7. CASE STUDIES ON EFFECTIVE COUNTERMEASURES OF FOUNDATIONS AGAINST LIQUEFACTION AND LARGE GROUND DISPLACE-MENT

The liquefaction and its induced large ground displacement caused significant damage to foundations of buildings, bridges and various kinds of industrial facilities. However, some foundations proved to have resisted against the liquefaction and large ground displacements during the earthquake. The authors investigated the structural characteristic such foundations in order to pursue effective countermeasures of foundations in liquefiable ground.

7.1 Foundations of Facilities of Sewage Plant

(1) Higashi-nada Sewage Treatment Plant

As mentioned previously, a large number of the foundations of the facilities of the Higashi-nada sewage treatment plant were severely damaged due to liquefaction and its induced ground displacements. However, some facilities and buildings survived without any damage or with very slight damage even in the area where the ground moved 2-3 meters in the horizontal direction.

Figure 29 shows a plan of the sewage plant, and three ranks of differential settlements of the buildings and the facilities of the plant. It can be found that not only the structures close to the canal but also those away from the canal suffered large differential settlements. Furthermore, it should be noted that deferential settlement of some structures located along the canal is very small, although the surrounding ground largely moved towards the canal. It seems that the distance of a building from the canal did not have a direct influence to the degree of differential settlements. For an example, differential settlement of the storage tanks located in northern-east corner of the plant varies into three ranks. It is also noteworthy that a half part of the control building caused a large differential settlement, but another half part hardly suffered any settlements. The result shown in Figure 30 seems to give us an instructive information to consider effective countermeasures of foundations against liquefaction and its caused large ground displacements.

Figure 30 shows a cross section along the A-A' line in Figure 29. It is clear that differential settlement of structures with an inground portion is smaller than those of structures without any inground portion. The half part of the control building, which has no basement suffered large differential settlement, but another half part of the building with a basement did not induce any settlement. It is also interesting to note that the magnitude of differential settlements of the tanks depends on the depth of their inground portions.

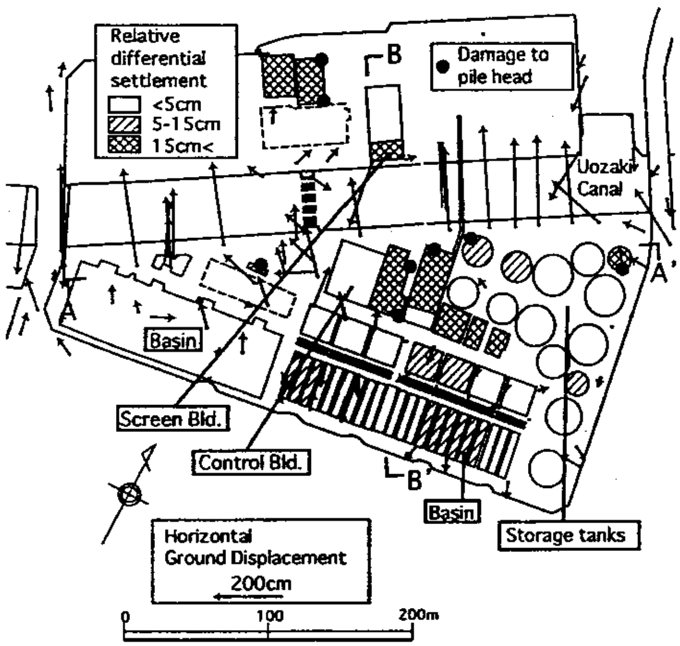

Figure 29. Plan of Higashinada Sewage Treatment Plant showing ranks of differential settlement and horizontal ground displacement

