Reconstruction of the Benten Viaduct after the 1995 earthquake

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SUMMARY

"Benten Viaduct" is a reconstructed bridge of Hanshin Expressway Kobe Route, which was suffered from the Hanshin/Awaji Earthquake seriously. This section had been consisted of 8 bridges before the earthquake and revived as an innovative structure, 19-span continuous rigid frame bridge with seismic isolators installed underneath the steel piers. This paper reports the outline of the seismic isolation design and techniques on the field for this innovative bridge structure, comparing the result of analysis with that of vibration experiment applied onto the actual bridge structure.

1. INTRODUCTION

The Hanshin/Awaji Earthquake occurred on January 17, 1995, caused tremendous damage on the Hanshin Expressway Kobe Route, especially at Benten section (referred in Figure 1). The reconstructed bridge, "Benten Viaduct", was determined to be the 19-span continuous rigid frame with steel deck along with the installation of seismic isolator. The general view of structure is shown in Figure 2.

Before the earthquake one of piers stood on the middle of separating zone and the other on the pedestrian lane, and they were of single RC pier. These piers were connected with the superstructure by means of steel bearings that were placed on top of the each pier. When the earthquake struck them, most of the columns were collapsed due to shear force causing bridge fail and girder buckling. Because they were located on National Highway Route 2 which is also a lifeline route of Kobe city, as much as 24 spans of girders and columns of this section were removed immediately. The remove work was completed within seventeen days.

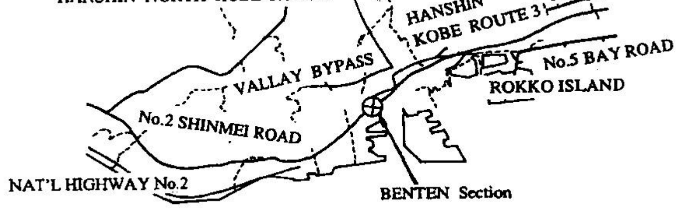


Fig. 1 Location

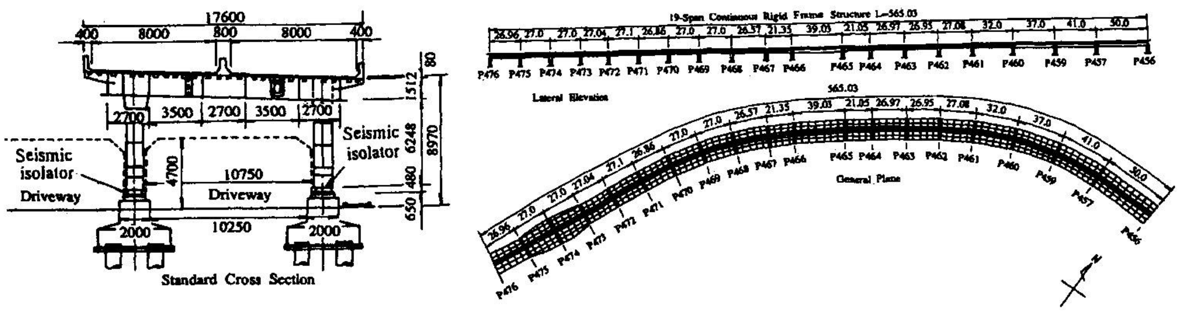


Fig. 2 General View of Benten Viaduct

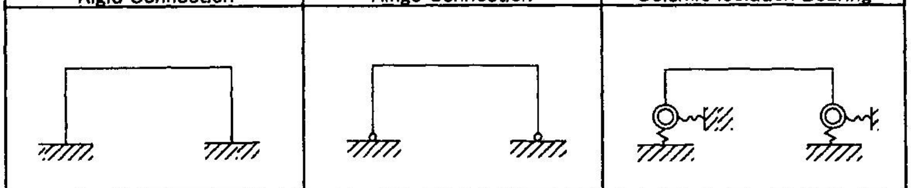
2. DESIGN

2.1 STRATEGY

For restoring the bridges in Benten section, we set the following three basic strategy.

1) The pile foundation could be utilized as they were since it was found that there had been no damage on it.
2) Steel deck and seismic isolation bearings could be used in order to decrease seismic force acting on the foundation.
3) In order to prevent bridges falling down each bridge pier and the beam of superstructure would be tied rigidly as much longer as could.

