6. DAMAGE DUE TO LIQUEFACTION AND ITS INDUCED GROUND DISPLACEMENT

6.1 Bridges and embankment

(1) Foundations of Rokko Liner

The "Rokko Liner" is a railway, which is connecting J.R. Sumiyoshi St. in mainland and the Rokko Island. It was reported that many foundations of bridges of the railway moved towards the sea several ten centimeters due to liquefaction-induced large ground displacements. Photo 30 shows that a steel girder of the railway dropped due to movement and inclination of its concrete caisson foundation of a diameter of 6.0 meters and a depth of about 40 meters. The surface ground in the neighborhood consists of fill about 20 meters thick, overlying soft Holocene clay of the original seabed sediment as shown in Figure 11. The foundation was penetrated into the Pleistocene gravel layer at a depth of about 40 meters beneath low the ground surface underlying the soft Holocene clay.

According to an on-ground survey conducted by Kobe City Government the top of the caisson foundation moved about 60 cm towards the sea. As shown in Figure 12, the quaywalls in front of the railway foundation displaced towards the sea, at a maximum about 3.5 meters, and consequently the ground behind the quaywalls widely moved towards the sea. Many ground fissures, about 30-50 cm wide were caused due to the large tensile strain of the ground as shown in Photo 31. The ground in Photo 31 moved towards the sea, from the right to the left, and the ground surface had been originally flat before the earthquake, but largely inclined.

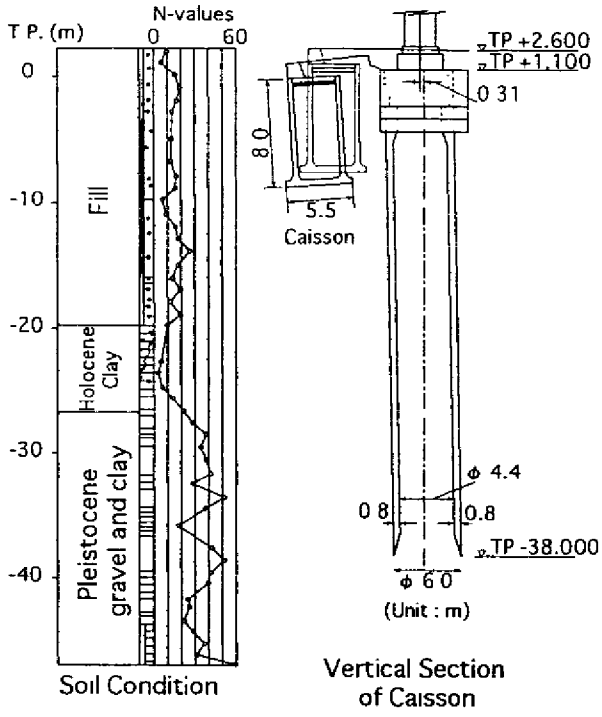

Figure 11. Profile of caisson foundation and soil in neighborhood (Rokko Liner) [19]