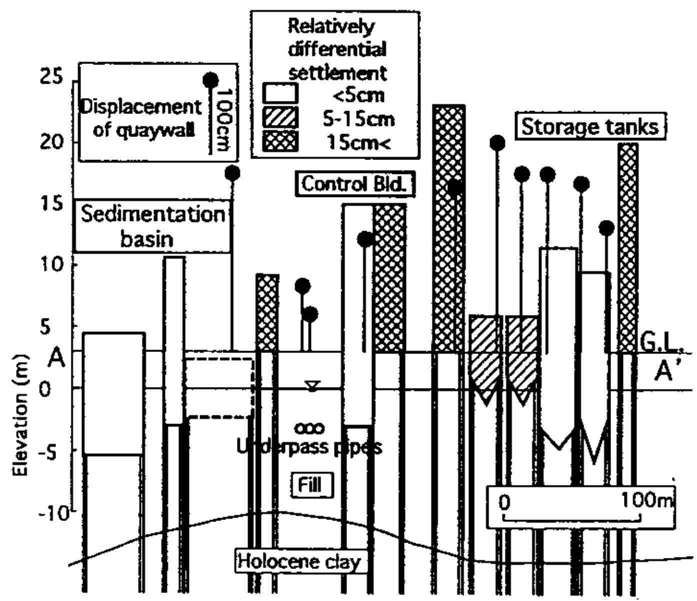

Figure 30. Depth of foundations and ranks of differential settlement of structures along A-A' line

Figure 31 is a cross-section along B-B' line in Figure 29. This figure also shows that the scale of differential settlement is depended on the depth of inground portion of structures. A building (Screen Building in Figure 31) along the canal consists of two parts. A large differential settlement above 15 cm was observed in a part without any basement, while no differential settlement was found in another part with a basement.

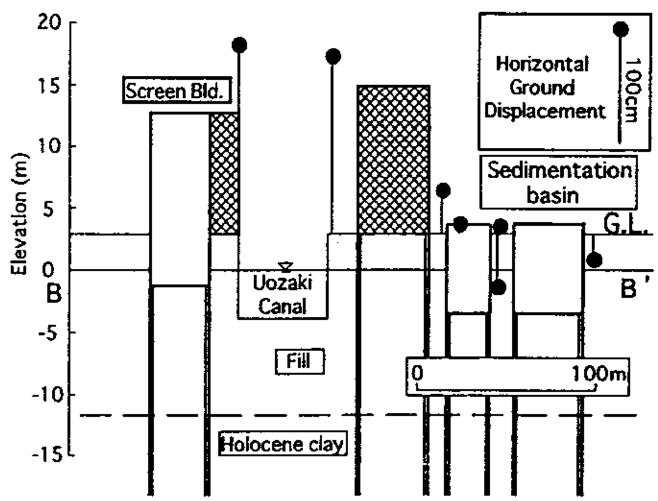

Figure 31. Depth of foundations and ranks of differential settlement of structures along B-B' line

Figure 32 shows a relationship between the so-called Aspect Ratio and differential settlements of the structures. The Aspect Ratio r_a is defined as follows;

$$r_a = \frac{h}{\sqrt{A}} \tag{1}$$

where, A and h are area of foundation and height of structure, respectively. The result in Figure 32 also clearly illustrates that the existence of the inground portion has a great influence to reduce differential settlements of the structures.

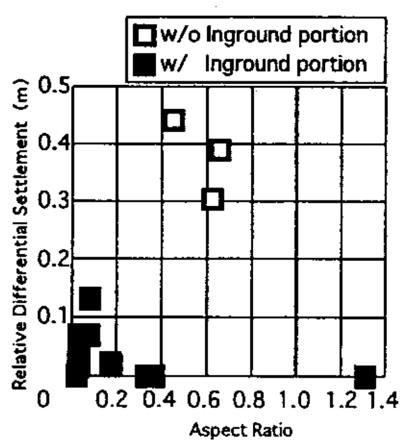

Figure 32. Relationship between differential settlement of structure and aspect ratio

(2) Shimagami Pumping Station

The Shimagami pumping station located along a shoreline at Nagata ward in Kobe City. The distance of the building from the quaywall is only 8 meters. As shown in Figure 33 the quaywall moved towards the sea at a maximum about 3 meters, and consequently the ground behind the quaywall displaced toward the sea. However, the building of the pumping station with a height of about 16 m hardly suffered any damage, besides the surrounding ground subsided more than 1.0 meter. This building has a basement about 8 m deep for northern half of the building and about 11 m for southern half, and is supported by cast-in-place concrete piles of diameters of 1.0-1.5 meters as shown in Figure 34. An inground wall, named as SMW (Soil Mixing Wall), with a width of 45 cm, was built for the excavation of the basement. This inground wall remained after the construction of the building and surrounded the concrete piles. It can be guessed that the existence of the inground wall had a great influence to prevent damage to the foundation piles, in addition to the existence of the basement.

