CHARACTERISTICS OF GROUND DEFORMATION DUE TO LIQUEFACTION

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ABSTRACT

The results of an investigation of soil liquefaction caused by the 1995 Hyogoken-Nambu earthquake are described. Massive and extensive soil liquefaction occurred in the coastal areas of reclaimed land, in old river beds, in Holocene deposits and in areas reclaimed from old ponds. A man-made island of weathered granite, or “Masado,” was also seriously damaged by soil liquefaction. The maximum distance from the epicenter to the liquefied sites was approximately 90 km. Several characteristics of liquefaction formation, strong earthquake motions recorded on Port Island, and damage to structures from this earthquake are discussed.

Key words: earthquake, earthquake damage, liquefaction (IGC: B4/E8)

INTRODUCTION

At 5:46 AM on January 17, 1995, an earthquake of magnitude 7.2 (Richter scale) (known as the 1995 Hyogo-Nambu earthquake) struck the southern part of Hyogo Prefecture. Sand boils and liquefied, ejected soil were observed at numerous sites, mainly in the coastal areas of Hyogo and Osaka Prefectures. In particular, massive liquefaction was observed on man-made islands. In addition, liquefaction was observed in inland areas with high ground water levels.

The well known phenomenon of sand liquefaction is caused by both negative dilatancy under undrained cyclic loading conditions and an upward flow of water after the earthquake motion. Actually, witnesses have reported that the ejection of liquefied materials continued on Port Island for nearly one hour after the earthquake. Another aspect of soil liquefaction is seismic isolation. Residents of a house in a liquefied area of Nishinomiya City reported that, during the earthquake, their furniture remained upright and they did not feel severe shaking. The reason for this behavior is that the liquefied layer acts as a seismic isolator. Because liquefied soil never transmits shear stresses, a structure lying on a liquefied layer can be isolated from horizontal motion. The same structure cannot however be isolated from vertical motion.

In this paper, observations of liquefaction phenomena are first presented, and then characteristics of liquefaction behavior and ground failure are discussed. Finally the seismic and liquefaction characteristics on Port Island are examined.

OBSERVATIONS OF LIQUEFACTION PHENOMENA

The earthquake's epicenter was 15 km north of Awaji Island, and the hypocenter depth (the seismic source) was 14.3 km below sea level. The duration of the main seismic shaking was rather short, approximately 5 to 10 seconds. The maximum observed horizontal acceleration was 818 gal in Kobe City. Figure 1 shows a map of the peak horizontal accelerations recorded during the earthquake. The estimated maximum distance to the epicenter from a site of liquefaction occurrence, Rmax, for a magnitude 7.2 shock is 88 km (Kuribayashi and Tatsuoka, 1975). Figure 2 shows the distribution of sites where sand boils were observed; all sites being within 90 km from the epicenter. The furthest site where liquefaction occurred is 90 km from the epicenter in Yabashi, Kusatsu City, in Shiga Prefecture. The next farthest site is 88 km from the epicenter in Kawauicho, Tokushima City, in Tokushima Prefecture. This earthquake was characterized by massive liquefaction. Problems were observed even in subsoil profile consisting of decomposed granite, called “Masado,” which had been considered highly resistant to liquefaction. Loose riverbank sand deposits also liquefied as expected, causing damage to levees. The sites observed in these areas correspond to the land reclaimed since 1868 (Fig. 3). A Comparison of Figs. 2 and 3 shows that the occurrence of liquefaction is due to both in-situ geologic conditions and the applied horizontal acceleration. Detailed investigations of these sites are now under-

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Fig. 1. Map of observed horizontal peak acceleration

Fig. 2. Distribution of sites where sand boils were observed
way. In this section, where and how liquefaction occurred at several sites is described.

Port Island

Port Island is an artificial island due south of Kobe’s central business district. This island was constructed in two phases. During the first phase, between 1966 and 1981, a 436 hectare area was reclaimed. In the second phase, the island was then extended southward by reclaiming 319 additional hectare. Figures 4 and 5 show the areas of Port Island where liquefied sand, rocks, and clay were ejected (see JGS, 1996, Photo. 3 and Photo. 21). As can be seen from these figures, the liquefaction spread throughout the island. The island was covered by brown soils; settled 20 cm on average and more than 50 cm in the most severe sections. The liquefaction in the first phase reclamation area was significantly greater than that in the second phase area.