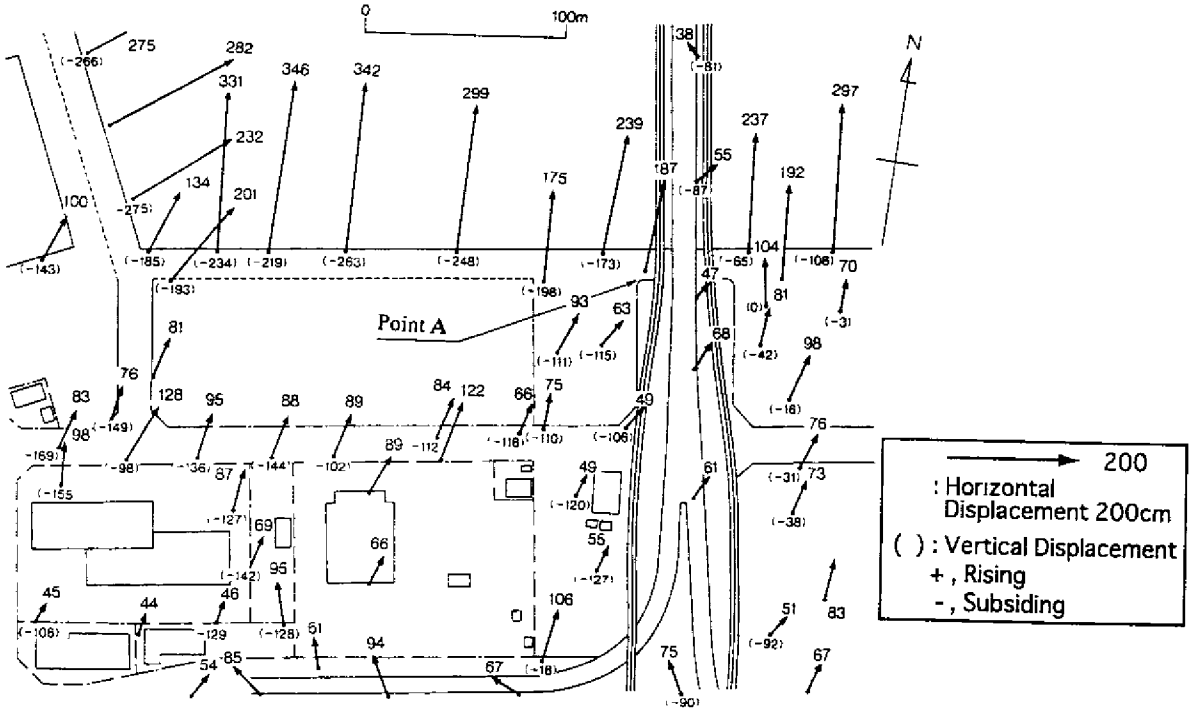

Figure 12. Liquefaction-induced ground displacement on northern part of Rokko Island [1] (At point A a steel girder of the railway dropped)

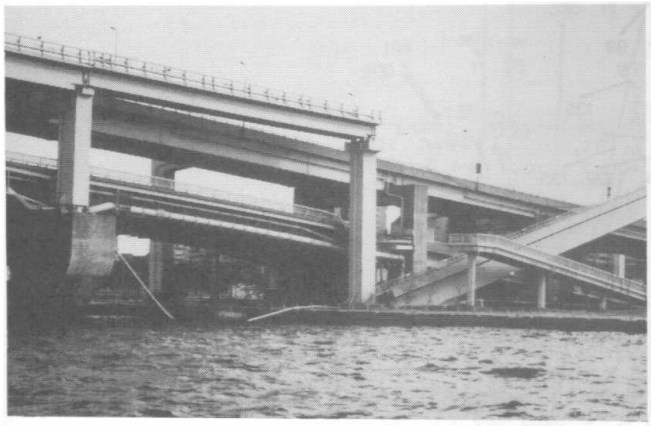

Photo 30 Bridge girder dropped due to ground displacement (A in Figure 12)

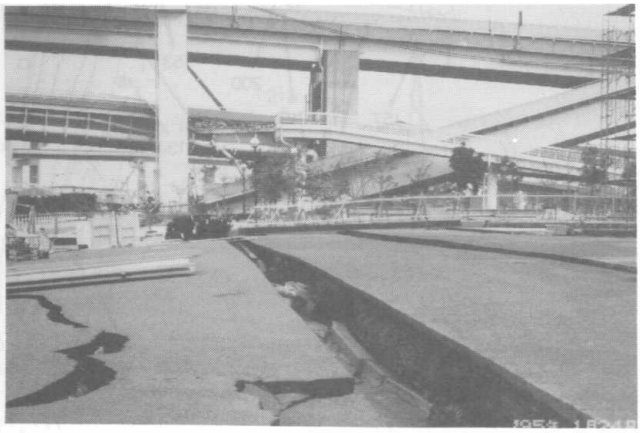

Photo 31 Ground fissure due to ground strain in northern part of Rokko Island

(2) Foundation of an approach to the Kobe Bridge

The Kobe Bridge is connecting the Port Island and No. 4 Pier of the Kobe Wharf in the mainland. The damage to the main span of the Kobe Bridge was reportedly slight, but a spiral shaped steel girder with two stories for an approach to the main span dropped as shown in Photo 32. The pier, seen in the photo moved towards the sea (toward the right direction in the photo) about 1 m according to the authors' aerial survey. Figure 13 shows ground displacements in horizontal and vertical directions measured by aerial survey. The ground of the wharf displaced towards the sea 1-3 meters. The wharf was reclaimed from the sea and the depth of the reclamation was about 13 meters.

