OBSERVATION AND SYNTHESIS OF LONG-PERIOD EARTHQUAKE GROUND MOTIONS AT THE AKASHI KAIKYO BRIDGE CONSTRUCTION SITE

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SUMMARY

The Akashi Kaikyo Bridge, the world's longest suspension bridge, spans almost 4 km across the Akashi Strait, constituting a remarkable engineering feat. The bridge, completed in April 1998, connects the city of Kobe and Awaji Island. The unprecedented large scale of this structure, whose fundamental natural vibration period is about 20 seconds, required for a specific seismological study to verify the design earthquake load in such a long-period range. Thus, a four-station array observation system has been used to monitor the long-period seismic activity around the bridge construction site. Since its installation in 1990, more than one hundred records, including aftershocks of the 1995 Hyogo Ken Nanbu Earthquake, have been obtained. This data is used to synthesize long-period ground motions induced by hypothetical huge earthquakes using empirical methods. Seismogenic sources along two of the most hazardous geological structures, namely: the Median Tectonic Line, and the Nankai Trough, are analyzed. Geological studies and historical data show that these structures can generate earthquakes of magnitude 8.0 or greater. The synthesized signals show peak displacement amplitudes of about 50 cm, although most of their acceleration response spectra show lower or equal level than those of the design spectra for the Akashi Kaikyo Bridge. These results show that the seismic hazard these geological structures represent to the bridge are acceptably included in its design spectra.

INTRODUCTION

For the seismic design of large structures such as suspension bridges, and high-rise buildings, it is a common practice to analyze their response to some typical observed strong motion seismograms or a scaled record of them. However, since none of these records measured the ground motion of a very large earthquake in the near field, which could develop important long-period ground motions, it is clearly desirable to employ more suitable seismograms for such vital design evaluation purposes. The seismic design of the Akashi Kaikyo Bridge, whose center span is 1991m long and its fundamental vibration period is about 20 sec, was not the exception. The design spectrum for this bridge was defined as the envelope of two response spectra on the ground surface, assuming that it consists of bedrock equivalent to a Type I soil, as defined by the Highway Bridges Specifications. One acceleration response spectrum was assumed generated by an M 8.5 earthquake at an epicentral distance of 150 km. and the other one was obtained probabilistically from past earthquakes of M 6.0 or larger, within a radius of 300 km [Nasu and Tatsumi, 1996].

The importance of this structure required for a specific seismological study to verify the design earthquake load in such a long-period range. Therefore, in 1990 an array observation system consisting of four stations was placed around the bridge construction site (Fig. 1), to monitoring the long-period seismic activity in this area. The installed seismographs are reliable from 0.025 to 70 Hz, having a resolution of 0.00005 kine. After an eight-year monitoring program, more than one hundred earthquake records, for both near-field and far-field earthquakes have been obtained by this array, which are used in this study to synthesize long-period ground motions induced by hypothetical huge earthquakes. Seismogenic sources stretched along two of the most

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hazardous geological structures, namely: the Median Tectonic Line, and the Nankai Trough, are analyzed. Geological studies and historical data show that these structures can generate earthquakes of magnitude 8.0 or greater, which could generate strong long-period ground motions at the bridge construction site. The Empirical Green's Function simulation technique [Irikura, 1986] that uses records of small events to estimate strong ground motions induced by larger events is used for the synthesis. In order to estimate realistic earthquake ground motions, parametric analyses are performed to investigate the effects of some source parameters on the synthetic ground motions, and to assess the variability of the estimated signals when these parameters are changed in a geologically acceptable range of values.

