付録 4 DAMAGE TO HIGHWAY STRUCTURES DUE TO THE HYOGOKEN-NANBU EARTHQUAKE

1. Earthquake and Ground Motion

The Hygoken Nanbu earthquake of Magnitude 7.2 occurred at 5:46 A.M. on January 17, 1995, in Hanshin area - one of the most densely populated areas in Japan, which extends from Osaka to Kobe. The name of the earthquake, which was officially given by the Japan Meteorological Agency (JMA), indicates the location of the epicenter and the fault zone. However, as the extent of the damage caused by this earthquake was revealed by intensive media coverage and investigations following this earthquake, the "Great Hanshin(-Awaji) Earthquake Disaster" is also widely used when referring to this worst natural disaster in Japan since the 1923 Great Kanto earthquake.

This Magnitude 7.2 earthquake was felt throughout the western part of Japan, as well as in Kinki area. The epicenter was located in the Awaji-shima island near the Akashi strait. The identified location of the epicenter by JMA is Latitude = 34.6°N, Longitude = 135.0°E, and the focal depth is 20km.

The fault rupture penetrated to the ground surface in Awaji-shima. The visible ground rupture indicates the fault's right-slip movement, as confirmed by the analysis of the seismic records. The movement of a segment of the Nojima Fault, followed by that of the Rokko fault and others on the Honshu side, is inferred to cause this earthquake; this is also supported by the distribution of hypocenters of aftershocks, see Fig. 1. Although earthquakes of this area were not unexpected to researchers, it was the largest to strike Kobe at a very short distance from fault zones.

The shaking intensity in JMA scale in several regions in the Awaji-shima island, and areas which extends from Sume-ku of Kobe to Nishinomiya, was announced to be 7; that roughly corresponds to shake intensity of IX or more on the Modified Mercalli Intensity scale (MMI). The distribution of the damage to traditional Japanese houses is concentrated in these areas, as shown in Fig. 2. The nature of the soil conditions and topography of the area narrowed by mountains in the north and by coastline in the south seems to be a predominant factor in the regional damage distribution in this earthquake, as well as the extent of the fault zone.

Peak horizontal acceleration of the ground motion exceeded 0.8g in Kobe. One of the ground accelerations, recorded at Kobe Marine Meteorological Observatory in Chuo-ku is shown in Fig. 3. This record also indicates the peak acceleration over 0.8g, and strong shaking lasted only 10 seconds. The acceleration response spectra for the three components of the record are shown in Fig. 1.4. The acceleration response in the range of short natural periods, 0.1 to 0.5 second, exceeds 1.2g, and peaks in the response spectra are found near the period of 0.4 second. These features are consistently characterized by the nature of the earthquake ground motion in the neighborhood of fault zones. It should also be noted that the value at this peak for the NS component is more than 2.5g for 5% damping, as can be seen in the figure.

One of the aspects of the ground motion that attracted wide attention for this earthquake is the high intensity of vertical components; the ground motion recorded at Kobe University campus shows that the UD acceleration was 1.5 times as high as the horizontal components. The extent of the contribution of the vertical acceleration to the heavy structural damage is an issue under debate and is currently under investigation.

2. Summary of Damage

In this section, an overview of the major damages to highway structures by the Hyogoken Nanbu earthquake is given. The major damage locations in the Hanshin area are shown in Fig. 5, indicating that the impact to the transportation system of the Hanshin area was quite extensive and devastating.

(1) Hanshin Expressway, Kobe Route

- Roll-over of concrete girder viaduct in Fukae area, Higashi Nada-ku (Photo 1)
- Collapse of two spans in Hamawaki, Nishinomiya (Photo 2)
- Collapse at Takashio, Nishinomiya (Photo 3)
- Collapse of steel pier at Tateishi Intersection
- Buckling of Steel Piers (Photo 4)
- Buckling of box steel girder at Hamanaka Intersection
- Collapse of Ramp Structure at Minatogawa

(2) Hanshin Expressway, Wangan Route

- Collapse of a side span of Nishinomiya-ko Bridge (Photo 5)
- Failure of bearings and cable anchor of Nishinomiya-ko Bridge
- Failure of bearings and transverse movement of the girder of Rokko Island Bridge (Photo 6)
- Failure of bearings and collapse of the girder of Nagigawa Bridge

(3) Meishin Highway

The upper structures collapsed at two location in Nishinomiya. Two wall-type RC piers failed in Amagasaki. At Mukogawa Bridge, damage of RC piers and beaarings was found.

