Aseismic design of the Akashi Kaikyo bridge

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Summary

A four-station array observation system has been used to monitor the long-period seismic activity around the Akashi Kaikyo Bridge construction site. Since its installation in 1990, more than one hundred earthquake records, including aftershocks of the Hyogoken-Nanbu Earthquake, have been obtained. These records are used to synthesize long-period ground motions due to hypothetical huge earthquakes, using empirical methods. Seismogenic sources along the Median Tectonic Line of southwest Japan, and the Nankaido Trough are considered as possible sources of large earthquakes. The synthesized signals show peak displacement values of about 50 cm, although most of their acceleration response spectra show lower or equal level compared with the design spectra for the Akashi Kaikyo Bridge.

1. Introduction

The Akashi Kaikyo Bridge, the world's longest suspension bridge, has a center span of 1990 m and its fundamental vibration period is about 20 seconds. There have been few studies 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 monitor the long-period seismic activity in this area. The installed pick-ups are reliable from 0.0025 to 70 Hz, having a resolution of 0.00005 kine. More than a hundred of earthquake records have been obtained so far by this array. Long-period ground motions were observed for far-field large earthquakes, which present peak displacement values of about 7 mm and dominant periods from 8 to 20 sec. Short-period ground motions of near-field small earthquakes were also observed, most of them corresponding to aftershocks of the Hyogoken-Nanbu Earthquake. These events show different features reflecting the effect of local soil conditions.

In the present study, records obtained by this array observation system are used as empirical Green's functions for estimating long-period ground motions around the bridge construction site, induced by hypothetical huge earthquakes. Seismogenic sources along the Median Tectonic Line of southwest Japan, and the Nankaido Trough are assumed as sources of large earthquakes, for which, synthetic ground motion are obtained to verify the design spectra for the Akashi Kaikyo bridge. The empirical Green's function simulation technique and source mechanisms of several past large earthquakes are used to synthesize these long-period ground motions.

2. Observed Earthquake Ground Motion

During the observation period, a total of 156 earthquake ground motions were recorded by this array, almost half of them being aftershocks of the 1995 Hyogo-ken Nanbu Earthquake. The number of observed records varies among the station, since they were triggered independently one another. A great variety of earthquake ground motion signals have been recorded from near-field small earthquakes to far-field large earthquakes with magnitude larger than M 7.0 and hypocentral distance longer than 1500 km.

The far-field earthquake records present peak displacements less than 7 mm, and dominant periods ranging from 8 to 20 sec, similar to the fundamental vibration periods of the Akashi Kaikyo Bridge. Some of these earthquake records are shown in Fig. 2, which are used in this study as empirical Green's function to synthesize long-period ground motions.

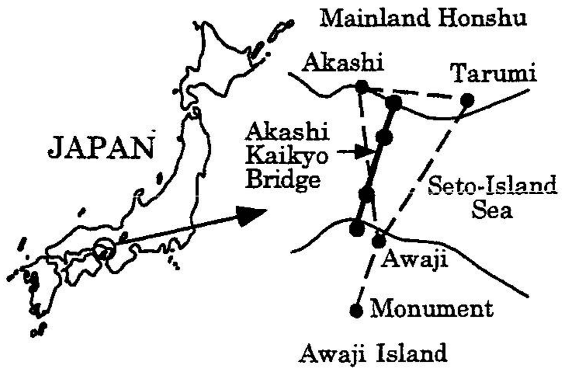

Fig. 1 Location of the Akashi Kaikyo Bridge along with location of the array observation system