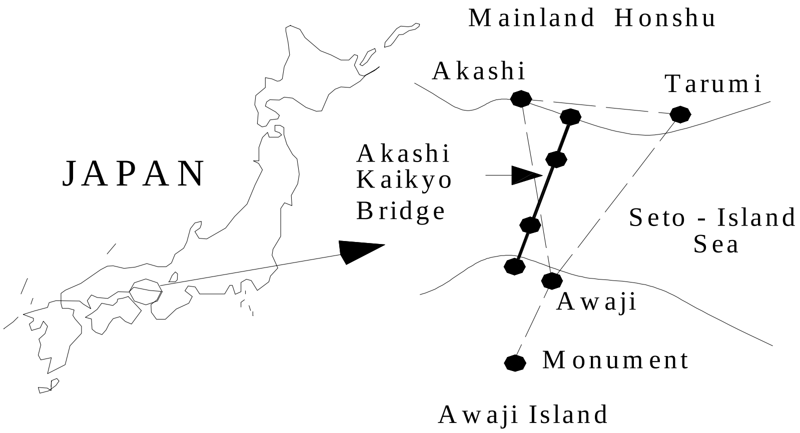

Fig. 1 Location of the Akashi Kaikyo Array Observation System

EARTHQUAKE GROUND MOTION DATABASE

During the eight-year observation period the Akashi Kaikyo Array Observation System recorded a total of 156 earthquake ground motions. Records from near-field small earthquakes and far-field large ones with magnitude larger than M 7.0 and hypocentral distances longer than 1500 km were obtained. A large number of aftershocks of the 1995 Hyogo-ken Nanbu Earthquake, which occurred just beneath the bridge construction site, were also recorded by this array. It constituted a valuable source of information to analyze the effect of this kind of near-field earthquake to the bridge, since at the time it occurred the bridge was in an early stage of its construction.

The far-field earthquake records (Fig. 2) present dominant periods ranging from 8 to 20 sec, which are similar to the fundamental vibration periods of the bridge. These kind of seismic waves that could be generated by huge near-field earthquakes, are of primary concern to analyze the seismic response of the bridge, therefore, they are used in this study as empirical Green's function to synthesize long-period ground motions. A complete list of this earthquake ground motion database is presented by Aguilar (1999).

SYNTHESIZING PROCEDURE

The synthesizing procedure used in this study is the Empirical Green's Function method (hereafter EGF). The basis for this method is to estimate the ground motion due to a large earthquake as a sum of small event records. The method proposed by Irikura (1986) is adopted, in which the synthesized strong ground motion $U(t)$ is given by

$$U(t) = \sum_{i=1}^{N}\sum_{j=1}^{N}\left(\frac{r}{r_{ij}}\right)F\left(t - t_{ij}\right) * u_{ij}(t) \tag{1}$$

where, $u_{ij}(t)$ is the small event used as EGF and r its hypocentral distance, r_{ij} the distance from the (i,j) sub-element to the observation site. The subscripts i and j specify the location of the small event on the target event's fault plane when it is divided into NxN sub-elements, and the notation * represents convolution. $F(t)$ and t_{ij} are defined as

$$F(t) = \delta(t) + \frac{1}{n'} \sum_{k=1}^{(N-1)n'} \delta\left[t - (k-1)\frac{\tau}{(N-1)n'} \right] \tag{2}$$

and

$$t_{ij} = \frac{r_{ij} - r_0}{V_S} + \frac{\xi_{ij}}{V_r} \tag{3}$$

where, r_o is the distance from the rupture starting point to the observation point, ξ_{ij} the distance from the rupture starting point to each sub-element *(i,j)*. V_S and V_r are respectively the shear wave and rupture propagation velocities, τ the rise time, and n' an integer number to shift to a higher frequency range the spurious high frequency that appear due to regular duplication of the small event slip function. From the similarity relations, N^3 is given by the seismic moment ratio of large to small earthquakes.