Photo 33 also shows an evidence of horizontal movement and/or inclination of a concrete caisson foundation supports the main span of the Kobe Bridge by a movable-bearing shoe. As shown in the photo, about half meters relative displacement was caused between the top of the concrete caisson and the bearing shoe, due to the movement at the top of the foundation.

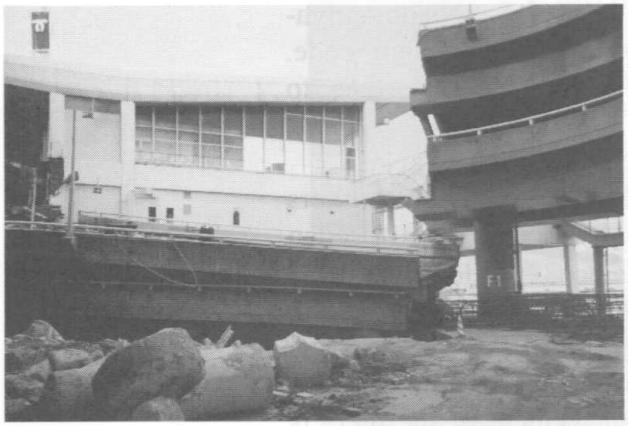

Photo 32 Bridge girder dropped due to ground displacement (A in Figure 13)

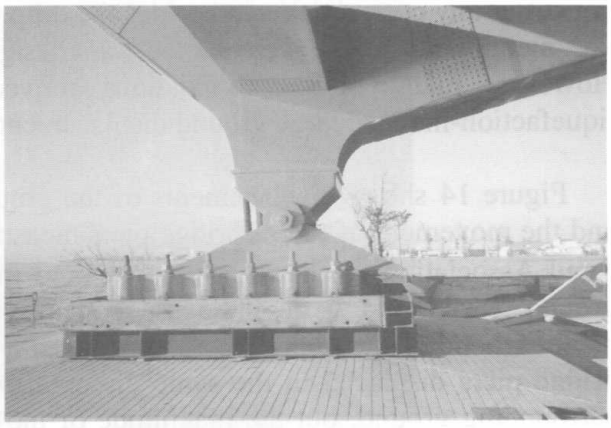

Photo 33 Movement of foundation of Kobe Bridge due to ground displacement (B in Figure 13)

