4. LIQUEFACTION IN COASTAL REGION

Severe soil liquefaction occurred in extensive areas of reclaimed land in Kobe and its neighboring cities. The soil liquefaction also induced large ground displacement both in the horizontal and vertical directions, which resulted in serious damage to various structures. Identifications of the locations where soil liquefaction occurred were made based on a reconnaissance survey during the past earthquakes. It was impossible, however, to determine the liquefaction areas using such a method, because the region to be investigated was too large and there were many areas that were inaccessible to outsiders such as oil storage base, public and private plants and facilities.

The authors identified the locations of liquefaction effects based on photographic interpretations as well as reconnaissance investigation and drew maps of sand boils, sand volcano and fissures[1]. The survey was carried out along the coastal region extending from Kobe City to the Mukogawa River that forms the borderline between Nishinomiya and Amagasaki cities.

Around 120 aerial photographs taken just after the earthquake were used in the photographic interpretation, the scale of which was 1/8,500. The accuracy of the photographic interpretation of ground failures can not be expressed quantitatively. In the case of ground fissures, however, it is believed that cracks of widths exceeding 15 cm could be discerned owe to the aerial photographs' scale of 1/8,500 used the interpretation.

The results of the photographic interpretation of ground surface failures from the aerial photographs was originally plotted on 1/2,500 scale maps, and they reduced to 1/4,000 scale in Hamada et al. (1995). Figure 4 shows an outline of the liquefied areas in the entire surveyed region. In this figure, the old coastline is also shown based on the topographical maps compiled by the Geographical Survey Institute during 1,908-1,910. It was found that liquefaction concentrated in reclaimed areas, and was particularly extensive in the newly reclaimed areas. Described in the following is the overview of ground failures in the reclaimed land areas.

4.1 Western Kobe

Reclaimed lands extending from Nagata Port to Wadamisaki were filled from 1957-1968 using decomposed granite from the Rokko Mountain as shown in Table 1. The filled lands were provided for the lots for oil storage base, infrastructures such as sewage treatment plant and waste disposal facilities as well as factories. Extensive liquefaction occurred in the reclaimed land areas, resulting in serious damage to various structures as shown in Photo1 for an example.

Liquefaction also occurred on the natural ground around Wadamisaki and causing the ground subsidence and differential settlement of low-rise buildings. Photo 2 shows a three-story building in Wadamiya-dori that sank about 1.1 meters relative to street and tilted considerably. The probable reason for the severe liquefaction effects of natural ground in Wadamisaki is that a thick sandy deposit of sand bar underlay ground surface.

Nos. 1 and 2 Piers of Hyogo Wharf in Photo 3, north of Wadamisaki were built in 1932 and No.3 Pier was in the 1960's, respectively. Significant liquefaction effects were observed in the newer pier, whereas less effects in the older pier. Damage to quaywalls was, by contrast, severer in the older ones. Quaywalls of the Pier Nos. 1 and 2 were completely collapsed and submerged due to the ground movement toward the sea, which resulted in large separation of a warehouse near the quaywall (Photos 4 and 5).

Liquefaction-induced ground subsidence and lateral spreading also occurred around ferry terminal in Harbor Land, causing damage to buildings as shown in Photo 6. In American Park, east of Harbor Land, almost entire area south of National Route 2 was covered with sand boil deposits and the ground near the quaywalls considerably moved toward the sea and partially submerged into the sea (Photo 7). In contrast with severe damage to the quaywalls, damage to the major buildings designed by the current building code appeared slight.

Piers Nos. 1-3 of Kobe Wharf south of central business district of Kobe were built in 1913, Nos. 4-6 in 1937, and Nos. 7 and 8 in the 1950's, respectively. The quaywalls moved considerably toward the sea and partially submerged into the sea, although minor sand boils were observed (Photo 8). Photo 9 shows the settlement of the parking area under the Port Terminal Station recently constructed on Pier No. 4. The foundation ground subsided by 1-2 meters, resulting in significant settlement of the floor slab of waiting room directly above the parking area (Photo 10).