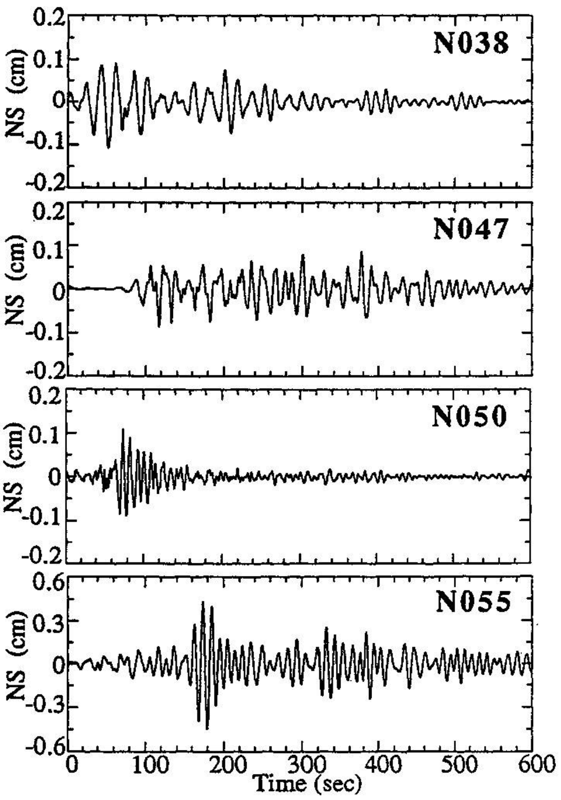

Fig. 2 Displacement time histories of events used as EGF, recorded at Akashi Station.

3. Synthetic Long-period Ground Motion Induced by a Huge Earthquake

The main concern of this study is to analyze the possible sources of huge earthquakes, that could generate long-period strong ground motion in the Akashi Kaikyo Bridge construction site. In this sense, two geological structures were identified, one being the Median Tectonic Line of southwest Japan (hereafter MTL), and another the Nankaido Trough, both of them south from the site of interest. Thus, hypothetical huge earthquake are assumed to be generated by these two seismogenic sources and, using the empirical Green's function method, synthetic ground motions are obtained at the array stations, which are compared with the design spectra for the bridge.

Simulation Method

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 here, in which the synthetic strong ground motion $U(t)$ is given by

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

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, i and j the specifying number of small event when the fault plane of the large earthquake is divided into NxN sub-elements, the notation * represents convolution. $F(t)$ and t_{ij} are defined as

EGF	Date	Mag.	Epicent. Dist.(km)	Depth (km)	Azimuth (°)
N038	92.07.30	7.0	932.0	0.0	237.9
N047	93.01.15	7.8	1132.0	120.0	225.8
N050	93.02.07	6.6	395.0	25.0	210.7
N055	93.07.12	7.8	964.8	27.0	202.5

Table 1 Parameters of the recorded signals used as Green's Functions

Fault Parameter	Fault 1	Fault 2
Length (km)	60.0	45.0
Width (km)	20.0	20.0
Strike (°)	263.0	257.3
Dip (°)	82.5	75.0
Slip (°)	180.0	180.0
Seismic moment	$2.2\text{x}10^{27}$	$1.4\text{x}10^{27}$

Table 2: Parameters of the two-fault-plane source mechanism along the MTL

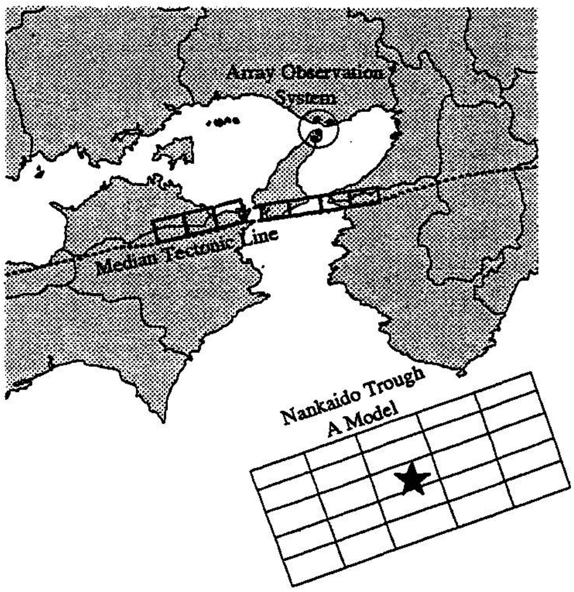

Fig. 3 Assumed two-fault-plane source mechanism on the MTL, along with the A model source mechanism on the Nankaido Trough.

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

and

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

where, r_o is the distance from the rupture starting point to the site, ξ_{ij} the distance from the rupture starting point to each sub-element (i,j). V_s and V_r are the S wave and rupture propagation velocities, τ the target event's 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. N is given by the ratio of seismic moments of the large and small earthquakes.