According to the strategy above, it was decided to adopt a continuous rigid frame. It was supposed that the additional piling reinforcement was needed for rigid connection or for hinge connection and finally it was concluded to adopt the structure of installing seismic isolation bearing on the foundation (referred in Table 1). Since the Benten Viaduct is warped to the seaside and the overhang length of cross beams differs slightly, analysis was made on the entire structural model of the two types shown on Figure 3.



		Rigid Connection			Hinge Connection			Seismic Isolation Bearing		
Column	Stress Resultant	V	H	M	V	H	M	V	H	M
	Dead Load	227.4	120.4	277.3	227.4	76.9	0.0	227.4	29.3	60.7
	Temperature	227.4	140.1	386.0	227.4	79.6	0.0	227.4	30.6	58.7
	Earthquake	241.2	177.2	531.1	267.9	133.8	0.0	260.1	100.6	10.9
Reaction Force on Pile		280≧184(tf/pile)			210≧184(tf/pile)			175≦184(tf/pile)		

Table 1 Comparison of Structure

Both east and west end of Benten Viaduct, 2 spans continuous steel box girder bridges were arranged as a absorber bridge. It was to prevent the adjacent simple girder bridges from a remarkable difference of vibration characteristics.

2.2 OUTLINE OF DESIGN

In static analysis model (a) in the Figure 3 was used. The superstructure consisted of main girders, beams, and piers which was supported by the two way horizontal spring as well as perpendicular and rotational ones. The characteristic of isolator is expressed in natural period (T) and the ratio of yield point load (Qd/Wu)[2]. In order to give an appreciate initial coefficient of bearing reaction for the static analysis model, the period and the ratio of yield point load were decided by applying a representative bridge pier that would satisfy the following three design objects.

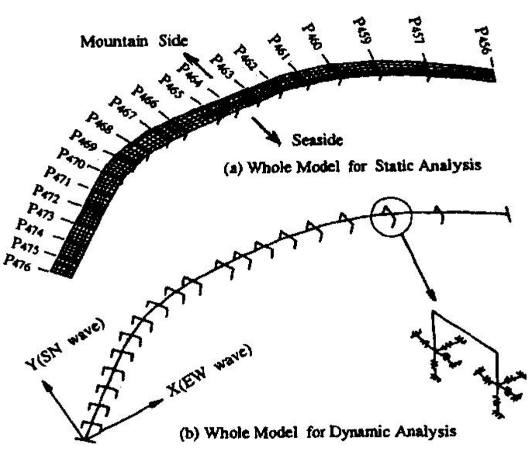


Fig. 3 Entire Models for Analysis

1) In the designed vibration from the horizontal bearing capacity piers will not excessively be plastic during the earthquake. (Khe<0.68)
2) In seismic coefficient method, a designed vibration can at least be decreased by the damping effect. (Dumping constant by the seismic coefficient at the vibration h>10%)
3) Seismic isolator will not be deformed extremely. (Horizontal bearing capacity during earthquake was investigated referring to the superstructure that deflects<250%)

A combination of T=1.4 sec Qd/Wu=12.6% has been adopted to satisfy the above condition.

From the static analysis, deflections were calculated for each bearing and for the girders at both ends. Girder's deflection reached ±84mm maximum depending on the various temperature range. Expansion joints was designed based on this movements.

In dynamic analysis model, the main girders and deck plates were assembled together to a piece of beam so that they would make an entire simple model. The seismic wave taken at the JR Takatori Station was applied [3] for the input of seismic vibration. Earthquake force of EW wave was put into chord direction of warped bridge and SN wave to the lateral direction simultaneously.

The time histories were exemplified in the Figure 4 for the response in the horizontal deflection of the seismic isolator and the bending moment at the beam joint at P470. Maximum deflections were 428mm in the longitudinal direction of bridge and 568mm in the transverse direction, which were observed after 6 seconds from the beginning of earthquake.

The results of natural vibration analysis on the entire model is shown on Figure 5 and all up to 5th modes shows inherent mode of horizontal direction. From the result of natural vibration analysis applied on a plane model, the mode for horizontal move at the bearing position is so remarkable that the similar tendency may be seen in a three dimensional model.

Again the stresses of intersection at the beam and the pier were investigated as members that receive axial compressive force and bi-axial bending moment by applying maximum response values.