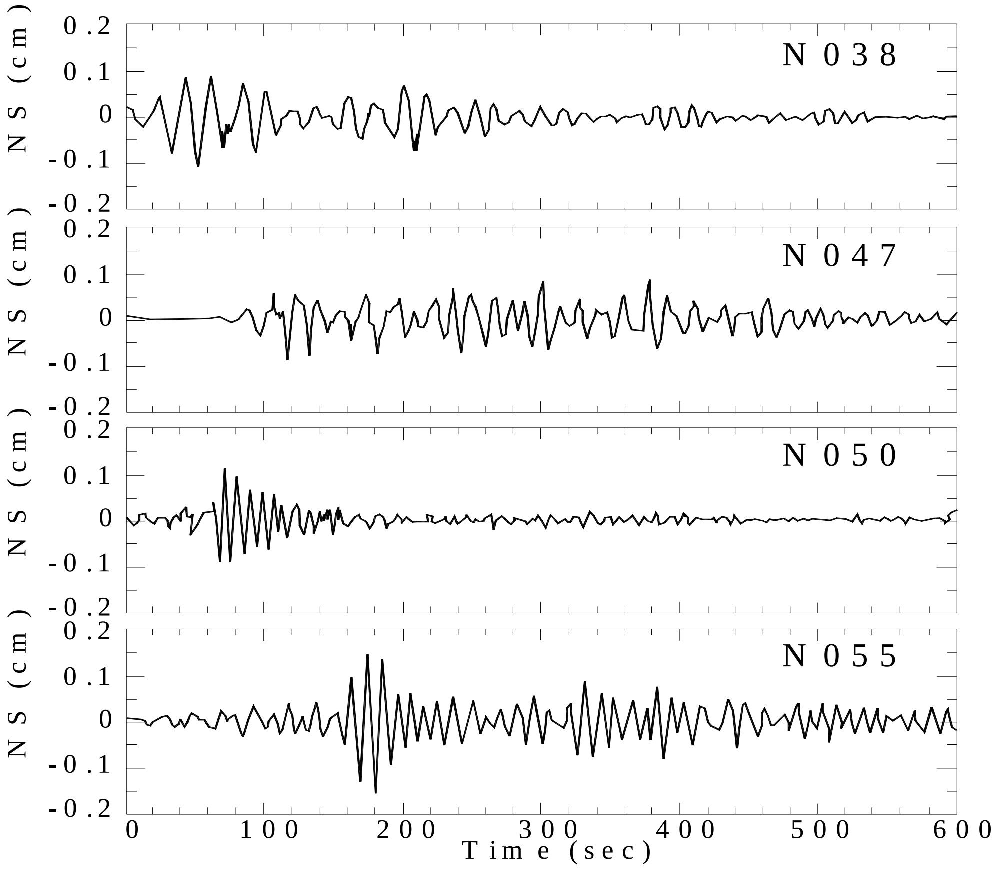

Fig. 2 Displacement time histories of events used as Green's Function, recorded at Akashi Station.

In order to avoid spatial aliasing, irregularities are included to the rupture-front propagation, changing randomly the rupture propagation velocity V_r as follows:

$$t_{ij} = \frac{r_{ij} - r_0}{V_S} + \frac{\xi_{ij}}{V_r} + t_{rmd} \tag{4}$$

where t_{rmd} varies randomly from $-0.1\xi_{ij}/V_r$ to $0.2\xi_{ij}/V_r$ (Takeo et al, 1997). Furthermore, the records used as Green's functions are band pass filtered in the range of 0.05 to 0.5 Hz, lower than the characteristic frequency f_o [Bour et al, 1997], at which artifacts appear in the finite sum.

SYNTHETIC LONG-PERIOD EARTHQUAKE GROUND MOTION

After the occurrence of the 1995 Hyogo-ken Nanbu Earthquake, which showed the devastating effects of large intraplate earthquakes, attention was drawn to evaluate the seismic hazard that this kind of geological structures represents to the Akashi Kaikyo Bridge. Two geological structures that could generate long-period earthquake strong ground motion at the bridge construction site were identified. The first one is the Median Tectonic Line of southwest Japan (hereafter MTL), which is an intraplate structure that according to seismological studies [Shiono, 1980], could generate earthquakes with magnitude as large as M 8.0. The other one is the Nankai Trough, an interplate structure that according to historical records can generate earthquakes with magnitude up to M 8.4. These two seismotectonic areas are south of the bridge construction site, at distances ranging from 90 to 150 km. The location of these geologic structures are shown in Fig. 3.

