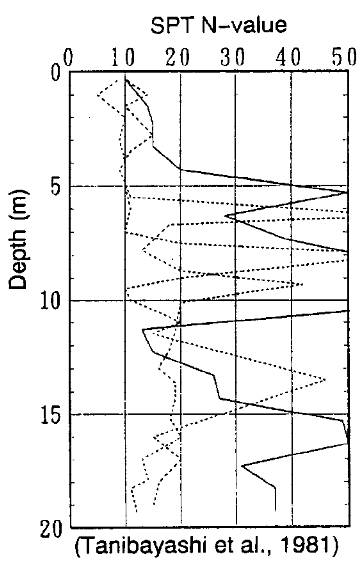


Fig.7 Increase in N-value due to treatment with sand drains plus preloading

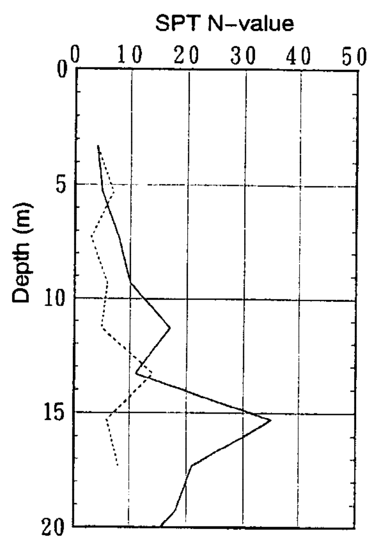


Fig.8 Increase in N-value due to treatment by the sand drain method

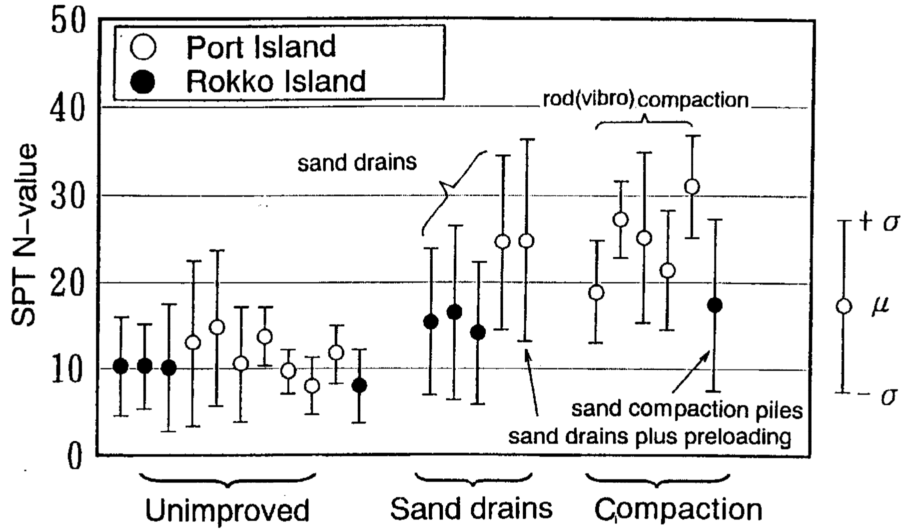


Fig.9 Comparison of SPT N-values before and after improvement

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

values in 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.

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

Figures 10 and 11 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.

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. Figures 12 and 13 show the contours of the ground subsidence thus measured. Figure 14 compares the measured ground subsidence in each zone treated by different methods. The average subsidence in the untreated zones was almost 40cm to 45cm. 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 30cm, 15cm, 12cm, 0cm and 0cm, respectively. The order of decreasing subsidence is the same as the order of increase in N-values in SPT, mentioned before.

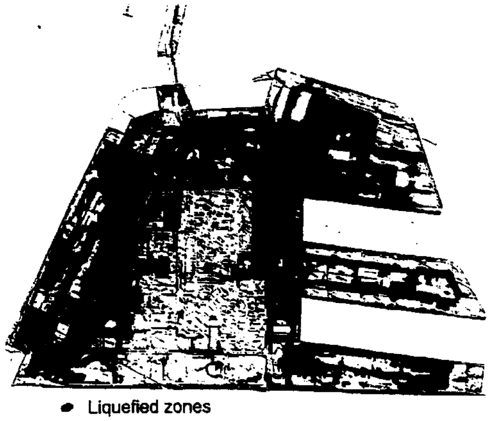


Fig.10 Zones where sand and water were ejected on Port Island from the 1995 Hyogoken-Nambu Earthquake

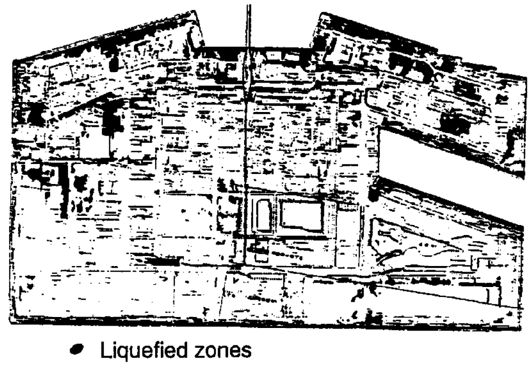


Fig.11 Zones where sand and water were ejected on Rokko Island from the 1995 Hyogoken-Nambu Earthquake