The areas where reclaimed soils were improved by one of several methods, such as sand drain, sand compaction pile, or rod compaction method, are indicated in Fig. 4. Figure 6 shows the geologic cross section between Port Island and inland Kobe City. The sea water depths in the first phase section of the island ranged from 10 to 12 meters, and depths in the second phase section were about 15 to 18 m. The thickness of the first phase reclaimed layer is more than 18 m, and that of the second phase layer is 24 m.

A decomposed granite soil known as “Masado” was used in the first phase reclamation area of Port Island, and sedimentary rock debris of the Kobe Group, which includes sandstone, mudstone and tuff, was employed in the second phase area. Liquefaction occurred in the layer of decomposed granite soil with an SPT N value of between 5 and 10. The liquefaction was severe and many unusual phenomena were observed at various sites.

As shown in Photo. 1, the warehouse and container yard areas on the island were completely covered with sand boils. A pedestrian bridge exhibited an approximately 50 cm settlement gap between the pile foundations and other areas as indicated in Photo. 2. Furthermore, all of the quay walls surrounding the island shifted seaward by about 3 m, and many large cracks appeared on the land side of the walls (JGS Photo. 6). Ejected sand was observed in and around the many cracks.
Rokko Island

Rokko Island, which is east of Port Island, is a reclaimed island which was constructed between 1972 and 1990. It has a 3.4 by 2 km rectangular shape, covering a 580 ha area. Figure 7 shows the distribution of locations where liquefaction was observed on this island. Compared to Port Island, the degree of liquefaction was much less severe, but, along the northern quay wall severe liquefaction did occur. The maximum ground surface subsidence was reported to be 3 m just behind the quay wall, which itself had translated 2 m seaward. There were many deep ground cracks parallel to the wall. The settlement gap between the pile of the Rokko Liner new transit system's foundation and the surrounding ground level was observed to be the same as the gap on Port Island. Figure 7 indicates the improved soil areas; where no significant liquefaction was observed.

Figure 8 shows the geologic section between Rokko Island and inland Kobe City. The sea water depth in the Rokko area was 10 to 12 m before reclamation, the same as the first phase of Port Island. The northern section of Rokko Island was reclaimed first using Masado, and later the southern section was reclaimed using both debris of the Kobe Group and waste fill from construction sites.

Photograph 3 shows the situation of ejected sand and gravel, similar to Port Island, in the container yard located on the southern side of Rokko Island. Cobbles with a grain size larger than 10 cm were ejected on the side of the collapsed crane. The movement of the quay wall surrounding the island and the settlement of the central part

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68

SHIBATA ET AL.

The geological section between Port Island and Kobe City (Reproduced from Kansai Jiban, 1992)

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The geologic section between Port Island and Kobe City (Reproduced from Kansai Jiban, 1992)

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Fig. 6. Geological section between Port Island and Kobe City (Reproduced from Kansai Jiban, 1992)

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The geologic section between Port Island and Kobe City (Reproduced from Kansai Jiban, 1992)
of the island where tall buildings have been constructed was less than that of both Port Island and northern Rokko Island. Photograph 4 shows the sand boils on northern Rokko near one of the Rokko Liner's piers in the same area where an overpass collapsed.

**Man-made Islands in Eastern Hyogo Prefecture**

Construction of the reclaimed lands along the coast of Kobe City began in 1953, and the total reclaimed area in western and eastern Kobe is approximately 530 ha. To the west of Ashiyahama, the four existing reclaimed lands are called Tobu 1 koku or Nadahama, Tobu 2 koku or Mikagehama and Sumiyoshihama, Tobu 3 koku or Uozakihama, and Tobu 4 koku or Fukaehama (see Fig. 2). These reclamations used Masado soils with scattered $N$ values obtained from mountainside housing development sites. The reclaimed lands were later sold to private companies. On these sites, liquefaction also occurred; because of this liquefaction and the resulting movement of quay walls, severe damage to tanks, factories, and machinery was incurred. Natural sand deposits exist along much of the original coastline. Many of the reclaimed areas have a high ground water table, consequently sand boils were observed everywhere.

