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EFFECTS OF THE HANSHIN-AWAJI GREAT QUAKE DISASTER ON THE AKASHI KAIKYO BRIDGE

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ABSTRACT

On January 17, 1995, an M7.2 earthquake occurred directly below the Akashi Kaikyo Bridge, causing great damage in areas around the bridge. At the time of the earthquake, the Akashi Kaikyo Bridge was still under construction; consequently it presented a unique opportunity to test the aseismicity of the bridge. Also included in this paper are a summary of the original bridge plans and local ground conditions — including geology and faults, an explanation of the design earthquake, and surveys of changes in the ground resulting from the earthquake.

KEYWORDS

Suspension; faults; displacement of foundations; structural skeleton.

INTRODUCTION

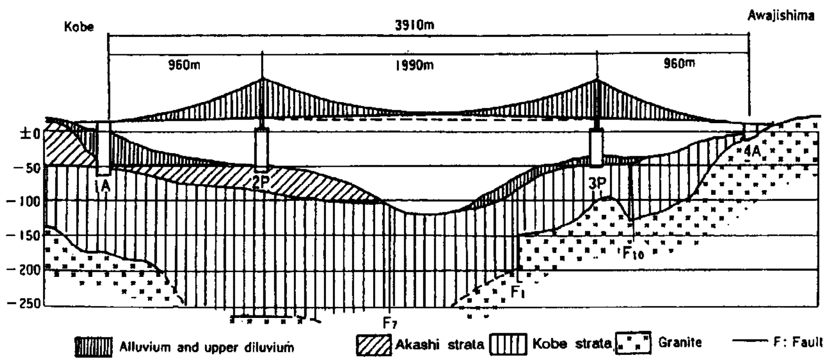
Early in the morning of January 17, 1995, an earthquake of magnitude 7.2 on the Richter scale (M7.2) struck with an epicenter near the Akashi Straits. This earthquake caused considerable damage in an area centering on nearby Kobe City. It also imparted significant motion to the Akashi Kaikyo Bridge, the world's longest suspension bridge which was under construction at the time. This gave us a unique opportunity to test the aseismicity of the bridge. This paper represents a report of the results of this work.

Photo 1 Construction work in progress at the Akashi Straits

GEOLOGICAL CONDITIONS UNDER THE AKASHI STRAITS

The Akashi Straits have a width of about 4 km and their central portion consists of a caldron-shaped valley 110 m deep and 400 m wide. This valley is steeply sloped at both ends. Detailed surveys of geological conditions under the Straits were initiated in the 1950s by the Ministry of Construction and other national agencies in anticipation of a bridge construction project, and the work was taken over, and completed, by the Honshu-Shikoku Bridge Authority (HSBA) before construction of the Akashi Kaikyo Bridge commenced.

Fig. 1 summarizes the results of these surveys. The strata comprises granite dating back to the end of the Mesozoic era, which is covered, in unconformity, by Kobe strata belonging to the Miocene epoch of the Neogene period, and then by the Akashi layer, upper diluvium, and alluvium belonging to the Diluvium epoch of the Quaternary period.



Geological time			Dates back to (X 1,000 Years)	Near Akashi Straits
Era	Period	Epoc		
Cenozoic	Quarternary	Alluvium	6 ~ 10	Alluvium
		Diluvium		Upper Diluvium
			2,000	Akashi strata
	Neogene	Pliocene	7,000	
			13,000	
			20,000	Kobe strata
		Miocene	26,000	
	Paloeogene			
Mesozoic		Cretaceous	65,000	Rokko Granite
		Jurassic	135,000	
		Triassic	190,000	

Fig. 1. Geological profile near the Akashi Kaikyo Bridge

Borehole surveys and sonic prospecting indicated the presence of east-west faults centered on F1, F6, and F7 as well as perpendicular south-north faults (see Fig. 2). All of these faults are within the Kobe strata or deeper layers, and they do not extend into the alluvium, upper diluvium, and Akashi layers. This indicates that these faults have not moved for at least the last two million years; that is, they are not active faults.