In order to include irregularities to the rupture-front propagation, to avoid spatial aliasing, the rupture propagation velocity V_r is changed randomly as follows:

$$t_{ij}=\frac{r_{ij}-r_0}{V_S}+\frac{\xi_{ij}}{V_r}+t_{rnd} \quad (4)$$

where t_{rnd} varies randomly from $-0.1\xi_{ij}/V_r$ to $0.2\xi_{ij}/V_r$ (Takeo and Kanamori, 1997).

Green's Functions

Simulation of long-period strong ground motions using EGF method requires that small events used as Green's function must have a good signal-to-noise ratio at long periods. Since most of the near-field earthquake records obtained by the Akashi Kaikyo array observation do not present this characteristic, we opted for using records of large far-field earthquakes, which inherently present long-period waveforms.

Four events recorded at Akashi station are used as Green's functions, namely: The M7.0 Sanriku Haruka Oki earthquake (N038), the M7.8 Kushiro Oki earthquake (N047), the M6.6 Notohanto Oki earthquake (N050), and the M7.8 Hokaido Nansei Oki earthquake. These events' parameters are listed in Table 1.

Fig. 2 shows the displacement time history of these four events recorded at Akashi station. These records were band-pass filtered in the range [0.05 - 0.5] Hz, which is the frequency range of interest for this study. Peak displacements ranging from 0.1 to about 0.5 cm are observed, and their dominant periods ranges from 8 to 20 sec.

Seismogenic Source on the Median Tectonic Line

After the 1995 Hyogo ken Nanbu Earthquake, the potential hazard that the MTL represents to the Akashi Kaikyo Bridge is investigated. Despite the recently high seismic activity observed along this geological structure, historical records for about 1000 years show that no destructive earthquake have occurred directly related with it. However, studies on seismicity of the MTL state that earthquakes with magnitudes as large as M 8.0 could occur owing to faulting along its active segment (Shiono, K., 1980).

Since long-period (2 to 20 sec) ground motions generated by huge earthquakes are of primary concern, a magnitude M 8.0 earthquake is assumed to be generated by this geological structure in this study. Thus, after the MTL's segmentation given by Kanaori et al (1994), two fault planes with a total length of 105 km, extending from eastern Shikoku to western Kii Peninsula, are assumed as its source mechanism (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 M 8.0 earthquake. The parameters of this source mechanism are listed in Table 2.

To analyze the effects of S wave and rupture propagation velocities, and of rupture starting point location on the synthetic signals, two parametric analyses are done. In the first one, for a given position of the rupture starting point, four sets of S wave and rupture propagation velocities, varying from 2.5 to 4.0 km/sec and from 2.0 to 3.2 km/sec respectively, are analyzed. Waveform and response spectra of the synthetic signals show similar characteristics in all the cases, reflecting little influence by these parameters.

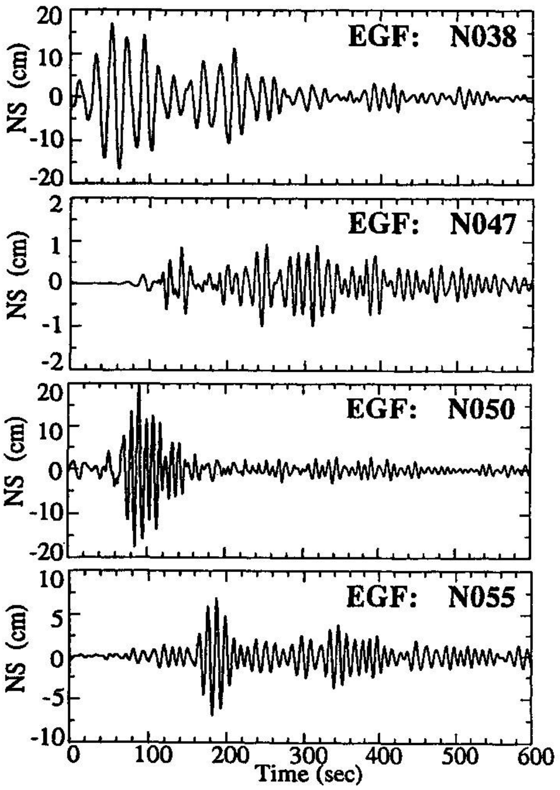

Fig. 4 Synthetic displacement time histories at Akashi Station induced by the MTL two fault plane source mechanism.