The man-made islands known as Minami Ashiyahama, Nishinomiyahama, Koshienhama and Naruohama were reclaimed by Hyogo Prefecture using mainly Masado. On these islands, liquefaction of the reclaimed soils and movement of the quay walls resulted in damage to bridge foundations when the foundations moved from their original positions.

Figure 9 shows one liquefaction zone in Koshienhama where a bridge girder from the Nishinomiya Port Bridge of the Hanshin Highway collapsed. Severe liquefaction of Masado occurred in this area (see JGS Photo. 23). In addition, a thin clay layer was found on top of the sand boils. This clay material is a dredged soil used in reclamation and not a natural marine clay.
Low-rise Housing Damage in Ashiyahama

The reclamation of Ashiyahama began in 1969 and was completed in 1975. After 20 years, this great earthquake struck the area. An alluvial clay layer of 3 to 5 m in thickness was deposited just beneath the old sea level, and the total thickness of the reclamation is 13 to 15 m. Figure 10(a) shows the geologic section of this land. The ground water level is 3.5 m below the ground surface.

The fill material used was mainly debris from mountainside construction sites, but as shown in Fig. 10(a) marine sand layer having an N value of approximately 10, exists about 5 m below the ground surface. Figure 10(b) shows the grain size distribution of both marine and mountain sands. The sand which erupted from the ground surface was the marine sand.

Figure 11 shows the zone of liquefaction in Ashiyahama. From the cracks in roads, building foundations, and around utility poles, massive amounts of sand were ejected, and many two story houses tilted and settled differentially. It is said that residents feel ill if their house tilts more than 2 degrees, and some of them had to be evacuated for this reason (see Photo. 5).

The Western Hyogo Prefecture

In western Hyogo Prefecture Wadamisaki, and Hyogo and Nagata Ports are located. The subsoil conditions in these areas consist of river sands and tidal sand banks; which can easily liquefy. The damage to quay walls protected by tetrapods is uncertain, however, all breakwaters exhibited large amounts of settlement. A small tank near the ports tilted, and ejected sand was observed around a large tank in the area.

On the grounds of Kobe Industrial High School, vent fractures with sand and gravel boils were observed. Figure 12 shows the map of liquefaction sites for Wadamisaki. The liquefaction conditions at Kobe Industrial High School are shown in Photo. 6.
Awaji Island and Naruto

As shown in Fig. 2, in the reclaimed lands of Awaji Island, large scale liquefaction was observed along the coastline. Liquefaction was observed on the land side of many quay walls in the island's fishing ports. On northern Awaji Island (Iwaya Matsuyo as shown in Fig. 2), cracking with sand boils was observed in rice fields (Photo. 7). It was also reported that sand boils were observed in one field in Naruto City, Tokushima Prefecture, and also in the coastal areas of Tokushima City.

Other Areas in Hyogo Prefecture

As can be seen in Fig. 2, liquefaction was observed not only in coastal areas, but also inland areas such as Nishinomiya City, Takarazuka City, and Kobe. At the school grounds of Mefu in Takarazuka City near the Chugoku Expressway, sand boils and ejected silt were observed. This site is near the Minami-Kiyoshi Kojinn Fault, a branch of the Arima-Takatsuki Tectonic Line. On the grounds of Nishinomiya High School at Shinike, both sand boils from vent-fracture and 60 cm of settlement were observed. This high school is very close to the Koyo Fault. Along the Koyo Fault, many sand boils were observed in the northern part of Niteko Reservoir and in the Manchi Dani Cemetery.

On the grounds of Nishinomiya Kita High School, at an elevation of 200 m above sea level, sand boils and ground settlement were observed (see Photo. 8). This school is close to the Ashiya Fault. Ejected sand was also found at Aoyama Dai in western Kobe. These four school grounds were constructed on land reclaimed from old ponds. The sedimentary river sands of the Muko River, which flows through Takarazuka and Nishinomiya Cities, were liquefied both in the current and historic river beds.