(4) Harbor Highway

Damage of RC piers, fracture of steel piers, buckling of columns near inspection holes

(Photo 7) were found. RC piers of Second Maya bridge suffered severe damage.

(5) National and Prefectural Highways

- Mondo Viaduct: Collapse of the roadway deck onto a Hankyu Railway line (Photo 8).
- National Highway Route 2, Hamate Bypass: transverse movement of double-deck girders.
- Iwaya Junction Overpass: Collapse of the upperstructure caused by steel pier collapse.

(6) New Transportation Systems of Kobe

Port Island Line suffered damages including failure of RC piers in Chuo-ku (Photo 9), downward displacements of girders, and unseasing of a continuous beam from the bearings. A girder of Rokko Island Line collapsed in the Rokko Island side of Rokko Bridge (Photo 10). Horizontal movement of the pier seems to have caused the damage.

(7) Other Bridges

- Nishinomiya Bridge: Fracture of RC Piers in the middle of the height (Photo 11)
- Kobe Bridge: Damage to bearings and considerable movement of girders

3. Steel Structures

In recent earthquakes in Japan, performance of steel structures has been fairly well due to ductile material properties. However, subjected to the Hyogoken-Nanbu earthquake which has impulse type earthquake ground motion with large amplitude, various types of new damage are found among steel structures. Following are brief summary of the damage.

3.1 Collapse of Steel Bridge Bearings

Steel bridge girders are supported by steel bearings which are sitting on top of piers. Half of them are so called "fixed hinges" which allows only rotation of girder ends. Extremely large and shock-type seismic force worked at the "fixed hinge" and broke them (Photo 12). For repair and retrofit of damaged bridges, more flexible rubber type base isolation bearings are recommended.

3.2 Buckling of Steel Piers

Due to strong earthquake force and, consequently large deformation of steel piers, buckling behavior is observed at the bottom of piers where maximum bending moment is expected (Photo 13). At the most of the buckled part, paint on the surface of piers is off and change of the color is observed. The reason of off-paint seems to be repeated inelastic strain experienced on the flange and web of the piers. So buckling with off-paint can be judged as inelastic buckling which gives more ductile restoring force characteristics. Most of observed buckling are of this type with moderate damage.

However, a few of steel piers collapsed due to breakage of the corner of rectangular section which is caused by excessive buckling (Photo 14). In some steel piers, elastic buckling without off-paint is observed especially around the inspection hole. The elastic buckling may introduce sudden collapse of structural system, which shall strictly be avoided.

Hybrid structural systems with use of both steel and concrete material are recommended to avoid buckling behavior and enlarge deformation capacities.

3.3 Cracks and brittle fracture of steel piers

In a few bridge frame piers, cracks are found at beam-column connection (Photo 15). Complete brittle failure of a steel pier is also observed (Photo 16). The reasons of cracks and brittle failure of steel piers are due to impulse type structural deformation caused by the direct hit by the fault. The damage can be compared interestingly with the cracks at beam-column connections of the buildings observed at the time of the Northridge Earthquake.

4. Concrete Structures

4.1 General Features of Damages in Concrete Structures

Concrete structures in transportation facilities such as highway bridges and elevated parts of railways were seriously damaged during Hyogo-ken Nanbu Earthquake. In Kobe, Ashiya and Nishinomiya areas, these transportation facilities run almost parallel with each other through the narrow area between mountains and bay line, and similar damages were observed in the concrete structures constructed in these areas based on the previous design codes before seismic details were developed for columns.

The damage typically observed in concrete structures is the shear or flexural-shear failure of reinforced concrete (RC) piers. In some cases, this led to the toppling of the elevated parts or the falling down of superstructures. Although these damages were caused by the excessive ground acceleration more than that considered in the past design, it can be said that seismic structural details in order to maintain adequate ductility during severe earthquakes were insufficient compared with those in the present seismic design codes. The damages of RC or prestressed concrete (PC) superstructures, on the other hand, were relatively small, and typical damage is the cracks in concrete at the fixed supports due to large longitudinal deformation.

Here is reported the summary of the damages of concrete structures focused mainly on Hanshin Expressway (Kobe Route 3).