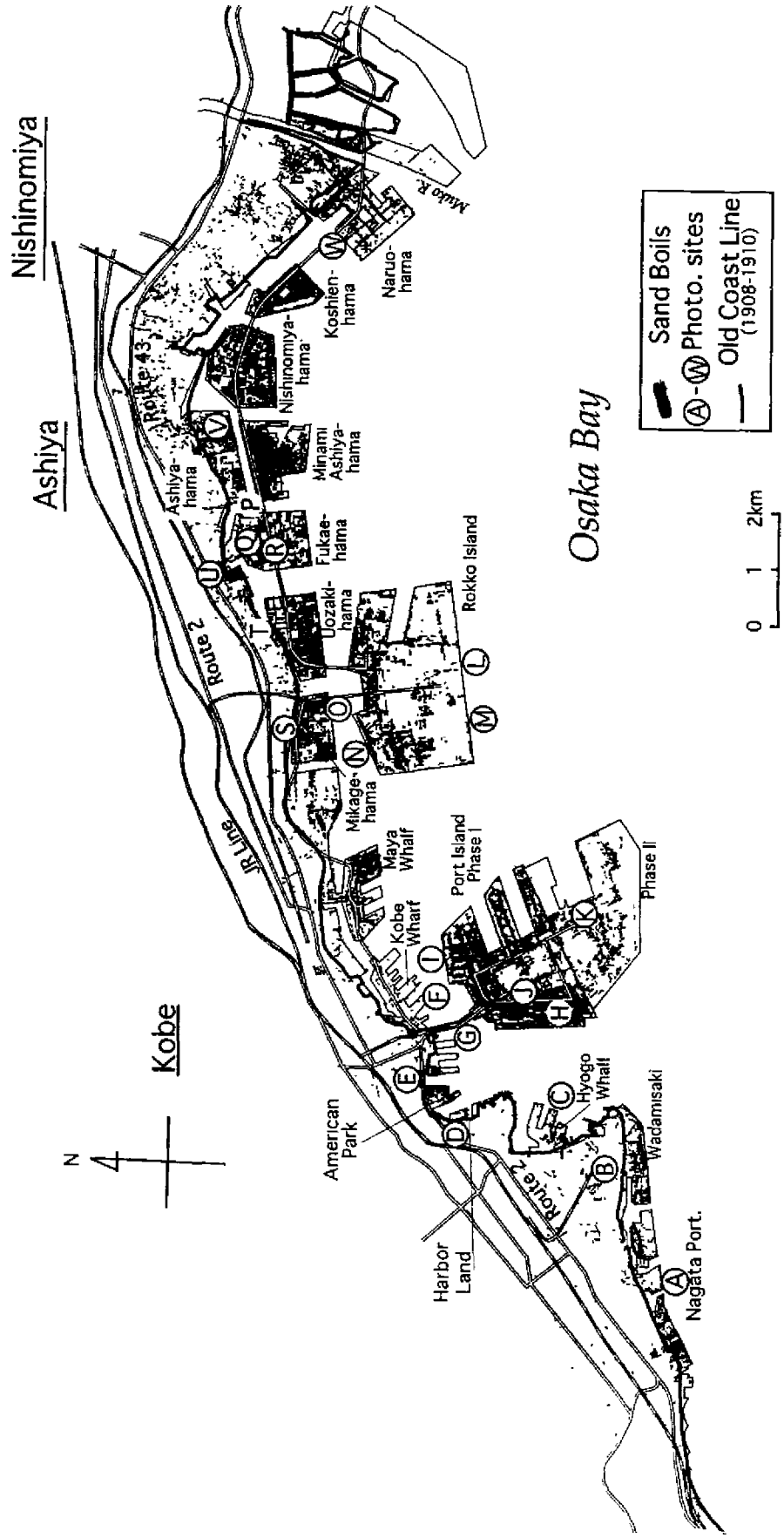

Figure 4. Zone of liquefaction in Kobe, Ashiya and Nishinomiya[1]