The liquefaction around the building caused a large settlement of the ground surface. Photo 59 shows ground subsidence and top of the inground wall, which appeared after the earthquake.

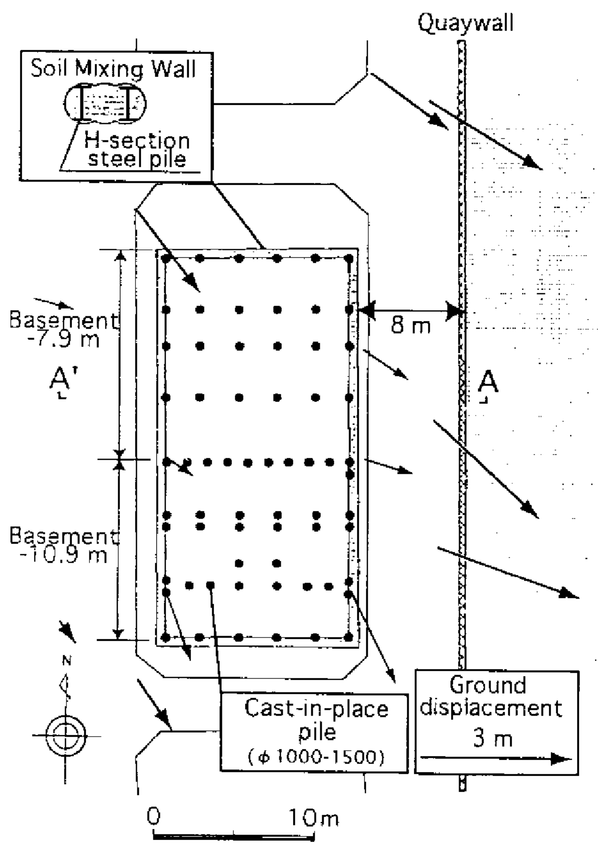

Figure 33. Plan of Shimagami Pumping Station and liquefaction-induced ground displacement