4.2 Highway Structures

<u>(1) Hanshin Expressway (Kobe Route 3)</u>

A large number of single column RC piers in Kobe Route 3 were seriously damaged due to the earthquake. Especially, RC piers in the Fukae Area (Pilz System: RC girders were rigidly connected with the piers) toppled laterally with superstructures almost over 600m. Including these, almost 150 piers were subjected to fatal damage.

Failure modes of the RC piers in Kobe Route 3, which are similarly observed in another highways, are classified roughly into the following three groups. However, most of the collapsed piers are due to brittle shear failure or flexural-shear failure at cut-off zone of longitudinal steels.

a) Flexural or flexural-shear failure at the bottom of pier (Photo. 17)

This failure mode is more ductile than the another two ones described below. In this case, spalling of cover concrete, buckling of longitudinal steels and unfastening of transverse hoops were observed in the bottom of the piers.

b) Flexural-shear failure at cut-off zone of longitudinal steels (Photo. 18)

Many piers were damaged due to this type of failure. Extending cracks were generated in cut-off zone of longitudinal steels due to insufficient transverse hoops and development length of cut-off steels, resulting in the flexural-shear failure. In some piers, rupture of longitudinal steels at the weak weld was observed.

c) Shear failure (Photo. 19)

Relatively short piers often collapsed by shear failure due to large seismic force caused by high stiffness. This type of failure was very brittle and the weight of superstructures could be carried no longer after the failure, resulting in the falling down of girders.

Kobe Route 3 was constructed in the latter half of 1960's. These structures were designed to withstand a horizontal earthquake acceleration of 0.2g and most of the piers had 16mm diameter transverse hoops at the spacing of 20～30cm based on the design code of those days. However, seismic details as for spacing of transverse hoops (especially, in cut-off zone), splices or welding of longitudinal steels and development length of cut-off steels, which are very important to keep adequate ductility during strong earthquakes, are considered to be insufficient compared with the latest design code. This is analogized from the fact that the damage of RC piers in Wangan Route, which were designed based on the latest seismic code, was relatively small and all repairable. In Wangan Route, damages of bearings was predominant due to the displacement of foundations.

(2) Meishin Highway and others

RC piers in Meishin Highway and others (Harbor Highway, National Road Route 2, 43 and so on) were also damaged during the earthquake (Photo.20). The failure mode of the damaged single column piers are almost the same as that observed in Hanshin Expressway. In Meishin Highway, however, a lot of damage of wall-type piers were observed near Amagasaki Area (Photo. 21). In these piers, longitudinal reinforcement buckled outside without crushing of concrete at the end of diagonal cracks.

In addition, a lot of RC columns supporting the subway platforms, for example at Daikai station of Kobe Kosoku Tetsudo Line, collapsed (Photo. 22) and a big settlement more than 2m was caused in the above National Road Route 2.

5. Concluding Remarks

In this paper, damage of highway structures due to the Hyogoken-nanbu Earthquake is briefly described. Failure mechanisms of several bridges are now being investigated, and results will be reported in next papers. Special thanks are given to Professor Kazuyuki Izuno(Associate Professor of Ritsumeikan Univ.), Professor Susumu Inoue(Associate Professor of Osaka Institute of Technoligy) and Dr.Akira Igarashi (Research Associte of Kyoto University) for thier help in making this report.