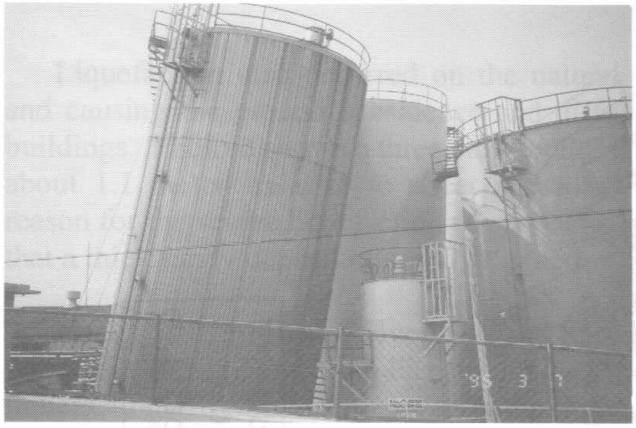

Photo 1 Tilting of oil storage tank (A in Figure 4)

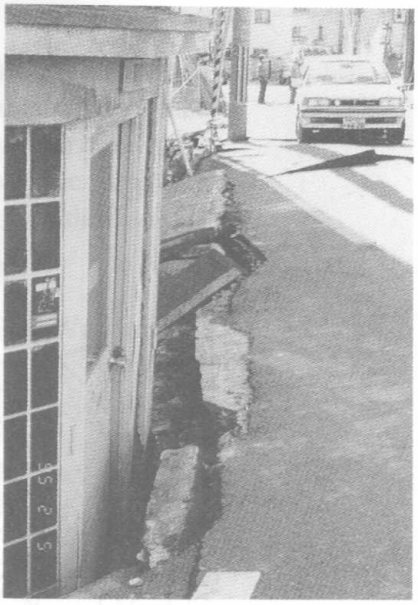

Photo 2 Settlement of building[8] (B in Figure 4)

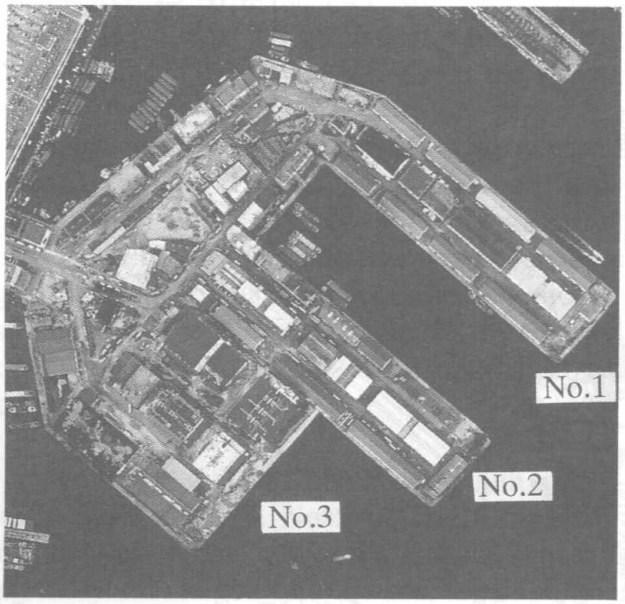

Photo 3 Post-earthquake aerial Photograph of Hyogo Wharf

Photo 4 Submerged quaywall (C in Figure 4)

Photo 5 Separation of warehouse due to horizontal ground displacement (C in Figure 4)

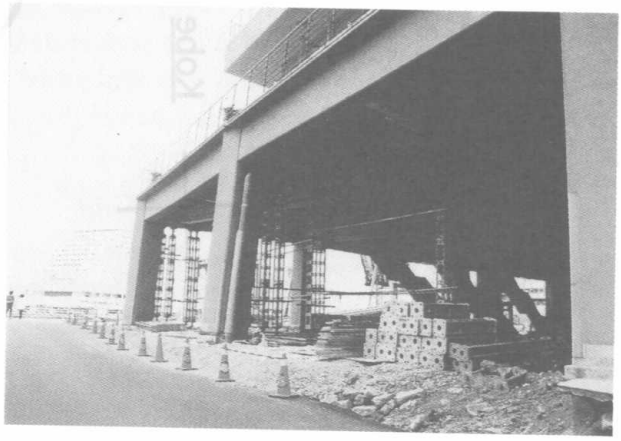

Photo 6 Damage to building due to liquefaction -induced ground displacement (D in Figure 4)