Osaka Prefecture

Liquefaction occurred in Osaka City, more than 35 km from the epicenter of the earthquake. The south bank of the Yodo River incurred particularly severe damage where a 1.8 km long section of the riverbank levee failed (see Fig. 13 and Photo. 9). The location of this levee is shown in Fig. 2.

Figure 14 shows the sites where sand boils were observed in Osaka City. It is possible that the number of sites may increase after further investigation. Widespread liquefaction was observed in reclaimed lands and alluvial lowlands along the rivers in western Osaka; the liquefaction was particularly severe in Nishi-Yodogawa Ward. Around the Uemachi Plateau, in areas of diluvial deposits such as Chuo Ward and Nishi Chuo,
only local sand boils were observed. In this region, the liquefaction was insignificant. This is consistent with predictions of expected liquefaction phenomena before this earthquake (Shibata et al., 1987). In addition, in southern Osaka Prefecture, sand boils were observed in the coastal areas such as Sakai Senboku.

CHARACTERISTICS OF LIQUEFACTION AND GROUND FAILURE

This chapter describes the engineering characteristics of the subsoil profile where liquefaction occurred.

Liquefied Subsoil and Grain Size Distribution

The effects of this earthquake revealed that a decomposed granite soil (Masado) can liquefy, although gravelly soils have been considered to be generally resistant to liquefaction. Masado was used for reclamation in the first phase of Port Island and also on northern Rokko Island, as well as other reclaimed land areas. Soils containing a gravel component differ in liquefaction strength from natural sands like the Japanese Toyoura Sand.

The soil used for the reclamation was transported by conveyor belt from mountain areas far inland. While the soil was in transit, crushing and weathering altered the grain size distribution to one higher in fines content than the natural material. The source of the material was rock debris known as the Kobe Group, which consists of tuff, sandstone and mudstone. This soil, used for most of Rokko Island and the second phase of Port Island, contains fines and gravels which are easily weathered.

Along the coastline from Nishinomiya and Amagasaki in eastern Hyogo Prefecture to Osaka, at the mouth of several rivers, many loose, fine alluvial sand deposits lie over a thick alluvial clay layer. These soils have a relatively uniform grain size and tend to be easily liquefiable.

Figure 15 shows the typical range of grain size for these three types of soils. Masado has a relatively large grain size; the soils of the Kobe Group resemble Masado but have a higher fines content. Kobe Group soils exhibit a lower liquefaction potential than does Masado. The loose, fine alluvial sands existing along the coast between eastern Kobe and Osaka have a relatively uniform grain size. The soils with this range of grain size have been known for their tendency to liquefy easily in experiments. Figure 16 shows the grain size distribution curve, including coarse gravels smaller than 150 mm.

With this earthquake, Masado underwent liquefaction for the first time. We have seen how the properties of Masado resulted in a somewhat different from normal...
liquefaction behavior, causing increased vent-fracture, less uplift of manholes, and less settlement of heavy structures.

**Liquefaction Strength of Masado**

The degree of liquefaction strength of a soil can be evaluated by cyclic undrained triaxial tests. One of the early studies of the strength of Masado for reclamation was undertaken by Tanimoto in 1974. He investigated the liquefaction potential of Masado. In his tests, grain sizes larger than 4.8 mm were excluded. The relationship between cyclic stress ratio and number of cycles is plotted in Fig. 17.

Recently cyclic tests have been conducted on an undisturbed sample of Masado, excluding grain sizes greater than 2.0 mm. In Fig. 17, the test results for samples of ejected Masado are indicated by dotted lines. For these cases, the cycle of stress ratio seems to be smaller than in the earlier tests. The liquefaction strengths obtained by Tanimoto seem greater than those for the recent tests, but his tests were performed before the Japanese standard for this test was established in 1990. The evaluation methods therefore differ between the two sets of tests. Consequently, the liquefaction strength data obtained by Tanimoto cannot be compared to the recent data for sand under cyclic conditions, even if the applied stress amplitude is identical. Torii and Tatsuoka (1982) reported that Masado exhibits a high degree of negative dilatancy and volumetric contraction during shear, and the liquefaction strength with a relative density of about 90% is similar to the strength of Toyoura sand with a relative density of 70%. This means that Masado can liquefy under very strong earthquake motion.