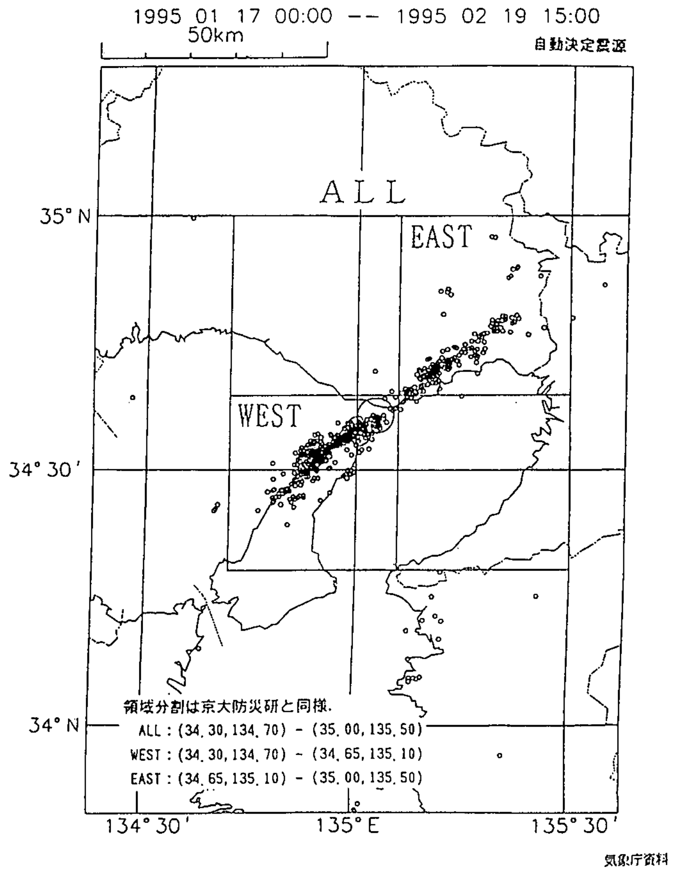

Fig. 1 Location of Main and Aftershock Epicenters by DPRI of Kyoto Univ. and JMA

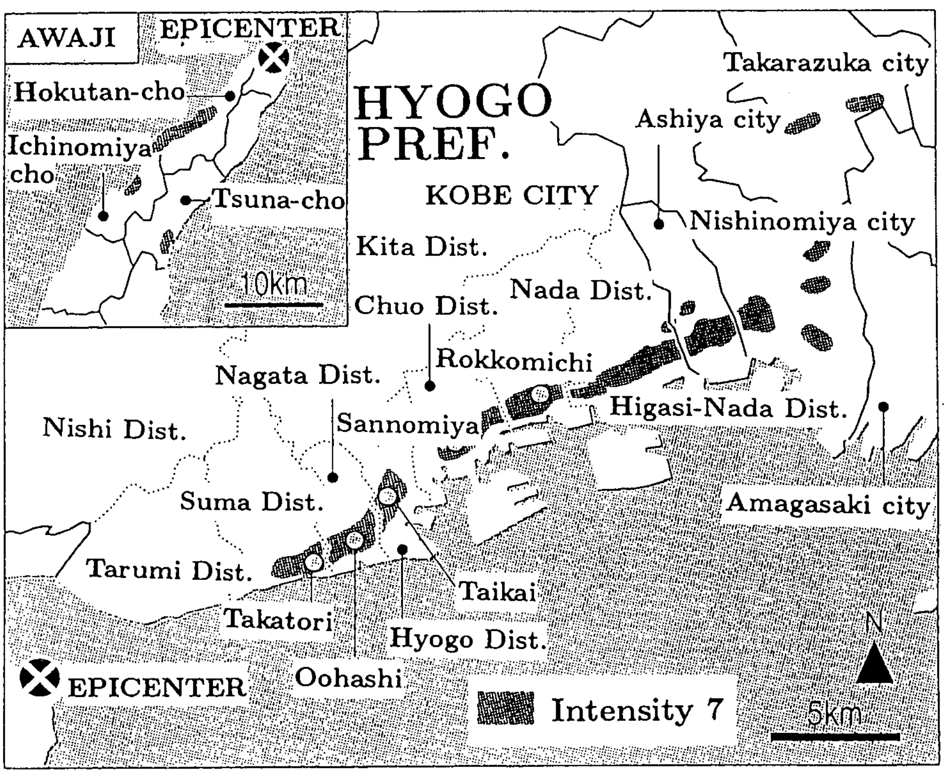

Fig. 2 The Areas of JMA Intensity Scale Ⅶ

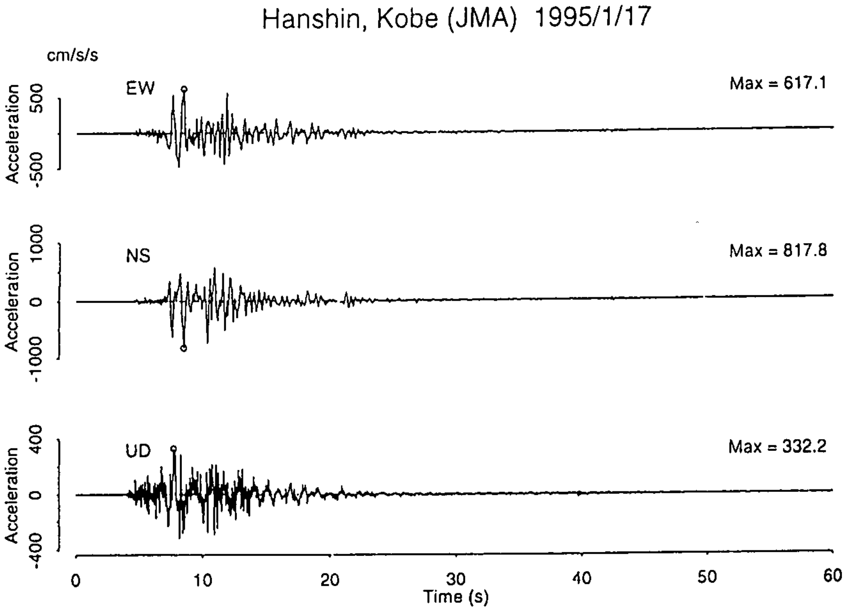

Fig. 3 Earthquake Accelerograms at JMA Observation Station in Kobe

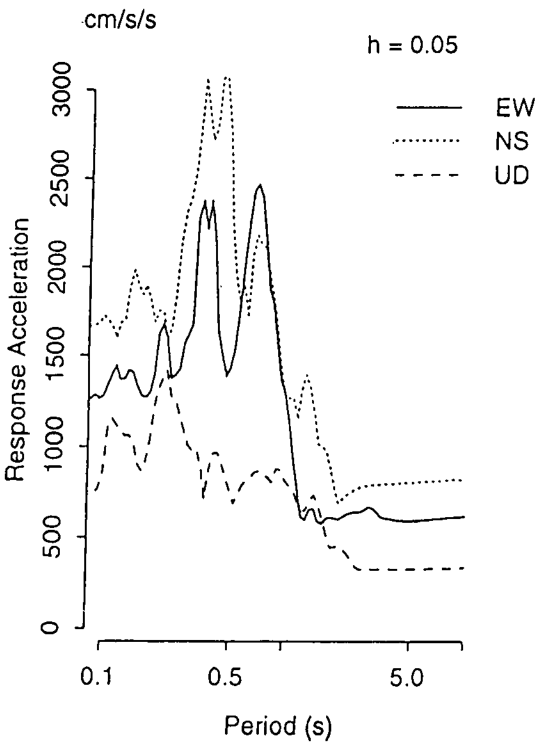