Photo 7 Submerged quaywall northeast of American Park (E in Figure 4)

Photo 8 Submerged Pier No.5 of Kobe Wharf (F in Fig. 4)

Photo 9 Settlement of parking area (G in Figure 4)

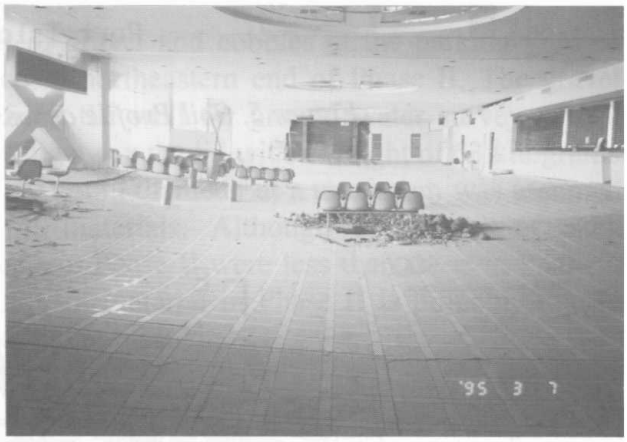

Photo 10 Settlement of floor slab (G in Figure 4)

4.2 Port Island

Port Island is a man-made island due south of Pier No. 4. A 436 hectares area was reclaimed first from 1966-1980 using decomposed granite from the Rokko Mountains to develop a city area in addition to expanding the port facilities. From 1986-1996, the island was then extended southward by reclaiming 319 additional hectare by using mainly crushed tuff, conglomerate, sandstone and mudstone of Kobe and Osaka Groups from western Kobe. Figure 5 shows a typical soil profile across northern part of Port Island (E-E' line in Figure 6). Thickness of the fill overlying soft Holocene marine clay are from 10-25 meters for the northern half of Port Island, called Phase I, and more than 25 meter for southern half, Phase II.