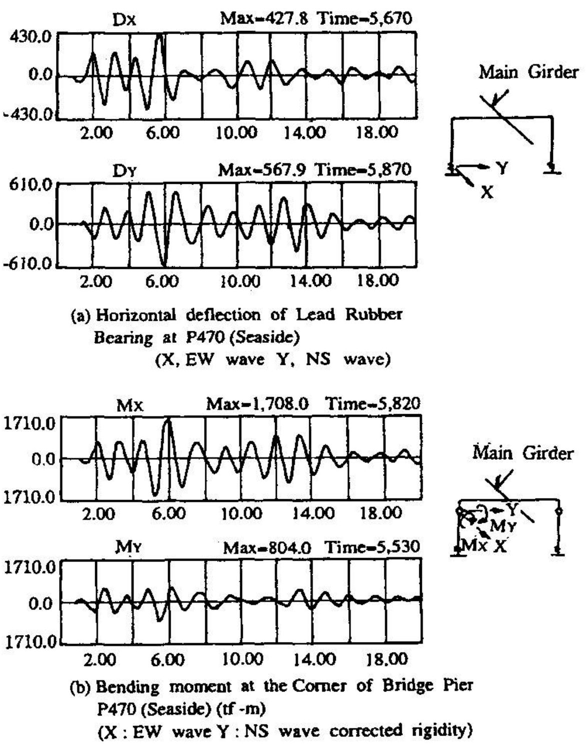


Fig. 4 An Example of Response Analysis On Time History

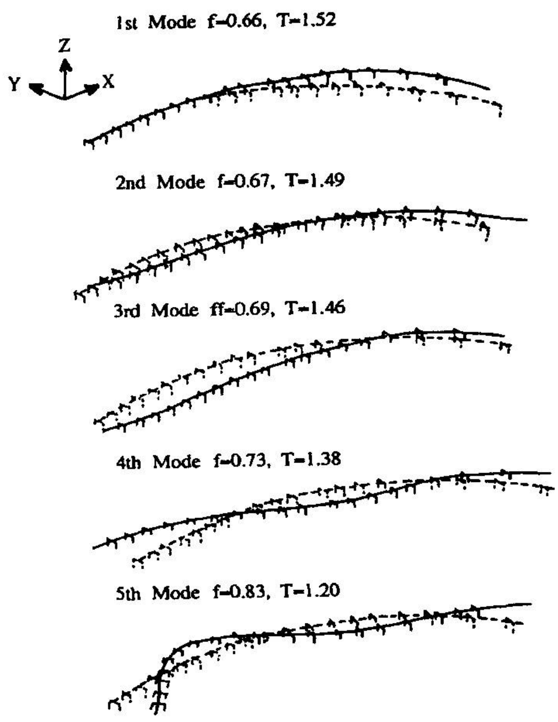


Fig. 5 Results of Natural Vibration Analysis

2.3 SEISMIC ISOLATOR

Seismic isolation bearing was designed referring to the "Manual of Isolation Design for Highway Bridge." There are two types of seismic isolator, LRB (Lead Rubber Bearing) and HDR (High Dumping Rubber). LRB is a laminated-rubber bearing concluding lead plugs inside to give bi-linear deformation characteristic, while HDR is made of laminated super elastic gum.

Benten Viaduct has so much dimension of statically indeterminate that LRB was supposed to be more effective than HDR, because it is softer on various temperature range and harder under strong earthquake force. Each LRB bearings was designed in the same height nevertheless the difference of their design load in order to make the deformation characteristics regular. The appearance of seismic isolation bearing is shown in Photograph 1.

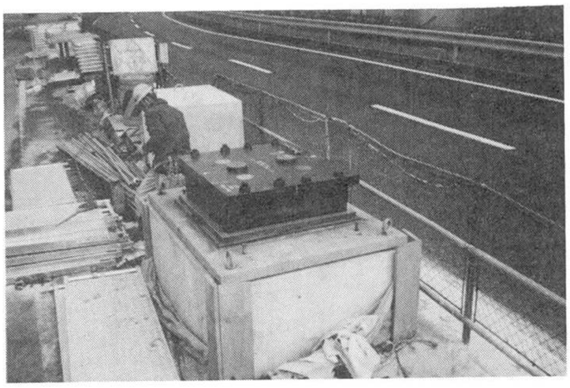


Photo. 1 Seismic Isolation Bearing

Through the static and dynamic analysis, seismic characteristics were corrected like below;

T (natural period of whole superstructure) =1.45 sec
h (dumping constant of isolator when horizontal displacement=100mm) =22 %
shear deflection of isolator (when Kh=0.23) = 50% (design capacity=150%)
shear deflection of isolator (when Kh=0.68) = 196% (design capacity=250%)
shear deflection of isolator (dynamic analysis) = 357% (design capacity=400%)

Also the response analysis on time history is confirmed in the rotating deflection of seismic isolator and axial force of pier, which led to carry the test confirming the effectiveness of bearing by using the response value for the 1/3 scale model bearing.