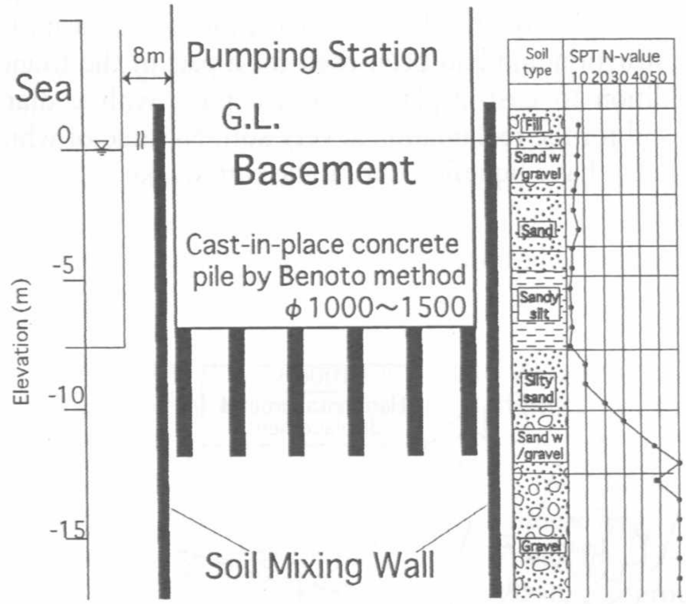

Figure 34. Cross section of Shimagami Pumping Station

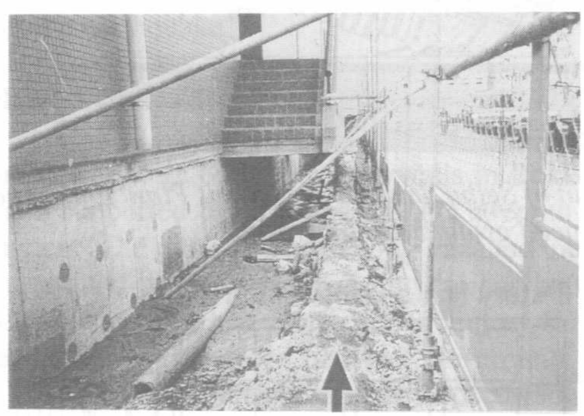

Photo 59 Inground wall of Shimagami Pumping Station, which appeared after the earthquake due to ground subsidence

(3) Seibu Sewage Treatment Plant

The Seibu Sewage Treatment Plant locates at Nagata Port in Kobe City. Figure 35 shows a plan of the plant, which was constructed on a ground reclaimed from the sea and the depth of the reclamation is about 10 meters. The plant has three sedimentation basins as shown in Figure 35. In two among them (A and B in the figure) large separations were observed at concrete casting joints after the earthquake, but any damage could not be found in another basin (C). This basin was constructed closely to quaywalls, and the quaywalls moved toward the sea about 2 meters during the earthquake.

As shown in Figure 36, the above ground portion of the structure is used for an office floor, and the basement has two stories, about 6 meters deep, much deeper than that of another two basins. Furthermore, a concrete inground wall, originally built for the excavation of the basin, had remained after the construction and had been used for a part of the foundation of the basin, in addition to cast-in-place concrete piles with a diameter of 1.5 meters. The soil for the reclamation is very soft, N-value of which below 10, and is assumed to have liquefied during the earthquake.

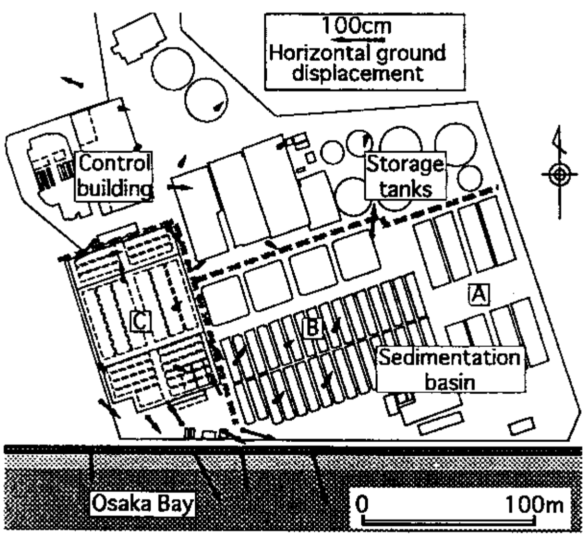

Figure 35. Plan of Seibu Sewage Treatment Plant and liquefaction induced ground displacement

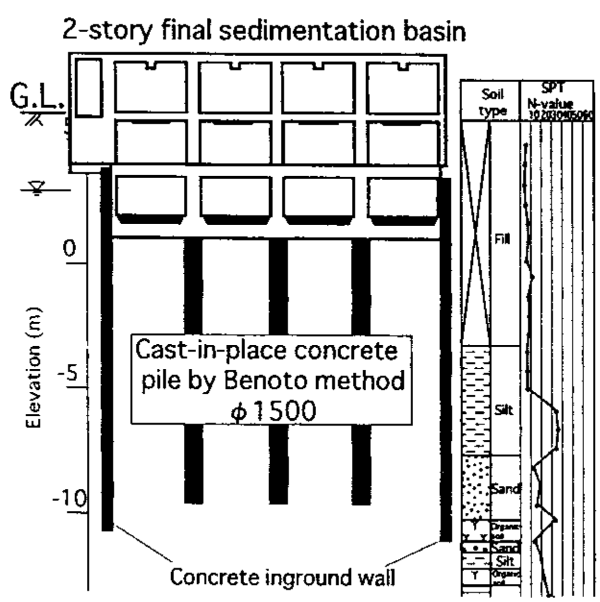

Figure 36. Structure of foundation of sedimentation basin (c)

7.2 Foundation of Buildings

(1) Foundation of the Oriental Hotel

The Oriental Hotel shown in Photo 60 located on the Central Pier of Kobe Port, and has 60m height above ground surface. The quaywalls in front of the building moved towards the sea and subsided shown Photo 61. The hotel building was constructed on cast-in-place concrete piles of about 1.0 meters in diameter and about 30 meters in length. The thickness of the reclamation is about 12 meters and the foundation piles reached into a firm Pleistocene gravel layer.