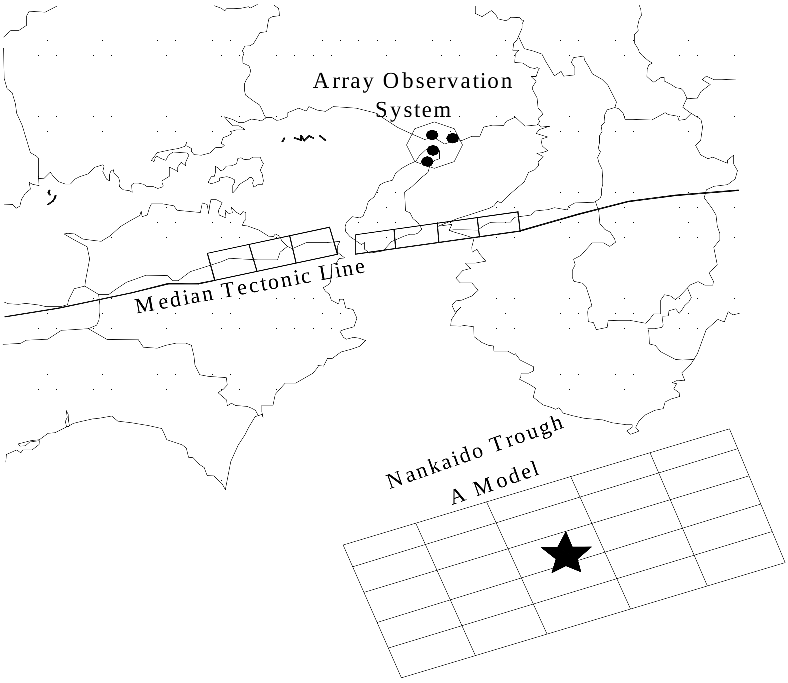

Fig. 3 Location of the MTL and the Nankai Trough, showing the source mechanisms assumed for the synthesis of long-period ground motions at the Akashi Kaikyo Bridge construction site.

The simulation of long-period strong ground motions are performed using records of large far-field earthquakes as empirical Green's function, since most of the near-field small earthquake records obtained by the Akashi Kaikyo Array do not present good signal-to-noise ratio in the long-period range. Four events recorded at the Akashi Station, namely: The M7.0 Sanriku Haruka Oki Earthquake (N038), the M7.8 Kushiro Oki Earthquake (N047), the M6.6 Notohanto Oki Earthquake, and the M7.8 Hokaido Nansei Oki Earthquake. These records are band-pass filtered in the range of 0.05 to 0.5 Hz. Peak displacements ranging from 0.2 mm to about 2 mm are observed, and their dominant period range from 8 to 20 sec. Fig. 2 shows the displacement time histories of these events, and Table 1 their location parameters.

Table 1: Location Parameters of the Earthquake Records used as Green's Functions

EGF	Date	Magnitude	Epicentral Distance (km)	Depth (km)	Azimuth (o)
N038	1992.07.30	7.0	932.0	0.0	237.9
N047	1993.01.15	7.8	1132.0	120.0	125.8
N050	1993.02.07	6.6	395.0	25.0	210.7
N055	1993.07.12	7.8	964.8	27.0	202.5

LONG-PERIOD GROUND MOTION INDUCED BY THE MEDIAN TECTONIC LINE

The MTL is a geological structure inland from the zone of convergence between the Asian and the Philippine Sea plates. It stretches for more than 800 km from Chubu District to Kyushu. Its central segment that extends from western Kii Peninsula to central Shikoku, with a length of 250 km, is the most active one, presenting average slip rates of 5 to 9 m/10^3 yr. [Shiono, 1980; Kanaori et al, 1994]. Fault scarps have revealed the MTL slip sense as dominantly right-lateral strike-slip movements [Kanaori et al, 1994]. According to historical records, for about 1000 years there have occurred no destructive earthquakes directly indicating faults break along the MTL, however, an earthquake of magnitude as large as M 8.0 has been usually considered possible to occur in this structure [Shiono, 1980].

For the synthesis of long-period (2 to 20 sec) ground motions two fault planes with a total length of 105 km, extending from eastern Shikoku to western Kii Peninsula, are assumed as the source mechanism of a magnitude M8.0 earthquake (Fig. 3). The seismic moment for the larger fault plane is assumed to be 2.24×10^{27} dyne-cm and 1.4×10^{27} dyne-cm for the smaller one, which, all together are equivalent to that of an intraplate M8.0 earthquake. Parametric analyses were performed to analyze the effect of both the S wave and rupture propagation velocities, and the location of the rupture starting point.

Synthetic displacement time histories that present the largest amplitudes and their corresponding acceleration response spectra for 2% damping factor are shown in Fig. 4 for each record used as Green's function. These signals present maximum displacement peak values of about 20 cm, and it is observed that the synthetic waveforms are similar to their Green's function, showing that the source has no effect on them. Similarly, it is observed that the design spectra for the Akashi Kaikyo Bridge reasonably envelop the synthetic ones.