The east-west faults, including F1 — which as noted do not enter the Quaternary layers, were very seen in sonic prospecting around the center of the straits. However, they were less clear in the east and west extensions. In choosing locations for the bridge foundations, the positional relations between the extension of F5, one of the south-north faults, and 3P, and those between the extension of F11 and 4A were surveyed by sonic prospecting and other methods. This work confirmed that neither fault extended into the area earmarked for the foundations. Thus, the foundations of the Akashi Kaikyo Bridge were placed so as to avoid the faults existing in the straits. The status of seabed faults after the Southern Hyogo Earthquake has been surveyed by the Maritime Safety Agency. The new faults located in this survey are shown in Fig. 3. There are apparently no new seabed faults in the vicinity of the bridge.

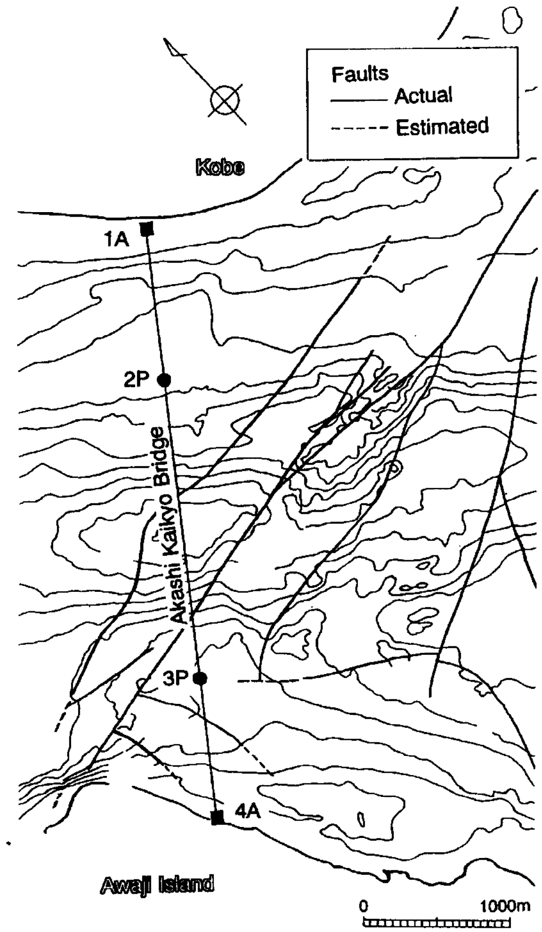


Fig. 2. Submarine geography and estimated fault lines near the Akashi Kaikyo Bridge