It was reported that at the stage of the structural design of this building, lateral flow of the liquefiable soil beneath the building towards the sea was considered to seriously affect the stability of the building[26)].Therefore, inground walls was designed and constructed to avoid the lateral flow of foundation ground. As shown in Figure 37, the inground walls, consisted of continuous cast-in-place piles of 1.0 meters in diameter and 12-19 meters in length, were constructed by mixing cement slurry into the ground, and the wall reached into non-liquefiable soil layer through the reclaimed liquefiable layer. It was reported that this hotel building did not suffer any structural damage and any settlement, and that no trace of the liquefaction was found on ground surface under the building, when the foundation was excavated after the earthquake[26)].

(2) Warehouses with friction pile foundation

Three warehouses were built near quaywalls in Rokko Island as shown in Figure 38 and supported by prestressed high strength concrete piles 40-50 cm in diameters. The piles 12 meters long installed into drilled holes and bounded to the ground by casting gravel into the gap between the piles and the drilled holes. The piles had many nodes and as shown in Figure 39, which induced large friction force between the ground (so-called nodular friction pile). During the earthquake sand boils occurred nearby ground and the quaywalls in front of the warehouses moved horizontally by 3-4 meters as shown in Figure 38. All of warehouses, although located about 30 m from the quaywalls, sustained no damage to the pile foundations as well as super structures[27)]. This is probably due to the compaction effect during the pile driving as well as drainage effect of the gravel around the piles in addition to flexibility of the piles. Similar examples of good performance of nodular friction pile foundations against large ground displacement were reported at Pier No. 2 of Maya Wharf and northwestern corner of Port Island[27)].