Fig. 4 5% Response Spectra of Acceleration

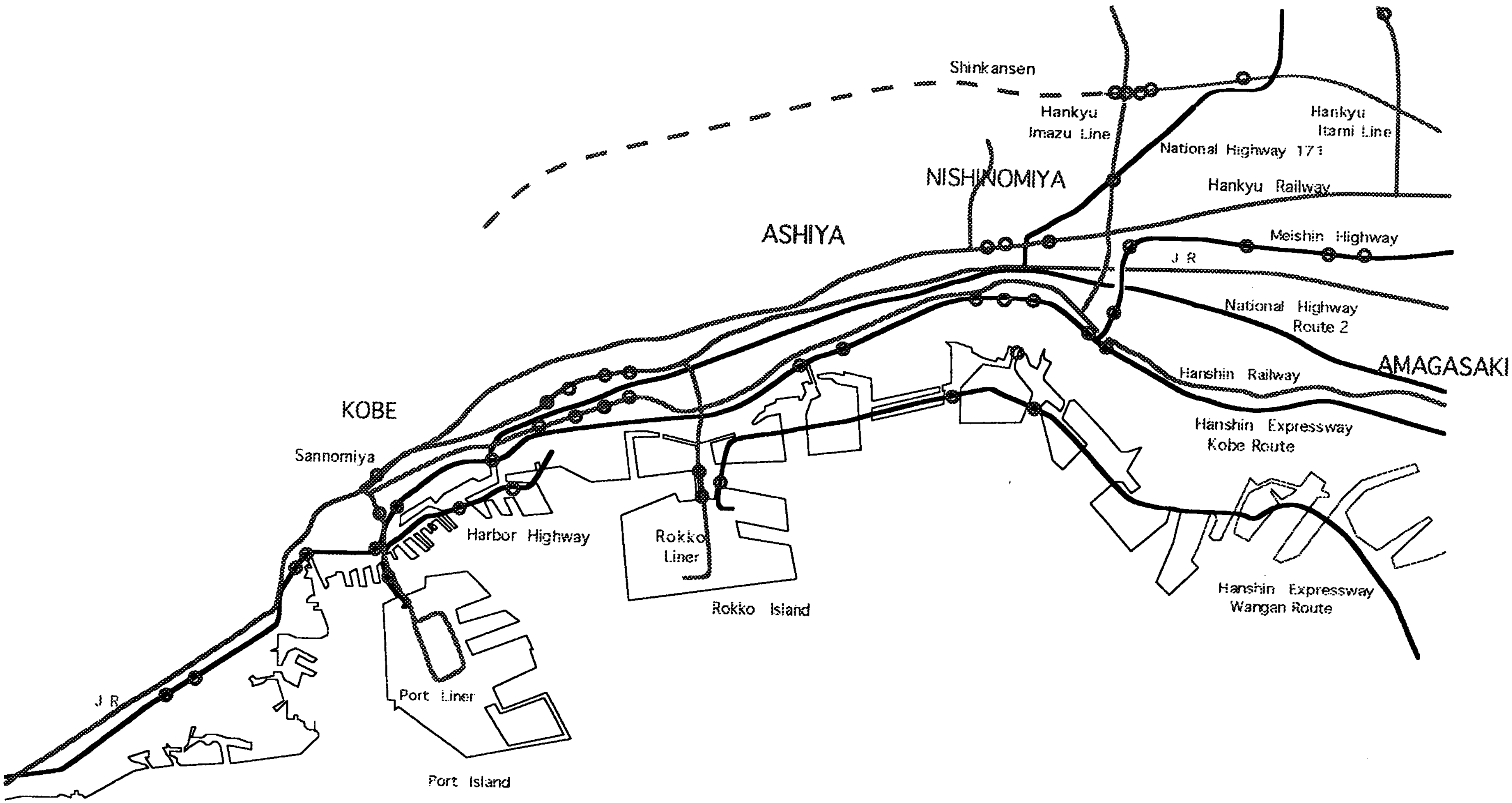

Fig. 5 Damage to Highways and Railways Due to Hyogoken Nanbu Earthquake

Photo 1. Roll-over of Concrete Girder Viaduct (Hanshin Expressway, Route No.3)

Photo 2. Fall-down of Girder (Hanshin Expressway, Route No.3)

Photo 3. Collapse of Concrete Pier (Hanshin Expressway, Route No.3)