Tanimoto also evaluated the liquefaction potential for a critical N value of 12 for a 200 gal design earthquake, and 19 for a 300 gal design earthquake. The fact that those soils liquefied during this earthquake is consistent with an N value for the reclaimed layer of about 5 to 10.

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![Fig. 17. Stress ratio of number of cycles](image)

**The Effect of Ground Improvement**

On Port and Rokko Islands, sand drains were used to accelerate consolidation of the alluvial clay layer. The drains were installed following reclamation, penetrating through the reclaimed layer. At the drain locations, it was observed that less significant liquefaction occurred, as indicated in Figs. 4, 5, and 7.

Two reasons can be considered why the reclaimed land with sand drains installed from the ground surface resisted liquefaction. One is that the reclaimed layer was densified during installation of the sand drains, and the other is that the drains in the reclaimed soil.

Ishihara in 1995 reported that N values prior to sand drain installation ranged from 9 to 15, and following installation N increased in value to 10–25. In addition, it was reported in the results of the Port Island and Rokko Island investigations that for both the sand compaction pile and rod compaction methods N values increased to 17 to 31. In addition, the results of this same investigation indicate a relationship between the ground improvement method and the amount of settlement itself; unimproved soil settled 40 to 50 cm, subsoil improved with sand drains settled 10 to 20 cm, and subsoil improved with sand compaction piles exhibited zero relative settlement.

In Fig. 5, the relationship between the ground improvement method used and the incidence of liquefaction on Port Island is shown. Areas (1) in the figure indicate sites where sand drains were installed from the ground surface, just as in the first phase of Port Island's reclamation. Area (2) indicates sites where sand drains were installed through the clay layer from the sea bed via floating rigs. The reclamation for the second phase of Port Island was conducted using a similar material as on Rokko Island, and liquefaction did occur there. The liquefaction was relatively limited to Area (2) shown in Fig. 5. From these observations, it can be concluded that sand drains installed from the ground surface after reclamation prevented liquefaction from occurring.

**Ejection of Gravel**

Because Masado used in the reclamation contains gravel, the ejection of gravel was observed in coastal areas and on man-made islands. Figure 16 shows that the ejecta included gravel and cobbles with diameters as large as 10 cm near the foundation of the crane which fell on southern Rokko Island. On Port Island, the ejection of coarse gravel was observed around the foundation of a highway near Kobe Bridge.

**Ejection of Cohesive Soil**

At two sites, cohesive soil was observed in the ejected soils. At Koshienhama in Nishinomiya City, the ejected soil contained a clayey material. Based on the in-situ investigation, it was found that this material is a dredged marine clay used as a fill during the reclamation.

Figure 16 shows the grain size distribution curve of a material ejected on Port Island (see Fig. 16). In the parking lot of the Portopia Land Amusement Park, a layer of finely graded cohesive soil, ejected with an average thickness of 10 cm, was deposited on top of the ejected sand layer (see Photo. 10). This area is about 1 km long and forms a boundary between the first and second phases of the island's reclamation. It is located to the old breakwater quay of Port Island's first phase construction. This
quay was constructed using the cut-and-fill method. It is believed that the ejected cohesive soil is a marine alluvial clay from a deposit beside the local wall area which had been replaced with sand. One probable explanation for the liquefaction behavior is that the clay material was softened by the earthquake motion and erupted from below the ground surface together with the upward flowing liquefied sand. Another possible reason was that erupted clay is the marine clay used in the reclamation.