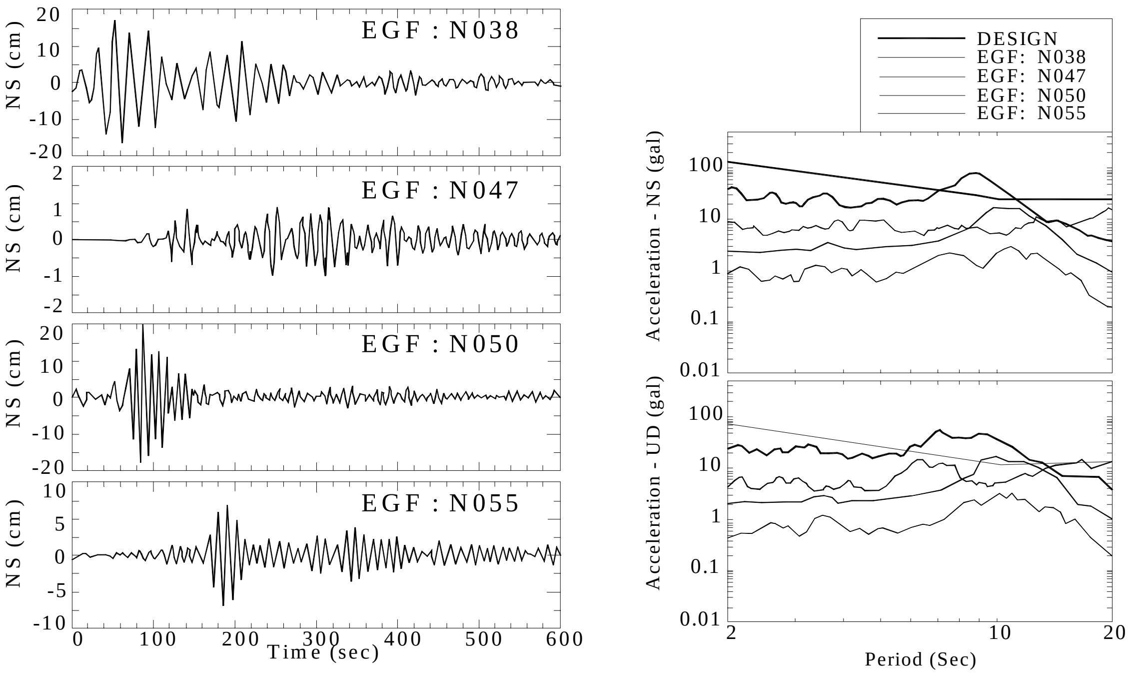

Fig. 4 Displacement time histories (left) and acceleration response spectra (right) of synthetic signals at Akashi station induced by an M 8.0 earthquake on the MTL.

LONG-PERIOD GROUND MOTION INDUCED BY THE NANKAI TROUGH

The Nankai Trough is another hazardous geological structure that according to historical records can generate large earthquakes. It is located along the southwestern coast of the Japanese Honshu Island, stretching for about 530 km, and marking the northern plate boundary between the Philippine Sea and Asian Plates. A series of large earthquakes that present a remarkable temporal regularity have occurred along this geological structure, which were accompanied by large crustal deformations [Kanamori, 1972].

The synthesis of long-period ground motions induced by this geological structure is performed assuming that huge earthquakes are generated around the epicenter of the 1946 Nankaido Earthquake, for which, four single fault plane source mechanisms of past earthquakes are analyzed. Thus, the A-Model is the source mechanism of the M8.0 Nankaido Earthquake, B-Model is that of the M8.2 Tokachi Oki Earthquake, C-Model is that of the M7.5 Hyuga-Nada Earthquake, and D-Model is a modified (M8.2) area of the source mechanism of the Nankaido Earthquake. Table 2 lists the source parameters of each model, and Fig. 3 shows the location of A-Model and the epicenter of the Nankaido Earthquake.