Photo 4. Buckling of Steel Pier (Rokko Liner)

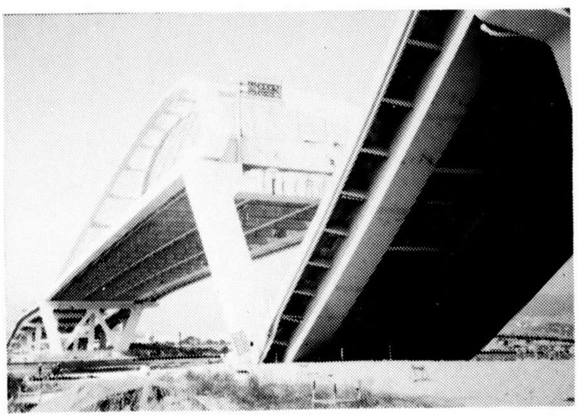

Photo 5. Fall-down of Girder, Nishinomiya-ko Bridge (Hanshin Expressway, Route No.5)

Photo 6. Failure of Bearing, Rokko Island Bridge (Hanshin Expressway, Route No.5)

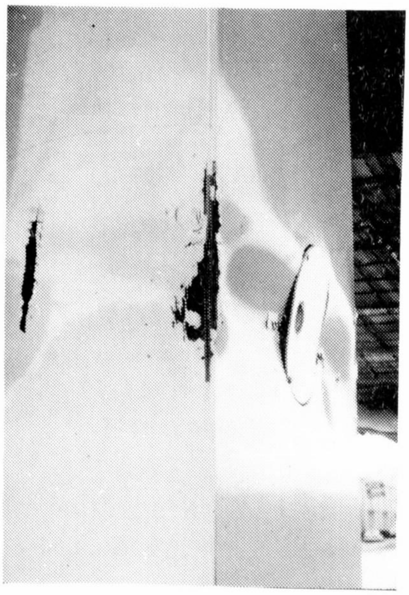

Photo 7. Elastic Buckling of Steel Pier
(Harbor Highway)