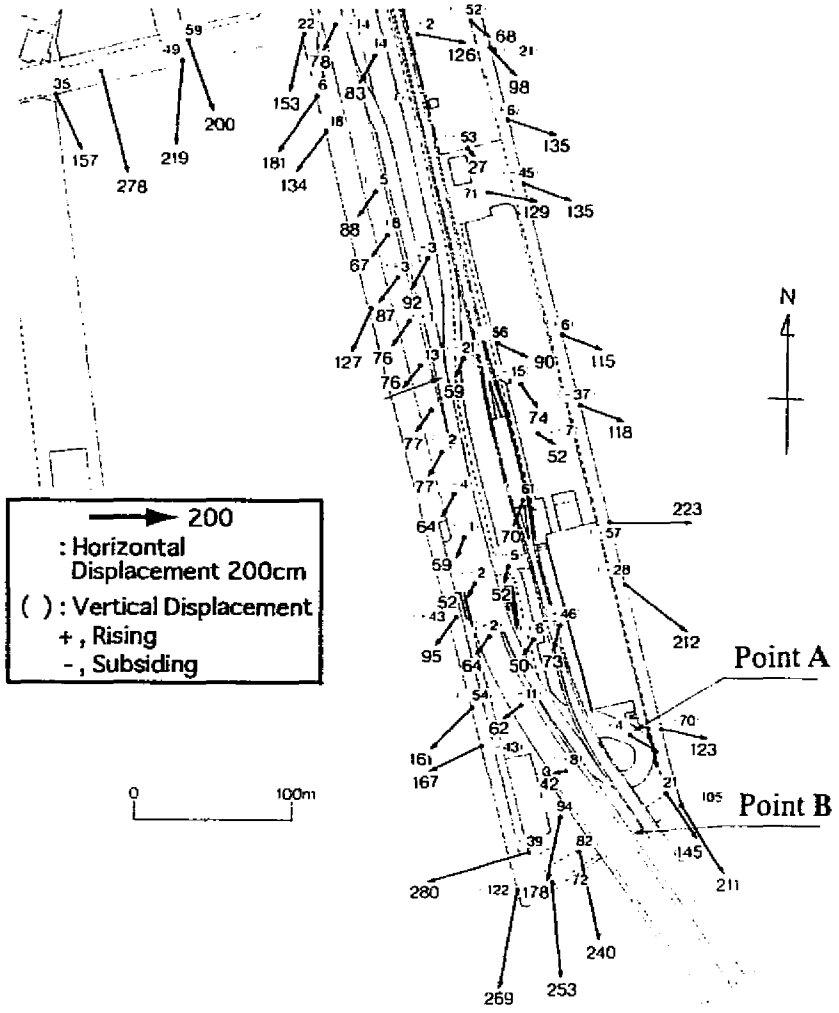

Figure 13. Liquefaction-induced ground displacement at Pier No. 4 of Kobe Wharf[1]

(3) Bridge Piers of No. 5 Bay Highway

The No. 5 Bay Highway is connecting Osaka City and Rokko Island in Kobe City, and was constructed in 1993. The bridges of this highway did not suffer any critical damage besides the drop of the girder at Nishinomiya-ko, mentioned in (4), because it was designed by latest design code. However, many bridge foundations moved and/or inclined due to liquefaction-induced large ground displacements.

Figure 14 shows displacements of the ground measured by the authors and the movement of top of bridge piers measured by a committee of Japan Road Association[22]. The light colored sand in Photo 34 boiled out of the ground surface, and it can be recognized that the ground in the neighborhood of the highway bridge, caused a significant liquefaction. The bridge piers displaced in the same direction with the displacement of the surrounding ground, but the magnitude of the displacement of the piers is smaller than that of the ground. The maximum displacement of the top of the piers was about 90 cm, while the surrounding ground moved about 1-2 meters. These piers have cast-in-place concrete pile.