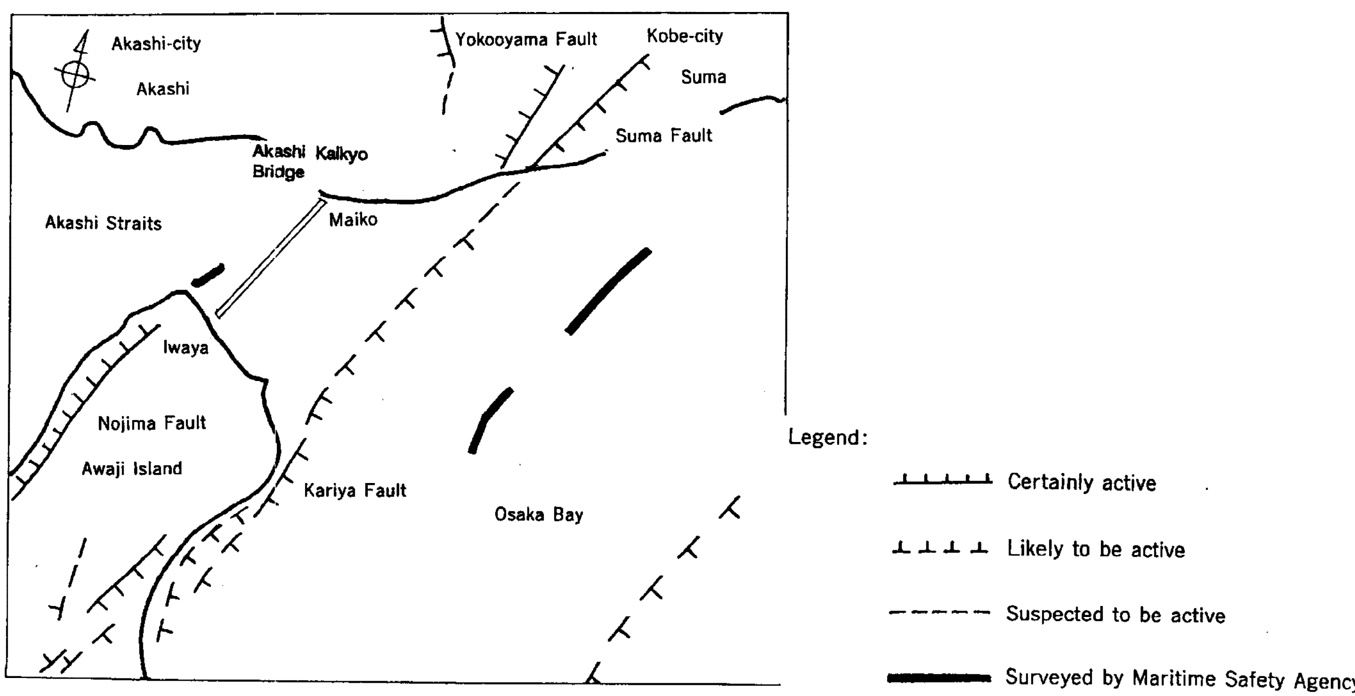


Fig. 3. Faults near the Akashi Kaikyo Bridge

SUBSTRUCTURES OF THE AKASHI KAIKYO BRIDGE

The foundations of the bridge comprise the anchorages 1A and 4A and the tower foundations 2P and 3P. The 2P and 3P tower foundations are in deep water (TP -60 m) in an area of strong tidal currents up to 8 knots. All foundations except 4A were laid on an unconsolidated layer consisting of soft rock since the bedrock is very deep.

The 2P and 3P submerged foundations are of the spread type and were constructed by the laying-down caisson method. They have a double-wall steel caisson structure and are cylindrical in shape to provide aseismicity and resistance to tides. They also feature a simple internal structure made possible by the use of super antiwashout underwater concrete.

The 1A and 4A foundations are of the gravity anchorage type. Anchorage 1A consists of a caisson foundation 85 m in diameter and 63.5 m in depth laid on the Kobe strata plus a main body which is 84.5 m in length and 63 m in width. Anchorage 4A is a spread foundation, 80 m in length, 63 m in width, and 23.5 m in depth (at the deepest point) laid on the granite bedrock. Fig. 4 shows the overall structure of these foundations.

DESIGN EARTHQUAKE FOR THE AKASHI KAIKYO BRIDGE

The input acceleration resulting from the design earthquake — which is common to all the bridge foundations — is defined as the envelope mapped by the following two acceleration response spectra (see Fig. 5):
[1] Acceleration response spectrum at the bridge site resulting from an earthquake of M8.5 off the Kii Peninsula (distance from epicenter: 150 km); and
[2] Acceleration response spectrum corresponding to earthquakes with a recurrence interval of 150 years based on a stochastic assessment of past earthquakes (within a radius of 300 km and of magnitude greater than M6), so as to take into account the possibility of earthquake forces stronger than [1] above.

The aseismatic design of each foundation was studied for safety by modeling ground conditions at the location of the foundation — taking into account soil nonlinearities and dynamic soil-structure interactions during an earthquake — and obtaining response values for the foundations through dynamic analysis.