The second parametric analysis is done locating the rupture starting point in each sub-element of the fault planes. The S wave and rupture propagation velocities are fixed to 3.5 and 2.8 km/sec respectively. Waveforms and response spectra present larger amplitudes when the rupture starting point is located vertically at the middle part and horizontally near the common edge of the two fault planes. Synthetic displacement time histories that present the largest amplitudes are shown in Fig. 4 for each record used as Green's functions. In every case the waveforms of the synthetic signals are similar to their Green's function, and maximum displacement peak values of about 20 cm are observed. Fig. 5 shows the horizontal (NS) and the vertical (UD) component acceleration response spectra of these synthetic signals for 2% critical damping, compared with the design spectra for the Akashi Kaikyo bridge. The design spectra reasonably envelopes the synthetic ones.

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	1.5×10^{28}	2.8×10^{28}	1.5×10^{28}	1.5×10^{28}
Rise Time (sec)	9.3	11.2	3.9	9.3

Table 3 Fault parameters of source mechanisms assumed on the Nankaido Trough

Seismogenic Source on the Nankaido Trough

Another geological structure considered in this study is the Nankaido Trough, which can generate large earthquakes with magnitude as large as M 8.4 according to historical records. Huge earthquakes are assumed to be generated by this structure around the epicentral 1946 Nankaido Earthquake, for which, four single fault plane source mechanisms of past large earthquakes are analyzed. A-Model is the M 8.0 Nankaido earthquake's source mechanism, B-Model is the M 8.2 Tokachi Oki earthquake's one, C-Model is that of the M 7.5 Hyuga-Nada earthquake, and D-Model is a modified (M 8.2)area of the source mechanism of the Nankaido earthquake. Table 3 lists the fault parameters of each model, and Fig. 3 shows the location of A-Model source mechanism.

A parametric study to analyze the influence of the rupture starting point location on the synthetic signals is done for the four source mechanisms. As could be expected, the large size of the fault planes and the different wave incidence angles render the synthetic sensitive to this parameter. Maximum peak displacement values of about 50 cm are obtained for B and C models, for the case in which the event N038 is used as Green's function (Fig. 6). As can be observed in Fig. 6, the waveform of the synthetic signals are similar to that of the observed one (Fig. 2), showing that the source mechanism has little effect on the signal's waveform.

Fig. 7 shows the acceleration response spectra of the synthetic signals obtained for the four records used as Green's functions, using B Model as source mechanism. The upper part of this figure shows the response spectra of NS component, and the vertical one is shown at the bottom. In this case also the design spectra for the bridge envelopes the synthetic ones quite well, especially those for the horizontal components.

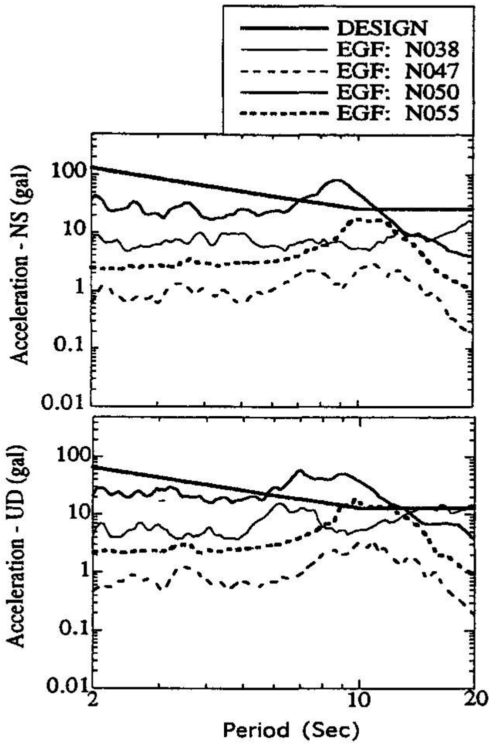

Fig. 5 Comparison of the acceleration response spectra of synthetic signals induced by the MTL (h=2%) with the design spectra for the Akashi Kaikyo Bridge. Components NS (top), and UD (bottom)