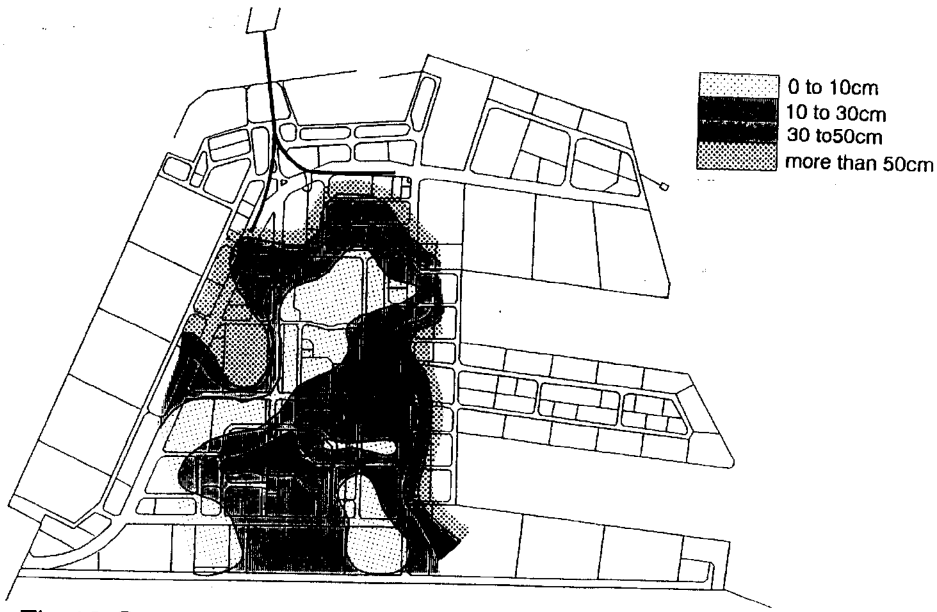


Fig.12 Contour lines of ground subsidence on Port Island

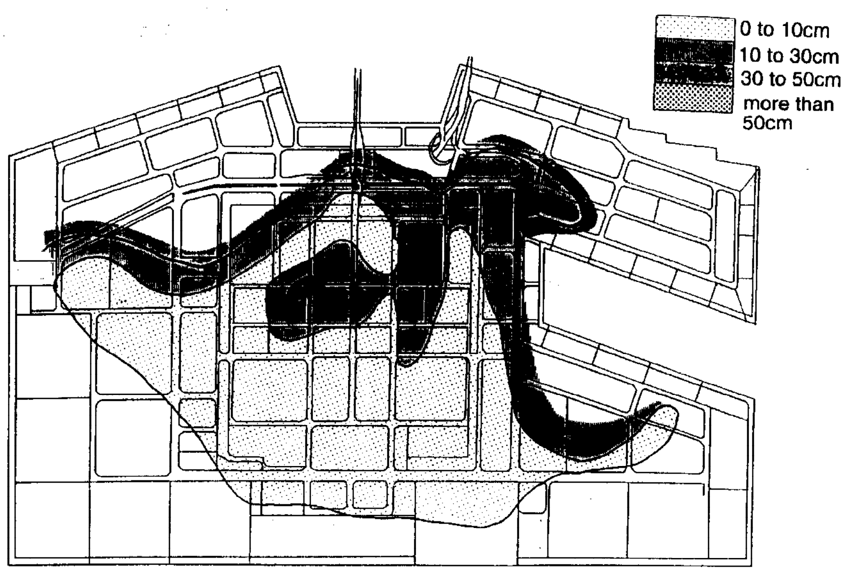


Fig.13 Contour lines of ground subsidence on Rokko Island

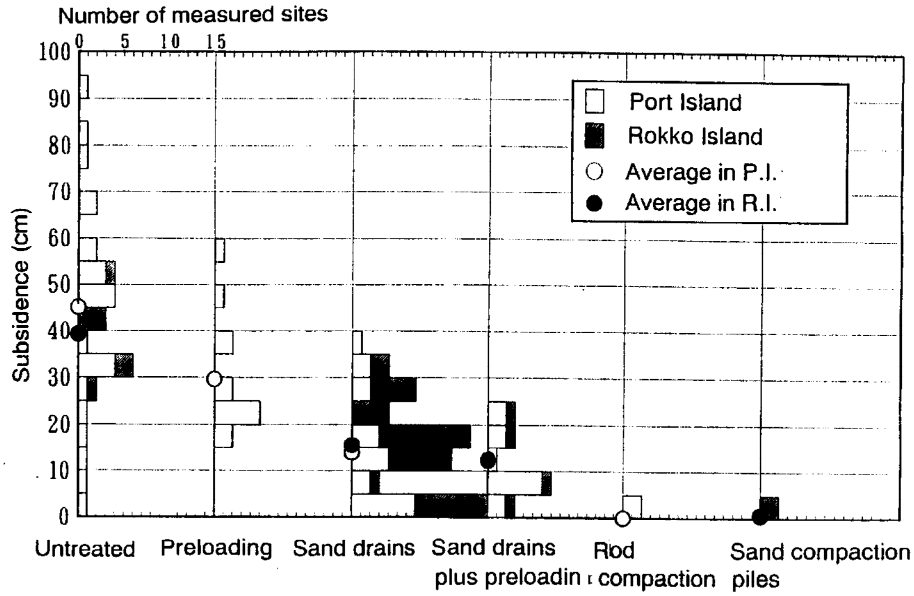


Fig.14 Comparison of ground subsidence in zones treated with different methods

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 10m to 15m and the subsidence was 45cm, 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. It must be stressed that the compacted subsoils did not liquefy even though very strong shaking, of 600gal or more, hit the site. Data on the unliquefied soil is important for the development of methods to predict liquefaction.

CONCLUSIONS

Subsoil conditions at liquefied and not liquefied sites 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 50cm due to liquefaction and caused damage to structures.
3. Soil improvement with sand drains or preloading decreased the liquefaction and ground surface subsidence.

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