2.4 EARTHQUAKE RESTRAINER

Benten Viaduct is a long continuous rigid frame bridge which is expected never to fail again. The bridge also has a dumping function against the vibration of earthquake. Besides multiple earthquake restrainers were recommended by the specification [4] by the Ministry of Construction in 1995.

Earthquake restrainers were installed at both ends of the structure where the girders are supported by seismic isolators on ordinary rigid frame steel piers. They were designed to work for longitudinal direction when the displacement became more than the limit given by Ductility Design Method. The steel members of the restrainers were designed by Allowable Stress Design Method using a horizontal force as much as bearing capacity.

Also, for transverse direction, bearing restrainers were installed on the isolators. They were set 5 mm's away from the surface of the upper plate of bearing, and designed with the earthquake force used in Allowable Stress Design Method. This means that, the seismic isolator is usually restricted its displacement not to break the expansion joint on the road and will perform its seismic ability only during a strong earthquake.

3. CONSTRUCTION WORK

3.1 SUBSTRUCTURE WORK

Before the reconstruction project, bearing capacity (qd) of existing pile foundation was researched by means of corn penetrating test. Bearing capacity of 300 to 600 tf/m^2 was confirmed in most part, however, there still found some foundations which had only 150 tf/m^2 of qd. Therefore, these foundations had to be reinforced with adding piles, and the number of them were fourteen, which was 30% of the foundations among Benten section.

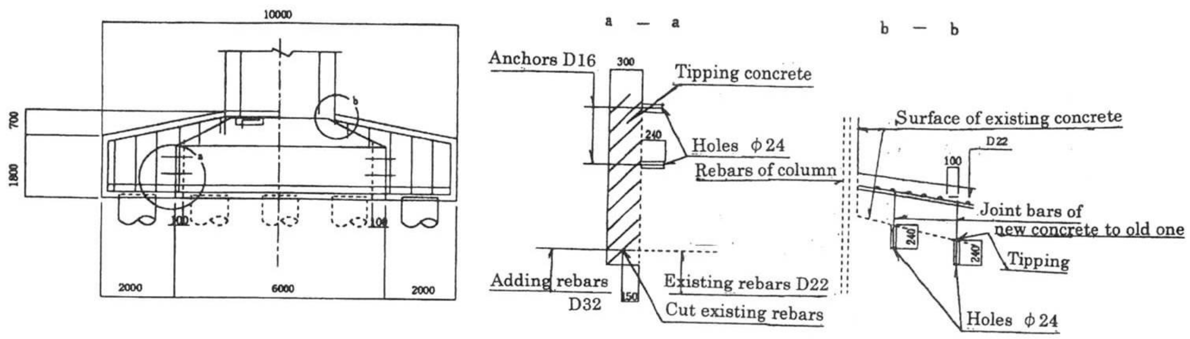


Fig 6 Reinforcement of Pile and Footing

As mentioned above, National Highway Route 2 was the only lifeline route to link the east and west part of Kobe., and the work site was located along the National Highway Route 2. Therefore, there were many controlling field dimensions which obliged the piling works to be took place ni stopping only two lanes ght and day out of six lanes. The location was so close from the downtown and/or residence area that many attentions were paid to save a vibration or noise from the piling work. The earth drill method and pile jacking with oil hydraulics were adopted regularly.

Also, the reinforced bars were jointed to the existing ones by means of enclosed arc welding. Details of reinforcement of footing are shown in figure 6.

3.2 SUPERSTRUCTURE WORK

The length of Benten Viaduct is as much as 686m, which causes ±28mm's expansions at both ends from the difference of temperature of ±10 degrees centigrade. To keep an adequate accuracy of erection, columns and cross beams were built up first. After that, plate girders with steel deck were erected measuring and correcting the errors at each pier points. The accuracy of erection was finally found to be less than 5 mm at the isolators point.