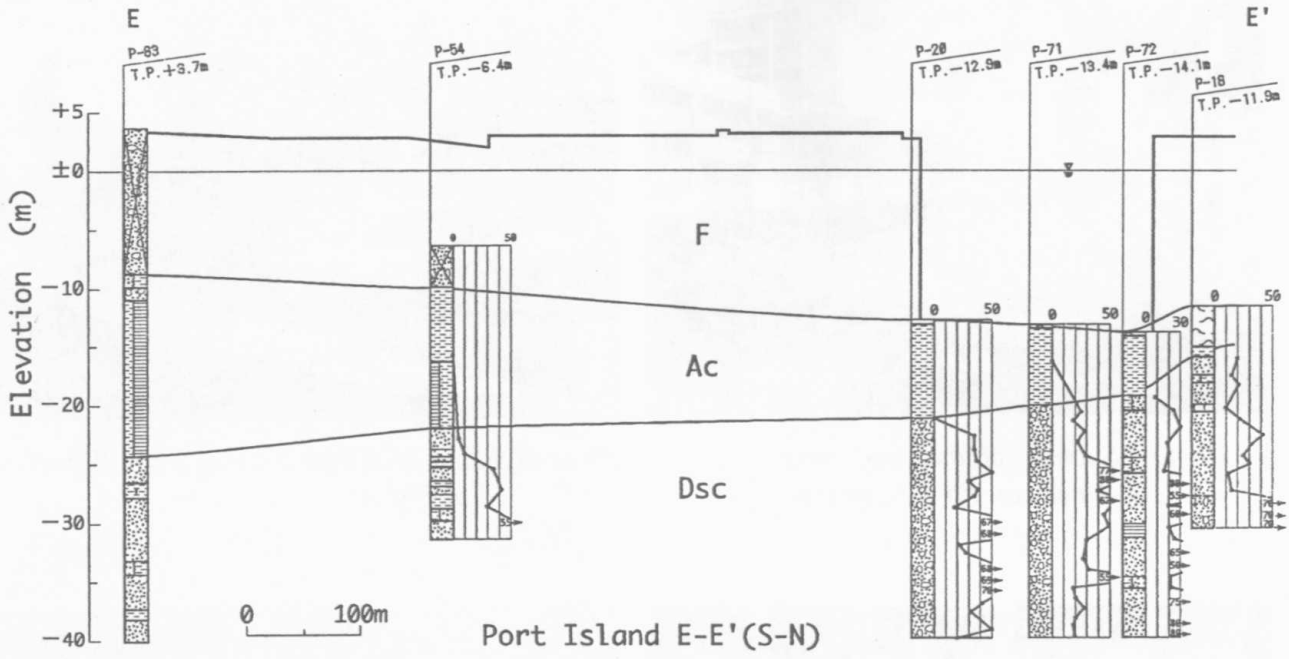

Figure 5. Soil Profile across northern part of Port Island[1)]

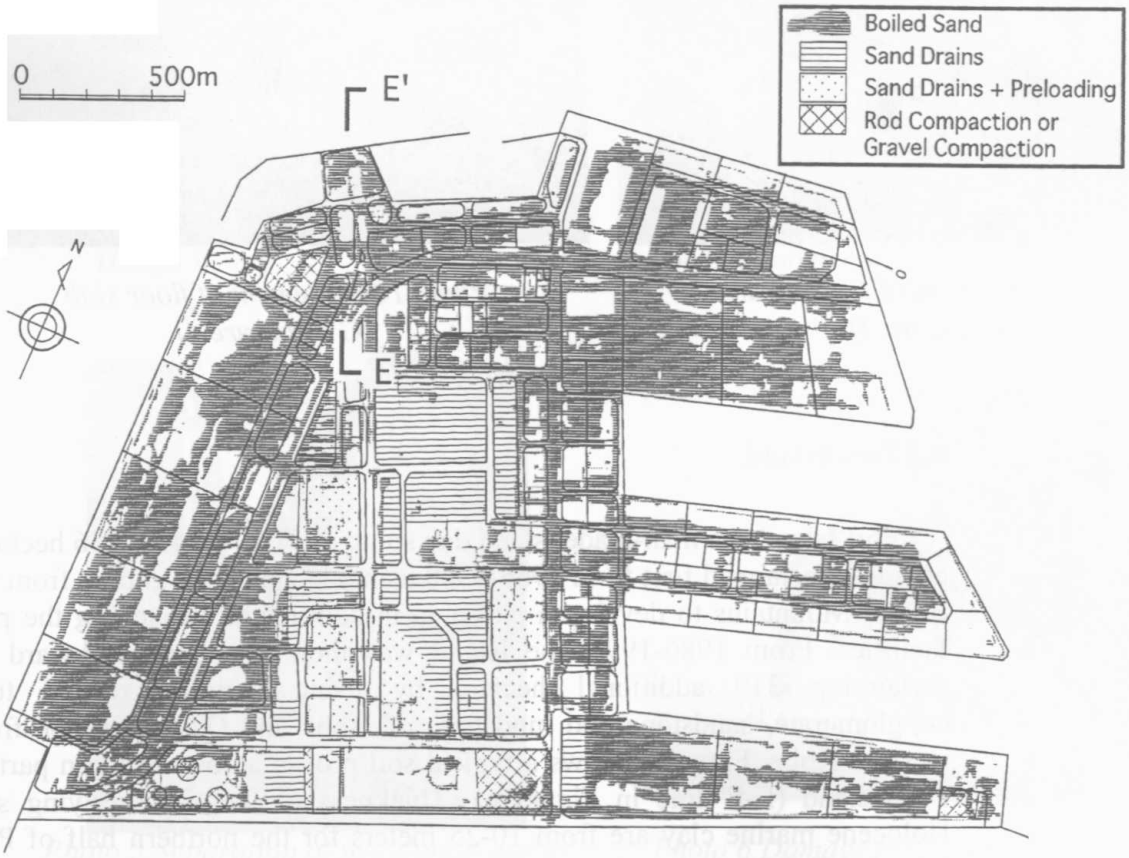

Figure 6. Soil improved area[9)] and zone of liquefaction[1)] in Phase I, Port Island