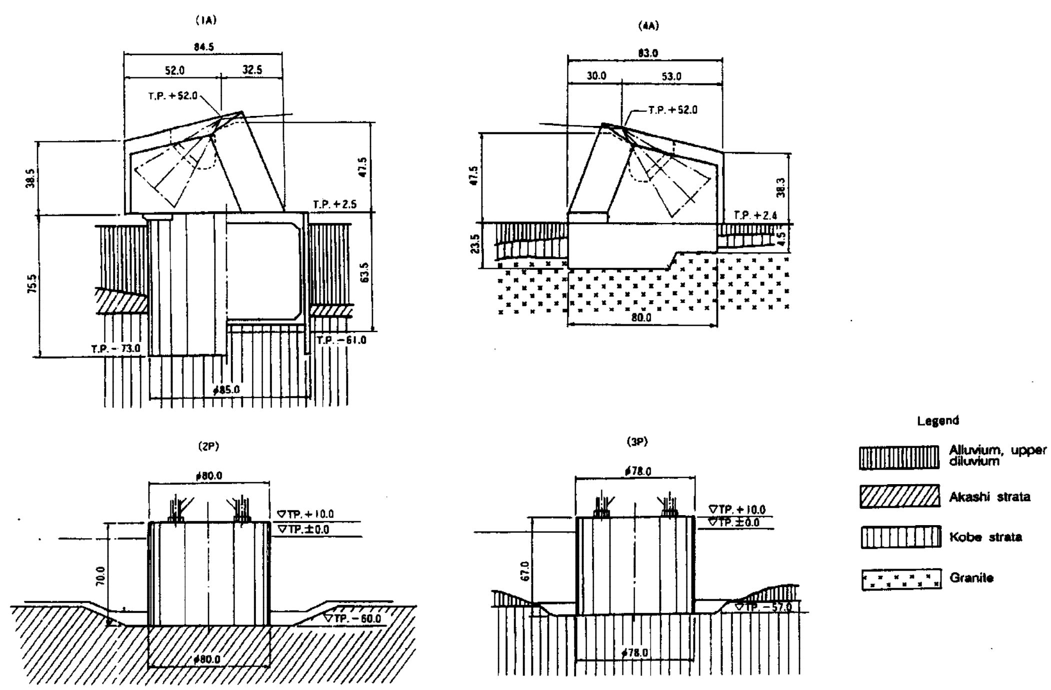


Fig. 4. Overall structure of the foundations (unit: m)

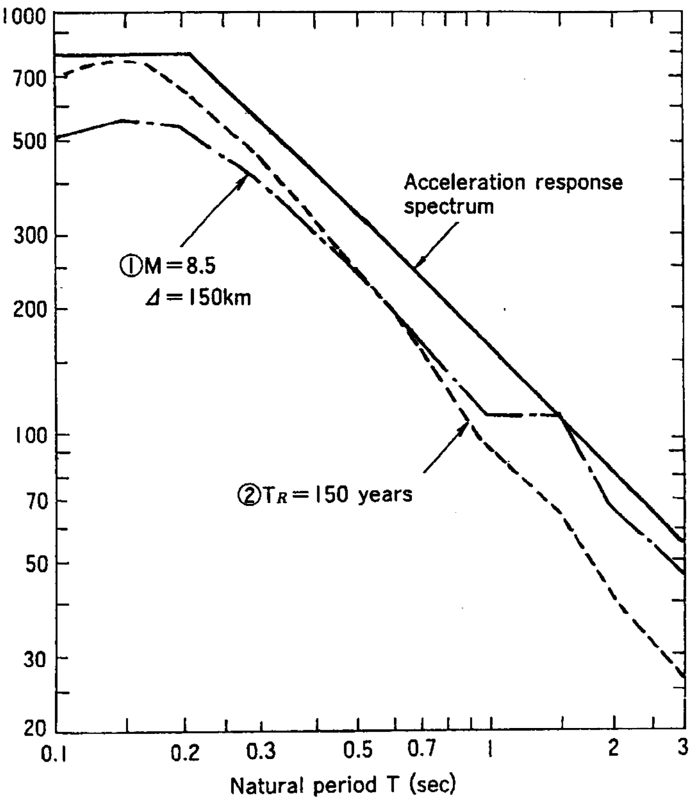


Fig. 5. Design acceleration response of the Akashi Kaikyo Bridge

CHANGES FOLLOWING THE EARTHQUAKE

When the Southern Hyogo Earthquake occurred on January 17, all cable strands for the Akashi Kaikyo Bridge were in place, and squeezing work was in progress. Immediately after the earthquake, a survey of conditions around the site was initiated to check for any influence of the earthquake on the bridge. The structure was checked, measurements were taken, and underwater video cameras were used to make observations. This survey yielded the results given below.

[1] No visible damage was caused to the completed anchorages and tower foundations, nor were the completed main towers or main cable structures damaged.