Camber for the dead load was solved statically with partial rigid frame model. It was found that a horizontal deformation of 3.2 to 4.7 mm would be caused by the influence of dead load. Since the actual stiffness of each member was supposed to be stronger than the designed one, the influence of camber on the isolators due to the dead load was ignored.

The steel piers were unstable on the soft seismic isolation bearings until they formed a three-dimension rigid frame. In the field work, a stabilizer system were invented as shown in photograph 2. This system was introduced to stabilize the columns before the erection of girder and deck, and it could save the accuracy of piers and bearings also. The stabilizer was designed to have a temporary horizontal bearing capacity against 0.15G.

Photo. 2 Stabilizer System

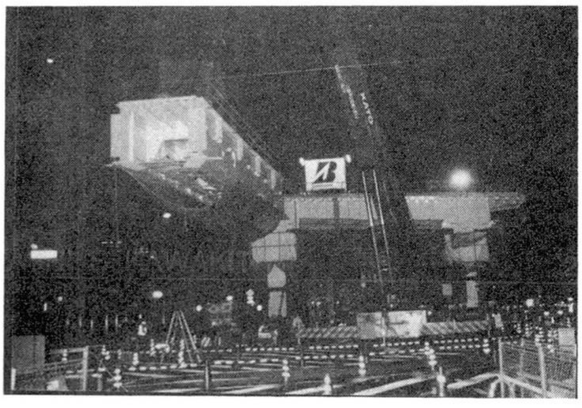


Photo. 3 Erection of Girder and Deck

3.3 ENVIRONMENTAL WORK

Various environmental works were also taken on the Benten Viaduct. For the effect of seismic isolators installed on the foot of piers, it was clarified by confirming test that the traffic vibration on the deck were not conveyed to the ground [5].

The low-noise pavement was introduced on the deck. The effects and durability have been investigated continuously.

Benten Viaduct also has aesthetic cover plates beneath the girder because Kobe municipal government had a plan to develop Benten section into a recreational area.

And more, advanced noise absorbers were adopted like other restored part of Kobe Route. It was installed on top of noise barriers to get the same effect as making noise barriers 1.5 to 2.0 higher.

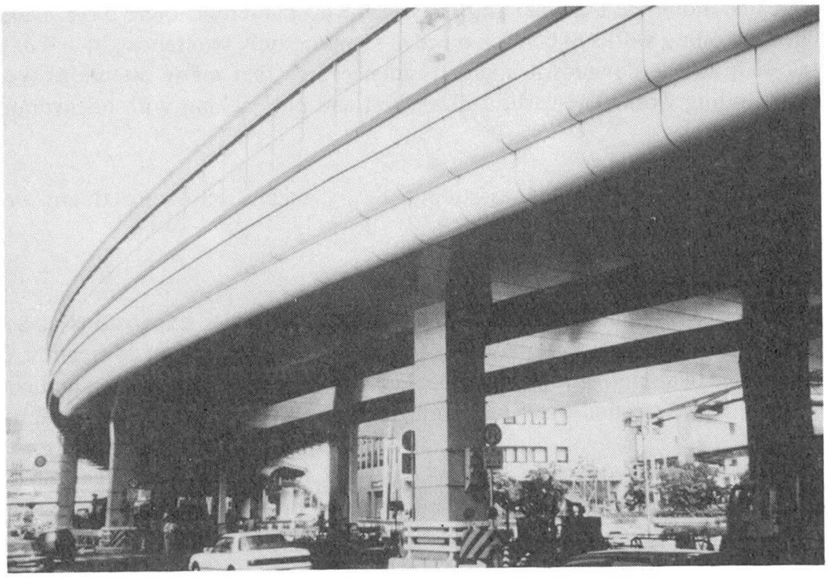


Photo. 4 Complete Structure of Benten Viaduct

4. CONCLUSIONS

Authors reported the outline of design as well as techniques taken on Benten Viaduct. Besides, a series of vibration test was carried out on the actual bridge and reported in another paper [5].

After those trial the viaduct could be completed and reopened on July 17, 1996. There were many new challenges in the designing method for this innovative structure and feasible actions for environment. Authors hope that it can be referred to another trial which will create a new style of bridge.

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