Structure of Liquefied Ground

In our field observations, we found several structures of liquefied subsoil: isolated sand volcanoes or boils, grouped sand boils, vent-fractures or cracks and lateral spreading. Typical sand boils resembling a small volcano have been well-known as evidence of a liquefaction event. In the present survey of liquefaction, we observed volcano-type sand boils on the Yodo River's banks and in the Wadamisaki district, among other places. Sand boils from vent-fractures were observed on many man-made islands, such as Port Island, Rokko Island, Ashiyahama (see Photo. 11), Nishinomiyahama and Koshienhama (JGS, Photo. 6, 1996). In order to study

Fig. 18. Sketch of vent-fracture in Minami Park

Photo. 10. Ejection of cohesive soils and Masado at Port Island

Photo. 11. Sand boils in Minami Ashiyahama

Photo. 12. Sand boils and vent fracture at Minami Park on Port Island
the structure of vent-fracture-type sand boils, test pits were excavated at Minami Park on Port Island (see Photo. 12) by the Kobe City Development Bureau. Figure 18 shows a sketch of one vent-fracture in depth. The width of the vent fracture is 2 cm and it was found to be continuous through the sand dike. The fracture plane was filled with a silty sand which might have been used to construct a backfill. The formation of cracking is due to the behavior of the rather well compacted, stiff surface layer, which did not liquefy under the earthquake motion and failed by fracture. When the surface layer is a natural, loosely sedimented sand, the formation of the sand volcano type of liquefaction is most common. The vent-fracture type of liquefaction has been reported by other researchers (e.g. Audemard and de Santis, 1991).

**Lateral Spreading on Man-made Islands**

Lateral spreading is a well known type of ground deformation due to liquefaction. Lateral spreading has been observed on several man-made islands. Figure 19 shows a typical example of the lateral deformation near a quay wall on Port Island. Lateral spreading has previously been associated with many large scale vent-fractures. On Rokko Island, the maximum lateral spreading was 5.23 m and on Port Island, 5.90 m (see Photo. 13).

**SEISMIC AND LIQUEFACTION CHARACTERISTICS ON PORT ISLAND**

At more than 400 stations, strong motion records of Hyogoken-Nambu earthquake were obtained (Fig. 1). The borehole array station installed on Port Island recorded ground motion where the liquefaction phenomenon was observed (JGS, Photo. 5, 1996). Soil profile at Borehole Array Station is presented in Fig. 20 and Table 1. The ground water level is 2.4 m below the ground surface before the earthquake and 3.5 m after the earthquake. In Fig. 4, the location of the array station is shown. For the borehole records, the orientation error of the underground seismometers was specified by using the displacement orbits for each underground level of motion in a horizontal plane. Figure 21 shows the displacement orbits. The main direction of earthquake motion is

![Fig. 19. Lateral displacement of ground near quay wall on Port Island](image)

![Photo. 13. Cracking and soil movement at Port Island observed in second phase construction](image)

![Fig. 20. Soil profile at Port Island Borehole Array Station](image)
about 30 degrees counterclockwise from the north. This direction is rather vertical to the main fault which lies 51–58 degrees clockwise from the north direction. This fact is consistent with the anticipated direction based on the double couple theory of faulting.

On the basis of these investigations it was concluded that the orientation of the seismometer at G.L.-83 m was shifted about 22 degrees counterclockwise in a horizontal plane. Figure 22 shows the acceleration time histories for each depth of seismometers. In Fig. 23, the peak acceleration of the horizontal component decreases on the ground surface due to liquefaction of the Msado reclamation fill. One can notice a drastic change in frequency content during the first strong S-wave phase, around 6 seconds on the time axis (14 seconds on the original time axis) occurred. This is expected due to the softening and liquefaction of the soil. The UD (up-down) vertical mo-

Table 1. Soil profile for Port Island borehole array observation station (Kobe City Development Bureau)