[2] Surveys by GPS and geometric methods indicate that both the tower foundation (3P) and the anchorage (4A) on the Awaji island side moved relatively by about 1.3 m in an almost westerly direction.

As the result of these foundation movements, the 1,990 m center span has widened to about 1990.8 m while the 960 m side span on the Awaji island side is now about 960.3 m. Fig. 6 shows these changes in the horizontal layout of the foundations.

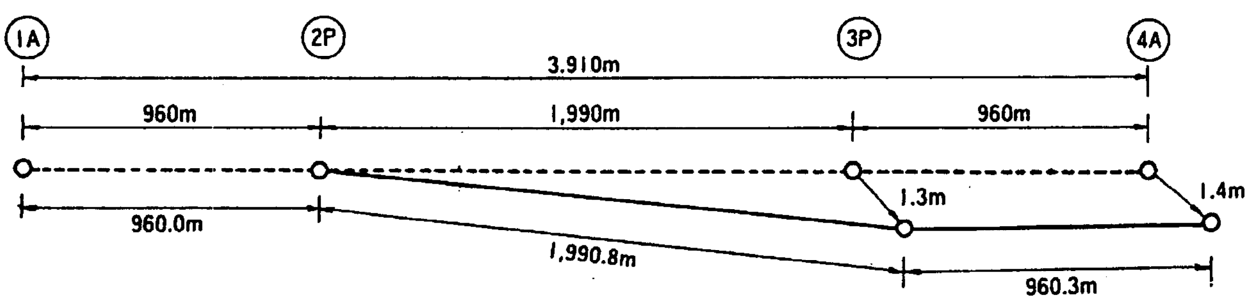


Fig. 6. Location of foundations following earthquake

Fig. 7 shows the absolute displacement of control points near the Akashi Straits as prepared from the results of surveys by the HSBA and the Geographical Survey Institute. As this figure makes clear, survey points on opposite sides of the Akashi Straits moved by 50 to 100 cm in the direction indicated by the arrows. It can be concluded from these results that the relative movement of the bridge foundations occurred because the ground on which they were constructed moved.

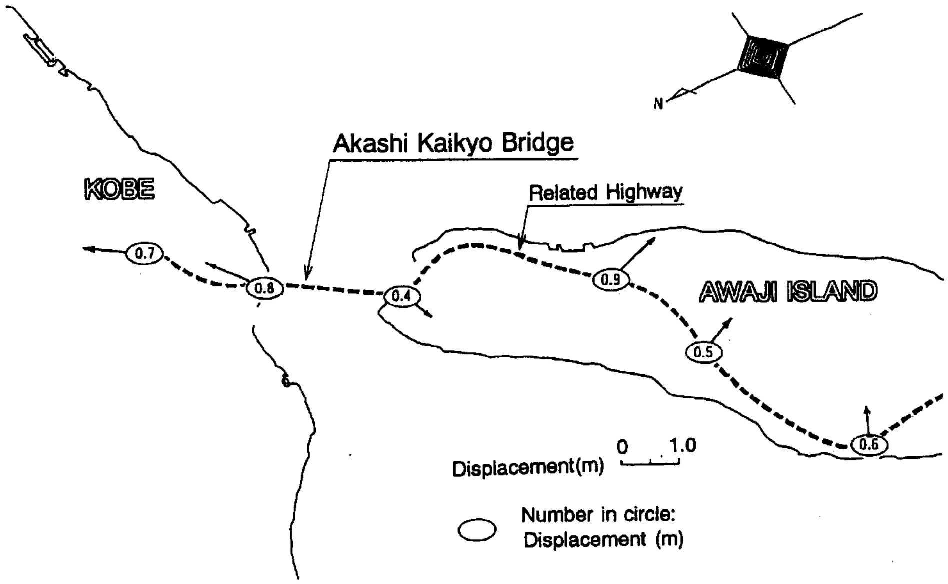


Fig. 7. Absolute displacement of control pPoints

[3] Although the foundations were located so as to avoid the known faults, a submarine survey was carried out within the construction area to identify any changes in the faults after the earthquake and to check whether any new faults had developed. Using underwater video cameras, bathymetric surveys, and sonic prospecting, no noteworthy changes were found in the seabed around the foundations.