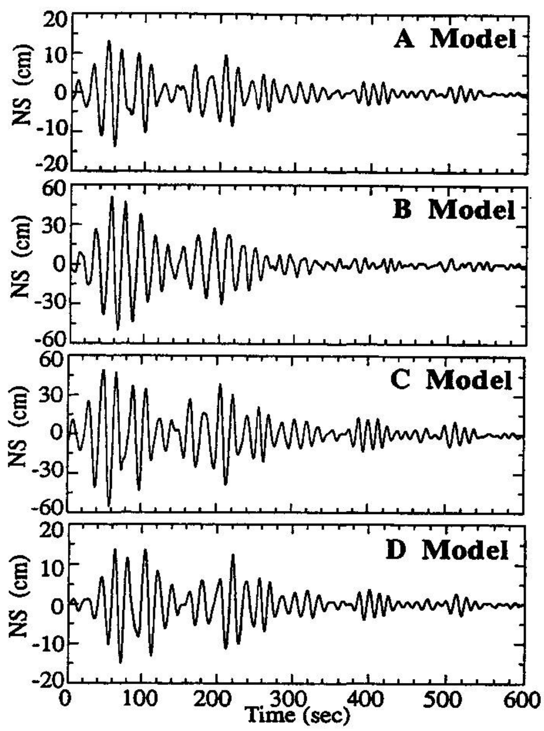

Fig. 6 Synthetic displacement time histories at Akashi Station induced by the Nankaido Trough. Event N038 is used as Green's function for each source model.

4. Discussion of Results

The results found in this study show that a hypothetical M 8.0 earthquake, that could occur on the Median Tectonic Line, would generate long-period ground motion with maximum peak displacement values of about 20 cm at the Akashi Kaikyo Bridge construction site. Synthetic acceleration response spectra obtained in this analysis show amplitudes lower or equal to the design spectra for the bridge. In this case, only when the Notohanto Oki Earthquake (N050) is

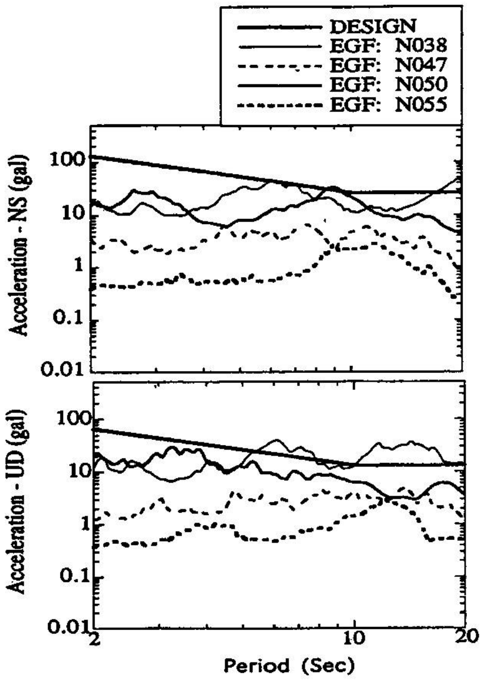

Fig. 7 Acceleration response spectra of synthetic signals induced by B model on the Nankaido Trough (h=2%) compared with the design spectra for the Akashi Kaikyo Bridge. Components NS (top), and UD (bottom)

used as Green's function, the synthetic response spectra becomes larger than the design spectra at periods around 9 sec. Therefore, considering that the design spectra was calculated for a 150 years return period, and the low probability of the occurrence of a M 8.0 earthquake along the MTL (about 1000 years return period), it can be concluded that the hazard this tectonic structure represents to the bridge is acceptably included in its design spectra.

On the other hand, the synthetic signals obtained at the bridge construction site, assuming a magnitude M 8.2 earthquake on the Nankaido Trough, present larger displacement amplitudes, with peak values of about 50 cm. However, most of their acceleration response spectra are enveloped by the design spectra for the bridge. In this case, only the response spectra of the signal obtained using event N038 as Green's function are larger than the design spectra, especially in its vertical component for periods longer than 10 sec. Therefore, for the worst earthquake case scenario the bridge's vertical vibration mode is the most critical one.

5. Conclusions

1. Earthquake 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 Nankaido Trough.

2. Synthetic ground motions generated by an assumed M8.0 earthquake in the MTL present peak displacements of about 20 cm; however their response spectra are reasonably enveloped by the design spectra for the Akashi Kaikyo Bridge.

3. Hypothetical huge earthquakes in the Nankaido Trough generate long-period ground motions whose peak displacement are about 50 cm in the bridge construction site. Most of the synthetic response spectra present lower or equal amplitudes than the design spectra for the bridge; however, for the worst earthquake case scenario the bridge's vertical vibration mode becomes the most critical one.

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