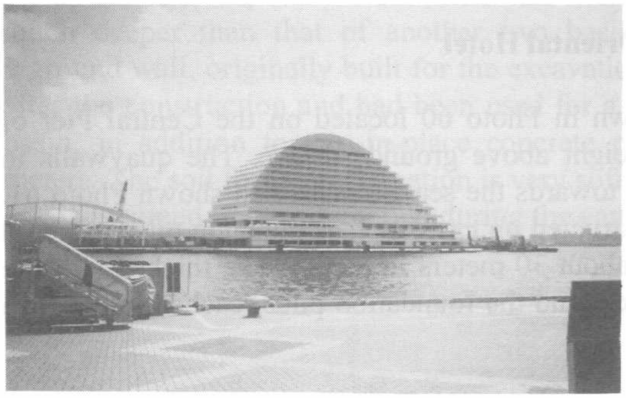

Photo 60 Oriental Hotel on Central Pier of Kobe Port

Photo 61 Ground in front of the hotel moved towards the sea and subsided

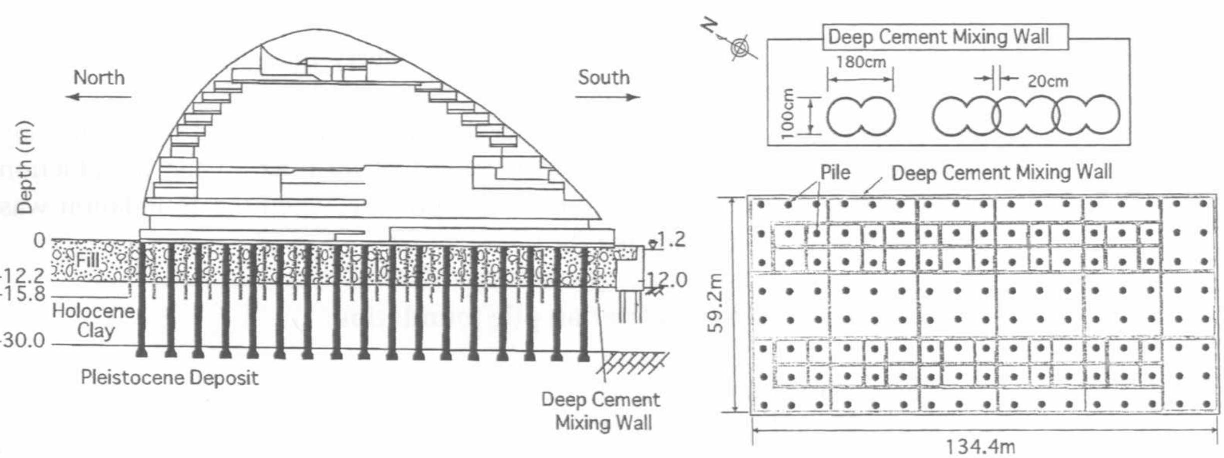

Figure 37. Section and plan of foundation of Oriental Hotel

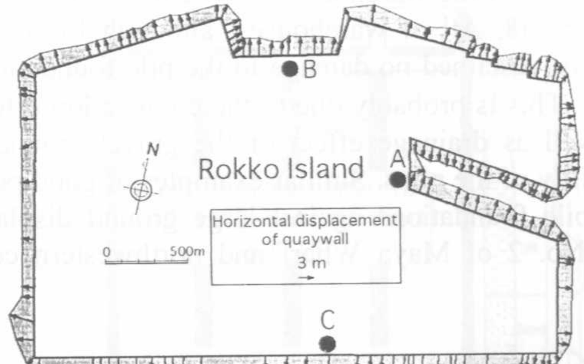

Figure 38. Map of Rokko Island showing displacement of quaywalls and locations of the warehouses

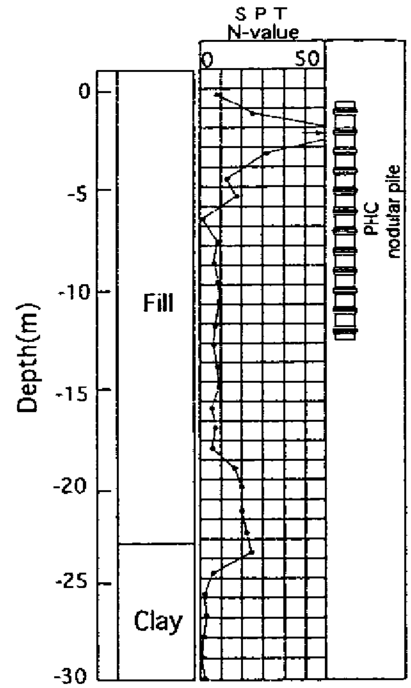

Figure 39. Soil Profile at Site A in Figure 38

8. CONCLUSIONS

Based on the investigation into the liquefaction, its induced ground displacement and performances of various kinds of structures in the 1995 Hyogoken-nambu earthquake, the following conclusions are obtained:

1. Extensive soil liquefaction occurred in huge areas within 50 km from the epicenter, however, liquefaction was also sporadically observed in extents from 50-90 km from the epicenter.
2. Most of the soil liquefaction occurred in ground newly reclaimed from the sea including two man-made islands. Liquefaction was also observed in Holocene sandy deposits and ground filled ponds.
3. Decomposed granite and Pleistocene and Pliocene deposits used for the reclamation liquefied extensively. Those contain a significant amount of fines and large gravel which had been considered to have high resistance to liquefaction.
4. The soil liquefaction induced large ground displacements in the horizontal direction along the shoreline in the reclaimed lands. Ground displacements were also observed in the inland several hundred meters away from the shoreline.
5. Many structures settled and/or tilted with severe damage to their foundation piles due to liquefaction and/or large ground displacement.

In contrast, structures supported on improved soils sustained little damage although the surrounding subsoil's liquefied.

6. The structures with a basement, inground portion, inground wall such as soil mixing wall, continuous concrete wall, and/or deep cement mixing wall survived with no or little damage. The building supported on nodular friction pile foundation also performed well.

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