[4] Regarding the tower foundations (2P and 3P), displacement of the bearing ground due to subsidence was measured with a sliding micrometer. The results are shown in Fig. 8. The 2P tower foundation subsided by about 20 mm (strain: 4×10^{-4}) as a result of the earthquake, probably because the bearing Akashi strata was compacted.

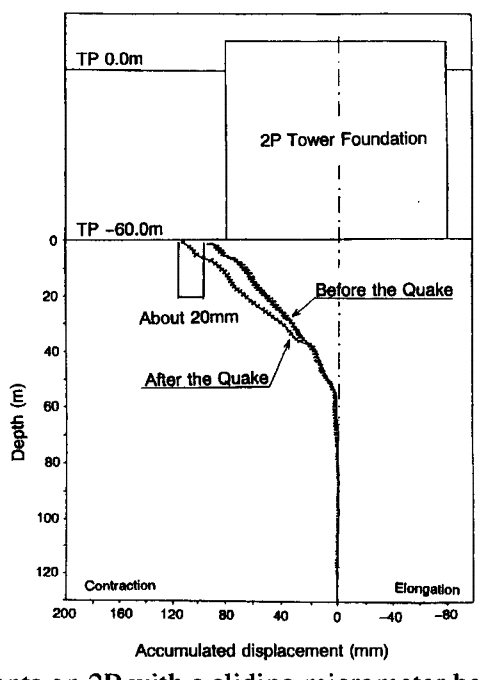


Fig. 8. Results of measurements on 2P with a sliding micrometer before and after the earthquake

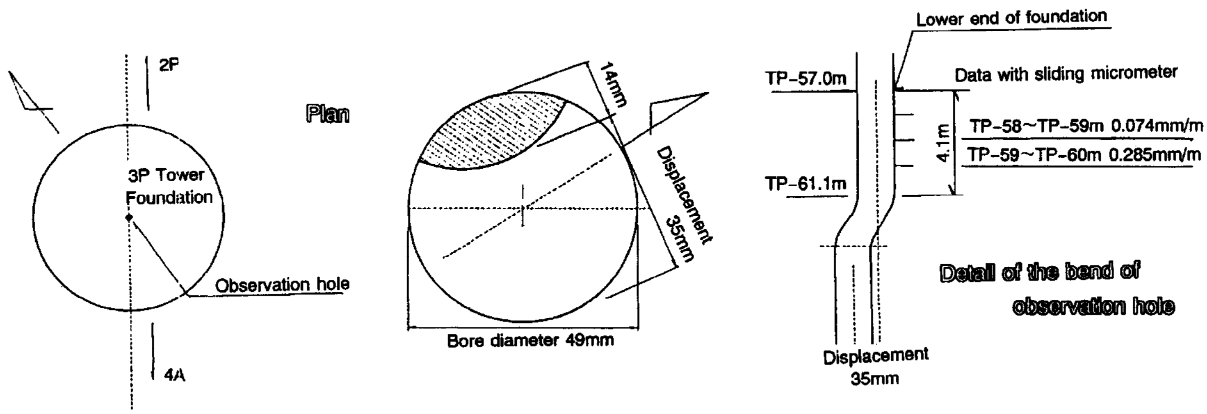


Fig. 9. Position of observation hole

In the 3P foundation, the measurement hole located 4 m below the seabed foundation was choked, making measurements impossible. The choked section was checked with a borehole camera, and a bend of about 35 mm was observed, as shown in Fig. 9. There was no curvature in deeper sections. This appears to be a result of partial sliding of a mud layer within the bearing Kobe strata.

TOWER VIBRATION

A number of seismographs were in operation at the bridge site, including some in the tower. However, these were not strong-motion seismographs, so they were unable to properly record the large vibrations caused by this earthquake. The only usable records obtained at the site are from seismographs at the top and mid-points of the tower shafts. A typical record is shown in Fig. 10. The vibration of the tower last more than a minute, which is much longer than the ground vibration. In the transverse component, the maximum velocity was reached more than one minute after the motion began.