Photo 8. Fall-down of Overpass Bridge
(National Road Route 171)

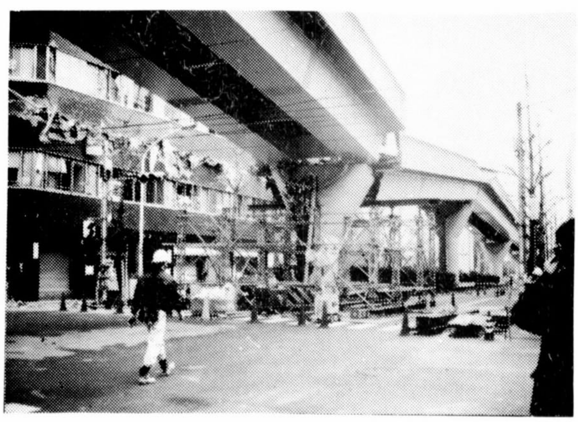

Photo 9. Collapse of Concrete Pier
(Port Liner)

Photo 10. Fall-down of Steel Girder
(Rokko Liner)

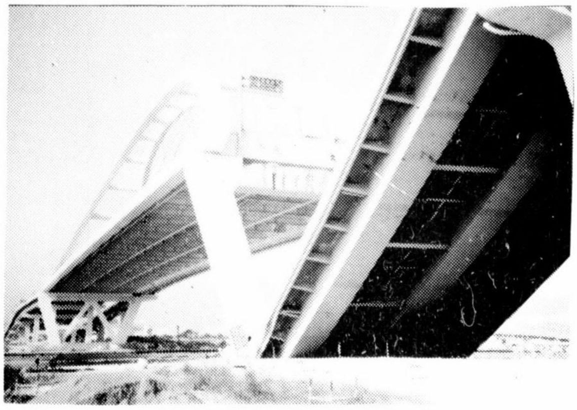

Photo 11. Collapse of Concrete Pier
(Harbor Highway)

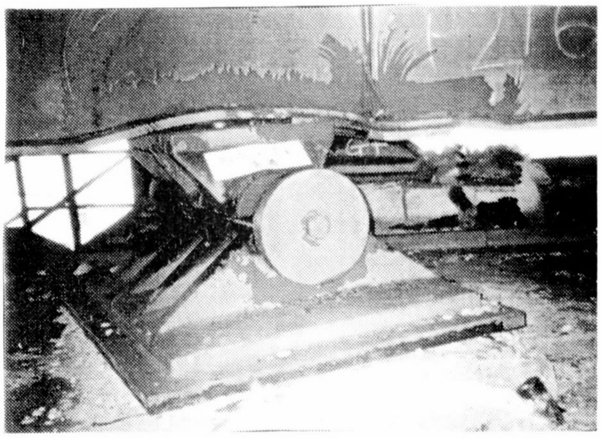

Photo 12. Failure of Steel Bearing

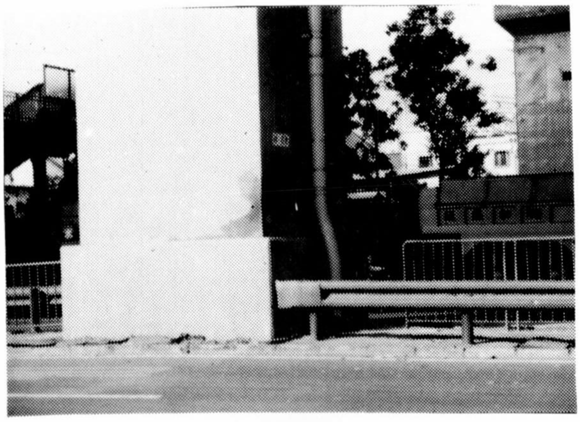

Photo 13. Buckling of Steel Pier
(Hanshin Expressway Route No.3)

Photo 14. Collapse of Steel Pier,
Tateishi Intersection
(Hanshin Expressway, Route No.3)

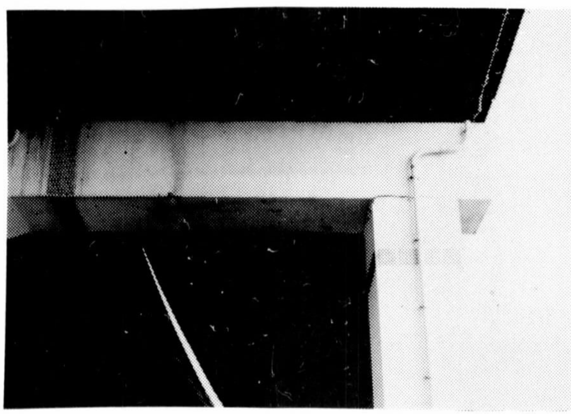

Photo 15. Crack of Beam-Column Connection (Harbor Highway)