Table 2: Source Parameters of the Assumed Source Mechanism on the Nankai Trough

Parameter	A-Model	B-Model	C-Model	D-Model
Length (km)	150.0	100.0	56.0	300.0
Width (km)	70.0	150.0	32.0	100.0
Strike (°)	250.0	246.0	207.0	250.0
Dip (°)	25.0	20.0	17.0	10.0
Slip (°)	116.6	128.0	90.0	116.6
Magnitude	8.2	8.0	7.5	8.2
Seismic Moment (Dyne-cm)	1.5x1028	2.8x1028	1.5x1028	1.5x1028
Rise Time (sec)	9.3	11.2	3.9	9.3

Parametric analyses were also performed to investigate the influence of the rupture starting point location on the synthetic signals. As could be expected, the large size of the fault planes and the different wave incidence angles render the synthetic signals sensitive to this parameter. Fig. 5 shows the synthetic displacement time histories at Akashi Station, using event N038 as Green's function, and the acceleration response spectra (h=2%) of the synthetic signals obtained using B-Model as source mechanism. Long-period ground motions with maximum peak displacement values of about 50 cm are obtained for B and C models. For this case also the design spectra for the bridge envelops the synthetic ones quite well, especially those for the horizontal components.

DISCUSSION OF RESULTS

The synthetic long-period ground motions obtained at two stations of the Akashi Kaikyo Array for a hypothetical M 8.0 earthquake on the MTL show that maximum displacement peak values ranging from 20 to 30 cm could be expected at the bridge construction site. These values resulted from a sensitivity analysis performed for several source parameters, which were changed within a realistic range of values. The sensitivity analysis shows that the synthetic signals are quite stable to variations of the S wave and rupture propagation velocities, however they are considerably sensitive to the location of rupture starting point. Waveforms with the largest amplitude are obtained when it is located at the central part of the two-fault-plane source mechanism.

The synthetic signals obtained at both Akashi and Tarumi stations present similar waveforms and they are also similar to their corresponding Green's function, showing that the source mechanism has little influence on the signal's waveform. However, the maximum peak displacement value at the Akashi station is about 20 cm, smaller than that at the Tarumi station, where it is about 30 cm. This difference in amplitude is also reflected by the synthetic signals' spectral amplitudes, in which it is observed that the response spectra at the Akashi station present smaller amplitudes than those at the Tarumi station in the period range from 2 to 8 seconds, but are almost the same for longer periods.

The largest variability observed in the displacement amplitudes and frequency contents of the synthetic signals is owing to the event used as Green's function. This fact, that has been stated by several researchers [i.e. Bour and Cara, 1997], implies the importance of choosing representative earthquake records to be used as Green's function. In this study, it is assumed that far-field earthquake records can adequately represent the long-period range of small events generated by the MTL, due to the lack of records with good signal-to-noise ratio at long periods for the small events corresponding to the assumed source mechanism.

On the other hand, the 2% damping factor acceleration response spectra of synthetic signals obtained in this analysis, show spectral amplitudes lower or equal to the design spectra for the Akashi Kaikyo Bridge, except for the case when the Notohanto Oki Earthquake (N050) is used as Green's function. In this case, the synthetic response spectra become larger than the design spectra at periods around 9 seconds, especially in the vertical component. However, considering that the bridge's design spectra was calculated for a 150 year return period [Honshu Shikoku Bridge Authority, 1977], and the low probability of occurrence of an M 8.0 earthquake along the MTL (about 1000 years return period), it can be concluded that the hazard this geological structure represents to the bridge is acceptably included in its design spectra.

On the other hand, the synthetic long-period ground motions obtained at the bridge construction site assuming an M8.2 earthquake on the Nankai Trough present larger displacement amplitudes, with peak values of about 50 cm. The acceleration response spectra of these synthetic signals are also well enveloped by the design spectra for the bridge. Only some synthetic response spectra are larger than the bridge's design spectra, especially in its vertical component for periods longer than 10 sec. From these results it can be concluded that even though the deterministic seismic hazard posed by the MTL at the bridge construction site is greater than that from the Nankai Trough, the low probability of occurrence of huge earthquakes along this intraplate geological structure makes the Nankaido Trough to be the most hazardous seismic source for the Akashi Kaikyo Bridge.