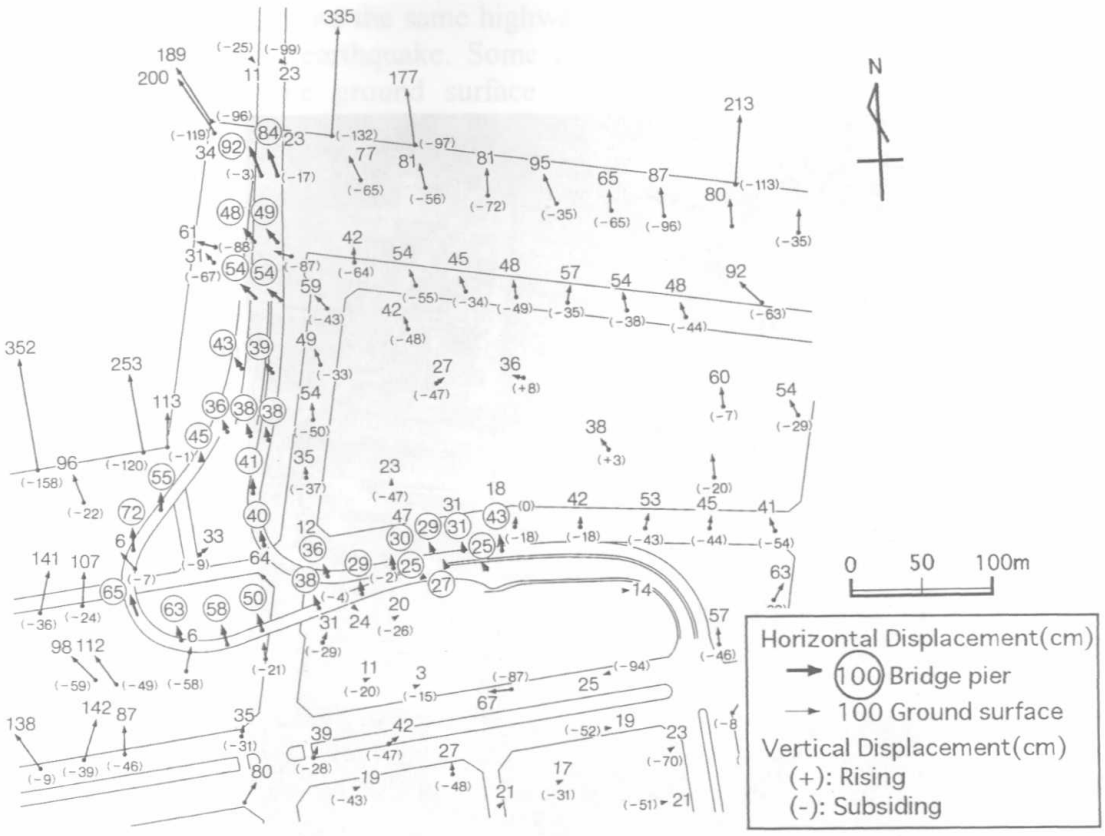

Figure 14. Displacements at ground surface[1] and at top of bridge piers[24] at northern part of Rokko Island

Photo 34 The No. 5 Bay Highway in Rokko Island

Photo 35 The No. 5 Bay Highway in Uozaki-hama

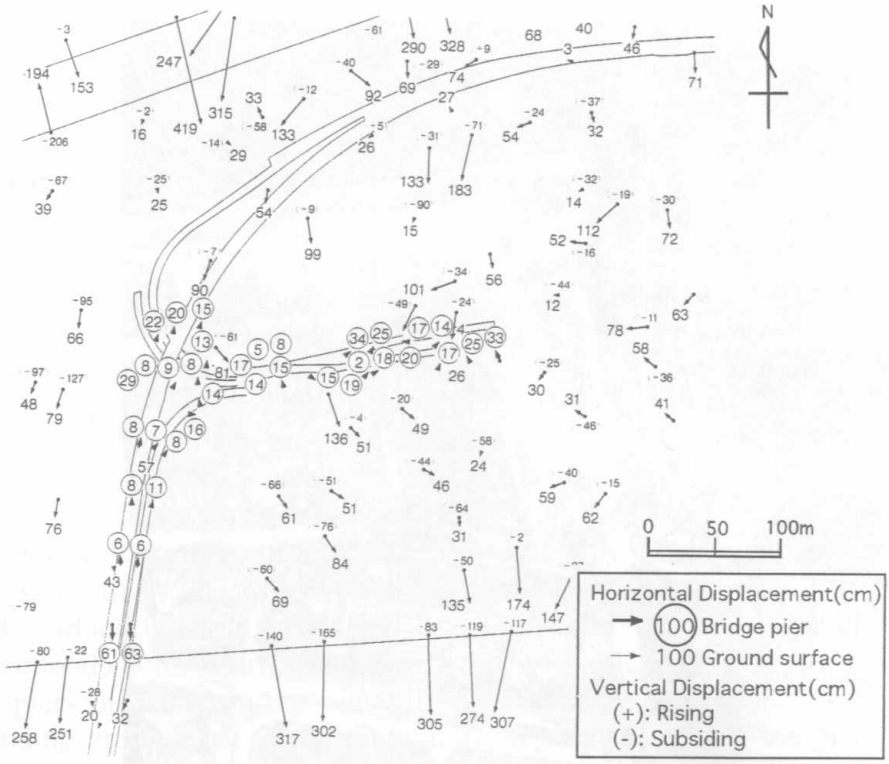

Figure 15. Displacements at ground surface[1)] and at top of bridge piers[22)] at southern part of Uozaki-hama