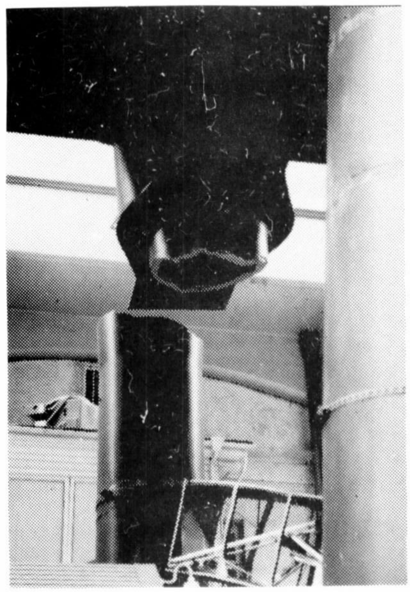

Photo 16. Brittle Failure of Steel Column
(Kobe Rapid Railway)

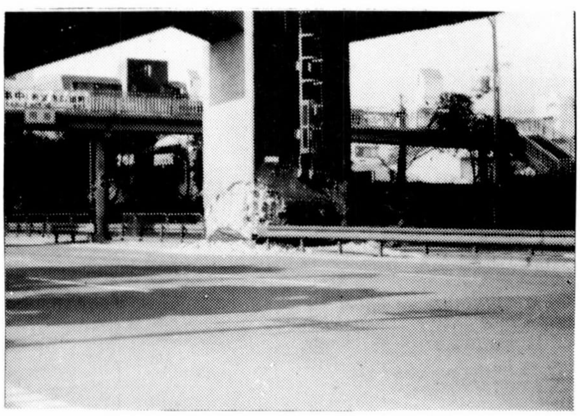

Photo 17. Flexural-Shear Failure at the Bottom of Concrete Pier
(Hanshin Expressway, Route No.3)

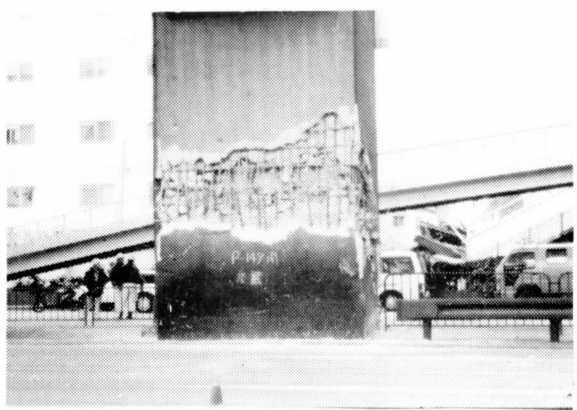

Photo 18. Flexural-Shear Failure at Cut-off zone of Longitudinal Steel
(Hanshin Expressway, Route No.3)

Photo 19. Shear-Failure of Concrete Pier (Hanshin Expressway, Route No.3)

Photo 20. Damage of Concrete Pier (Harbor Highway)

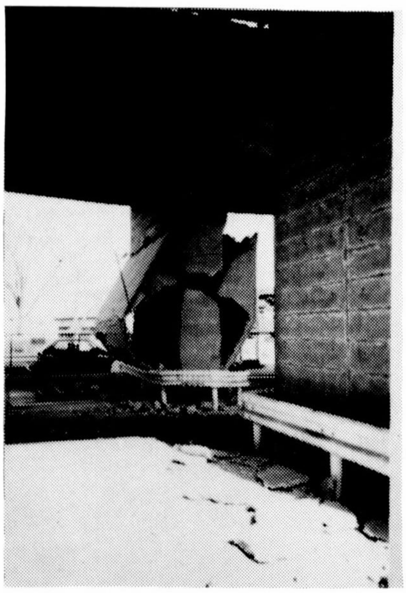

Photo 21. Damage of Wall Type RC Pier (Meishin Highway)

Photo 22. Failure of Center Columns (Kobe Subway)