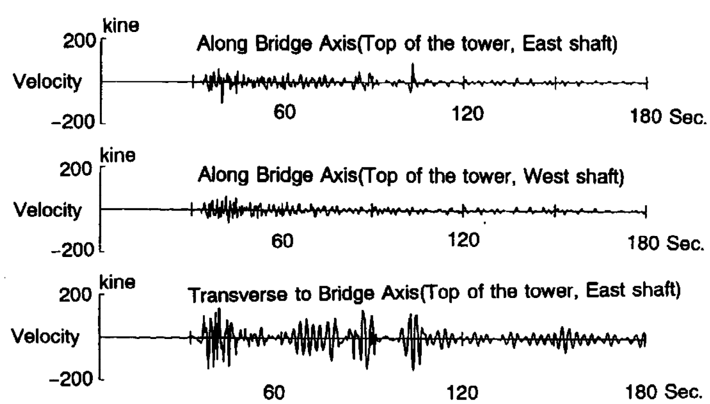


Fig. 10. Velocity record at the top of tower 2P

EFFECT OF DISPLACEMENT ON THE SUPERSTRUCTURE

The effect of the earthquake displacement on the skeleton structure of the bridge is shown in Fig. 11.

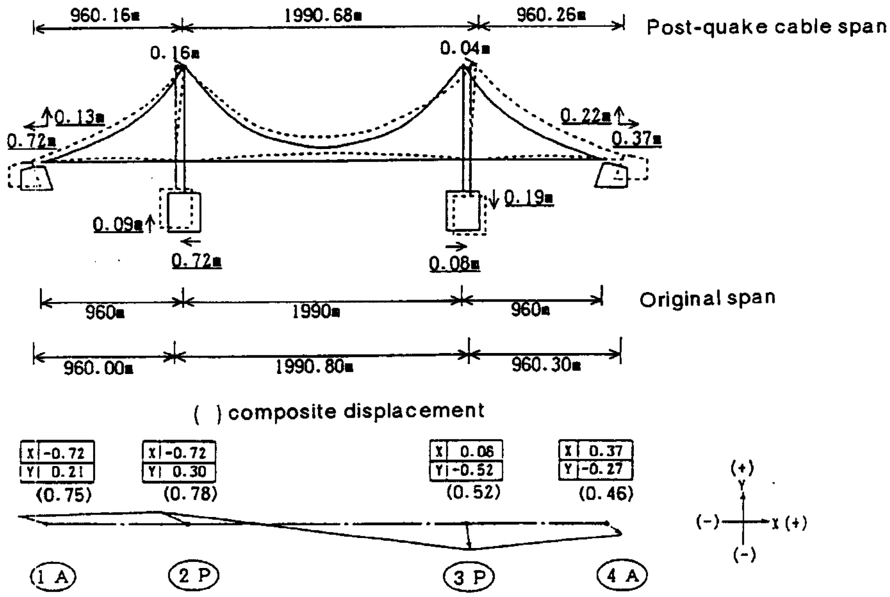


Fig. 11. Effect on the structural skeleton of the Akashi Kaikyo Bridge

The effects of these changes caused by the earthquake, and the countermeasures being implemented, are summarized in Table 1.

Table 1. Effects of structural changes and HSBA's countermeasures

Issue	Effects of earthquake and countermeasures
Strength	An analysis in which the earthquake-induced foundation displacement is added to the completed structure indicates that no stress-related problems will arise as regards towers, cables, the stiffening girder, etc.
Alignment	Although some of vertical alignment exceeded 3 due to reduced cable sag in the center and the side spans, this presents no problems as regards the highway structure ordinance. Further, the horizontal alignment is now off by about 0.03 degree at the towers, but this is not expected to present problems as far as vehicular traffic is concerned.
Span	The increased 2P-3P and 3P-4A spans will be coped with by adjusting the length of the stiffening girder now being fabricated.

CONCLUSIONS

In the history of bridge construction, there is probably no precedent for this case — a large suspension bridge under construction being hit by a massive earthquake from directly below, resulting in foundation displacement and elongation of the spans due to crustal deformations. The influence of the foundation displacements on the superstructure was studied, confirming that their effects are within design tolerances from both mechanical and displacement viewpoints. Consequently, the elongated spans are being coped with by small adjustments in the length of the stiffening girders.

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