Photo 35 shows the same highway and it's surrounding area in Uozaki-hama after the earthquake. Some amount of sand boil deposit was also observed on the ground surface. The highway bridges reportedly had inground wall foundations. Figure 15 shows the displacements at tops of the bridge piers as well as at the ground surface, which were measured by previously mentioned investigation groups. Compared with the displacement of the bridge piers in Port Island, which had cast-in-place concrete pile foundations, the displacements of the piers with inground wall foundations in Uozaki-hama are much smaller. This suggests that inground wall foundations are more effective to counter the ground displacements.

Figure 16 is a relationship between the displacements of the bridge piers and those at the ground surface[24]. It can be said that with pile foundations. The result in Figure 16 also suggests that inground walls and caissons are more effective for the foundations in the ground with a high potential of liquefaction and its induced ground displacement.

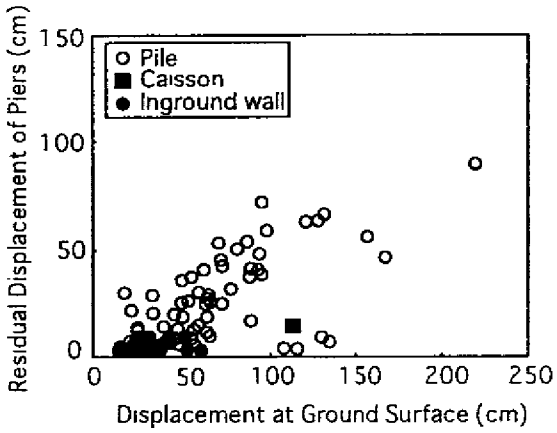

Figure 16. Relationship between the displacements of the bridge piers and those at the ground surface[22]

(4) Foundations of Nishinomiya-ko Bridge of No. 5 Bay Highway

A steel girder of a side span of the Nishinomiya-ko Bridge between Nishinomiya-hama and Koshien-hama dropped from pier as shown in Photo 36. The quaywalls in front of the pier moved towards the sea about 2 meters as shown in Figure 17, and the ground behind the quaywall also moved towards the sea. The ground displacements in the neighborhood of the pier reached above 2 meters. It was reported by a committee of Japan Road Association[22] that a large relative displacement between two neighboring piers, which was combinatorially caused by a permanent displacement of the concrete caisson foundation about 23 meters long due to liquefaction and a dynamic displacement due to the inertia force was the cause of the fall of the girder.

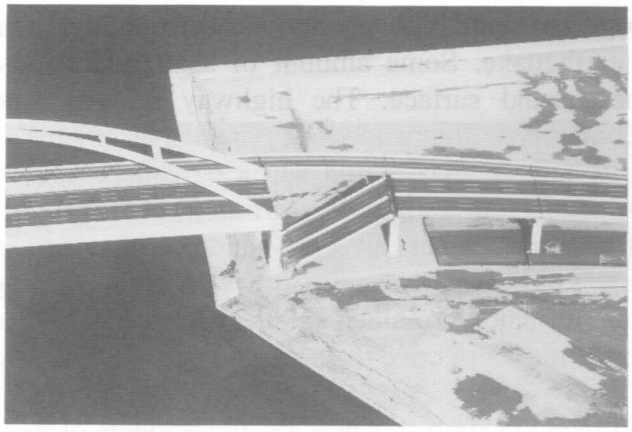

Photo 36 Steel girder of Nishinomiya-ko Bridge dropped due to liquefaction and inertia force (A in Figure 17)