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Soil type</th>
<th>P-velocity (km/sec)</th>
<th>S-velocity (km/sec)</th>
<th>Poisson's ratio</th>
<th>Location of seismometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–2.0</td>
<td>Sandy gravel</td>
<td>0.26</td>
<td>0.170</td>
<td>0.127</td>
<td>G.L.-0.0 m</td>
</tr>
<tr>
<td>2.0–5.0</td>
<td>Sandy gravel</td>
<td>0.33</td>
<td>0.170</td>
<td>0.319</td>
<td>G.L.-16.0 m</td>
</tr>
<tr>
<td>5.0–12.5</td>
<td>Sandy gravel</td>
<td>0.78</td>
<td>0.210</td>
<td>0.461</td>
<td>G.L.-32.0 m</td>
</tr>
<tr>
<td>12.6–19.0</td>
<td>Sand with gravel</td>
<td>1.48</td>
<td>0.210</td>
<td>0.490</td>
<td></td>
</tr>
<tr>
<td>19.0–27.0</td>
<td>Alluvial clay</td>
<td>1.18</td>
<td>0.180</td>
<td>0.488</td>
<td></td>
</tr>
<tr>
<td>27.0–33.0</td>
<td>Alluvial sand</td>
<td>1.33</td>
<td>0.245</td>
<td>0.482</td>
<td></td>
</tr>
<tr>
<td>33.0–50.0</td>
<td>Sand with gravel</td>
<td>1.53</td>
<td>0.305</td>
<td>0.479</td>
<td></td>
</tr>
<tr>
<td>50.0–61.0</td>
<td>Diluvial sand</td>
<td>1.61</td>
<td>0.350</td>
<td>0.475</td>
<td></td>
</tr>
<tr>
<td>61.0–79.0</td>
<td>Diluvial clay</td>
<td>1.61</td>
<td>0.303</td>
<td>0.482</td>
<td></td>
</tr>
<tr>
<td>79.0–85.0</td>
<td>Sand with gravel</td>
<td>2.00</td>
<td>0.320</td>
<td>0.487</td>
<td>G.L.-83.0 m</td>
</tr>
</tbody>
</table>

Fig. 21. Displacement orbits at several depths

Fig. 22. Acceleration versus time histories
Liquefaction is however strongly amplified even when the liquefaction occurred.

Figure 24 shows the distribution of $N$ values (number of Blow counts) in SPT tests before and after the earthquake. Due to the occurrence of liquefaction and the outflow of pore water, reclaimed soil was compacted and consequently the $N$ value increased. The results of P-wave and S-wave velocity investigations before and after the earthquake are shown in Fig. 25. From this figure, a significant increase of shear wave velocity cannot be seen in the soil layer.

An increase in water pressure of about 173 kPa in the alluvial sand layer was recorded 14 min after the earthquake at a depth of 37 m just below the alluvial clay layer.

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![Fig. 23. Distribution of peak ground motions](image)

![Fig. 24. Distribution of $N$ value before and after earthquake](image)
in the second phase construction area of Port Island. The value of the increase of pore water pressure corresponds to about 49% of the initial vertical effective stress. The value of the increase of pore water pressure corresponds to about 61% of the initial vertical effective stress at the same alluvial sand layer (G.L.-32 m) of the Borehole Array Station. In addition to the in-situ investigation, we have carried out a numerical analysis of liquefaction using a cyclic elasto-plastic model and Biot type two phase mixture formulation (Oka et al., 1994). The numerical results (Oka et al., 1996) indicates that the soil layer above a depth of 20 m and the soil layer at a depth of 33 m were liquefied. This result agrees well with the above observation.

CONCLUSIONS

Based on the investigation of the liquefaction and related damage to civil structures caused by the 1995 Hyogoken-Nambu earthquake, the following main conclusions were drawn.

1. Massive liquefaction was observed on man-made islands constructed from Masado, a kind of weathered granite, particularly at Port and Rokko Islands.
2. It was confirmed that Masado, a weathered granite soil with a rather homogeneous grain size distribution, is vulnerable to liquefaction. In addition, ejected gravels and cohesive soils were also observed.
3. Extensive liquefaction occurred in ground reclaimed from the sea and old ponds and in sand deposited during the Holocene period.
4. From the borehole array strong seismic motion records at one site where liquefaction was observed, it was found that: the ground was subjected to a very high acceleration of greater than 500 gal, the magnitude of the horizontal acceleration components dropped near the ground surface, and the period of horizontal seismic wave increased because of the softening and liquefaction of the soil.
5. In subsoil improved with the sand or rod compaction pile and sand drain methods, liquefaction was less significant. In particular, even the sand drain method seems to have been effective in preventing liquefaction.
6. Several types of liquefaction effects were observed, such as sand volcano-type boils, aligned sand boils and vent-fracture type structures.

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