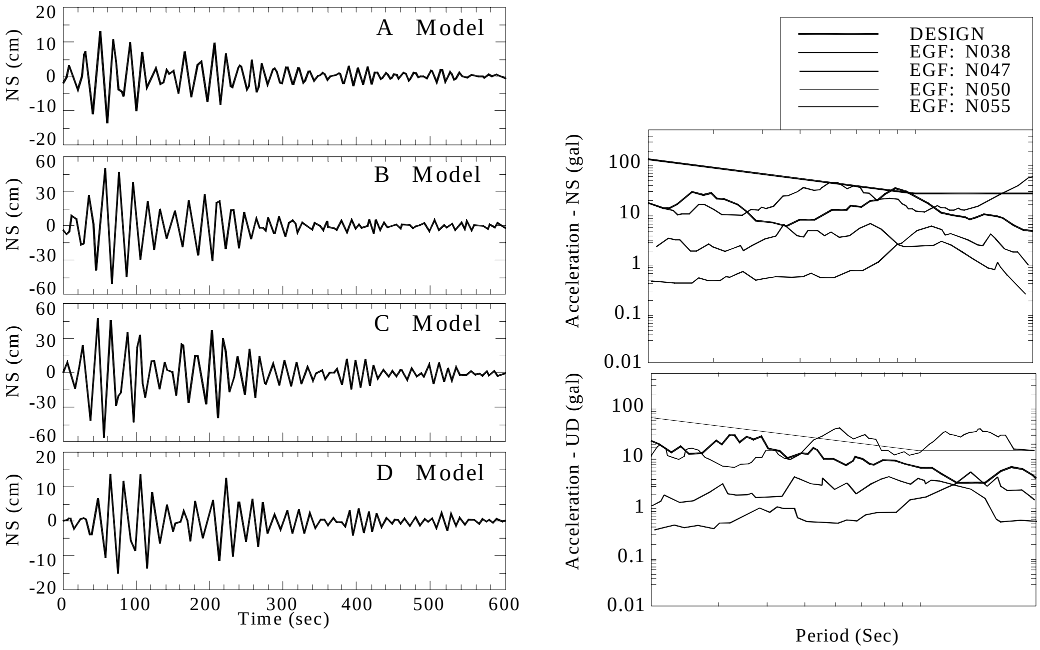

Fig. 5 Displacement time histories (left) and acceleration response spectra (right) of synthetic signals at Akashi station induced by an M 8.2 earthquake on the Nankai Trough.

CONCLUSIONS

a) Far-field records obtained at the Akashi Kaikyo Array Observation System are used to synthesize long-period strong ground motions around the bridge construction site. Huge earthquakes are assumed to be generated by two of the most hazardous geological structure in this area, namely: the Median Tectonic Line and the Nankai Trough.

b) The potential seismic hazard that the Median Tectonic Line represents to the Akashi Kaikyo Bridge is analyzed assuming a hypothetical M8.0 earthquake, which could be generated by faulting along the seismic gap of this geological structure.

c) The synthetic long-period ground motions thus obtained present peak displacements ranging from 20 to 30 cm, however almost all their response spectra are reasonably enveloped by the design spectra for the Akashi Kaikyo Bridge.

d) Spectral amplitudes for the worst scenario earthquake become marginally larger than the design spectra for the bridge, especially in its vertical component. However, considering that the design spectra was calculated for a 150 years return period, and the low probability of occurrence of a M 8.0 earthquake along the MTL, it is concluded that the hazard this geological structure represents to the Akashi Kaikyo bridge is acceptably included in its design spectra.

e) Hypothetical huge earthquakes in the Nankai Trough generate long-period ground motions whose peak displacements are about 50 cm at the bridge construction site. Most of the synthetic acceleration response spectra present lower or equal amplitudes than the design spectra for the bridge. However, for some combinations of source mechanism and earthquake record used as Green's function, the synthetic response spectra become marginally larger than the design spectra, especially in their vertical component, showing that for the worst scenario earthquake the bridge's vertical vibration mode becomes the most critical one.

These results show that the deterministic seismic hazard posed by the MTL at the bridge construction site is greater than that from the Nankai Trough. However, the low probability of occurrence of huge earthquakes along this intraplate geological structure makes the Nankai Trough to be the most hazardous seismogenic source for the Akashi Kaikyo Bridge.

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