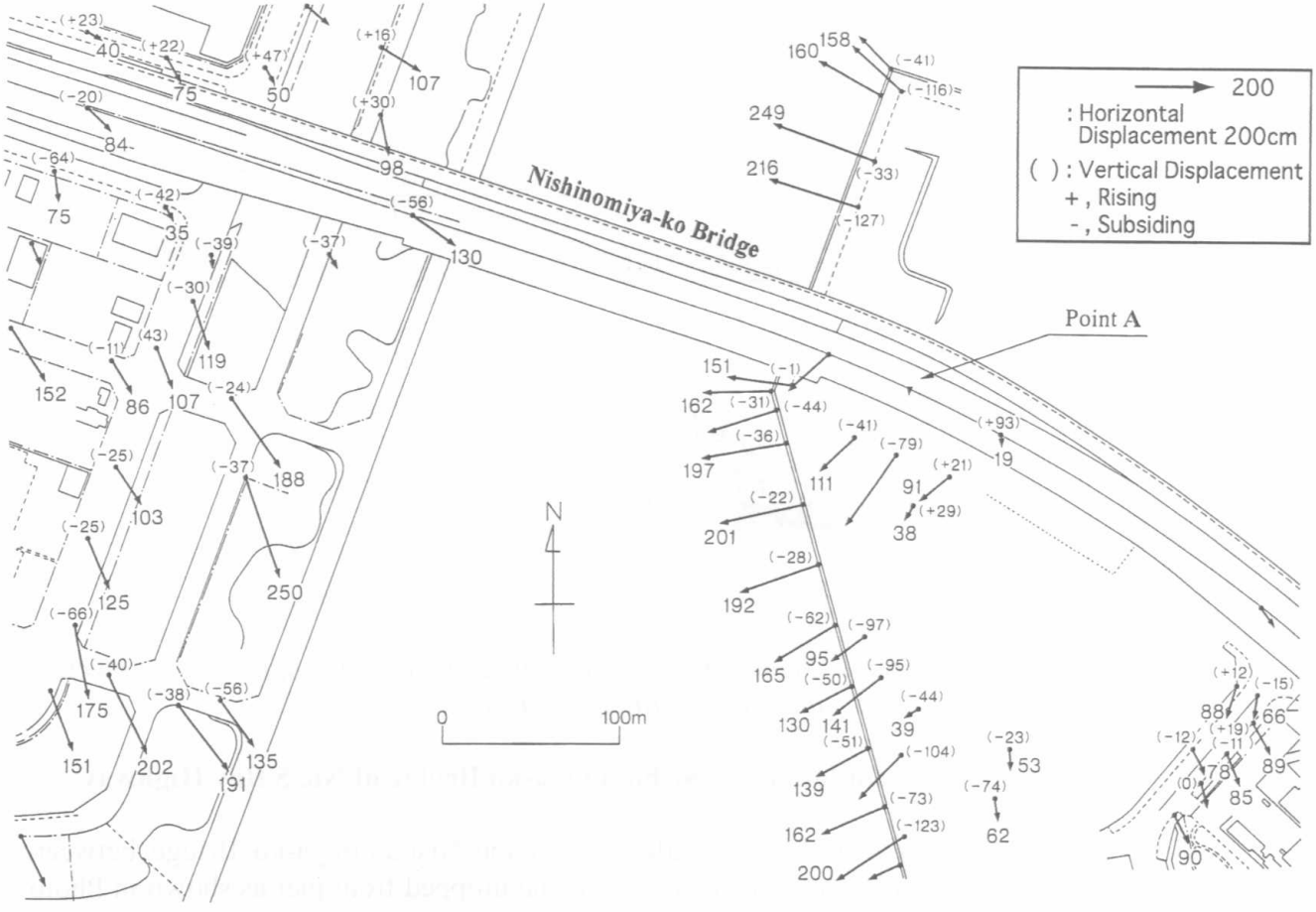

Figure 17. Liquefaction-induced ground displacement at Nishinomiya-ko Bridge[1)]

(5) Movement of embankment of the Miya-gawa River in Ashiya-hama

Figure 18 shows an example of large displacement of river embankments and the ground behind them. Both banks of the Miya-gawa River in Ashiya-hama moved towards the center of the river about 1-2