STUDY OF CRUSTAL STRUCTURE UNDER THE AKASHI KAIKYO BRIDGE AND ITS APPLICATIONS TO SYNTHESIS OF NEAR-FIELD GROUND MOTION

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A series of explosion seismic experiments were conducted along the *1995 Keihoku-Seidan Profile*. Most of the records acquired during the experiments at the foundations of the Akashi Kaikyo Bridge had very poor S/N ratio. However, the explosion signals could be detected successfully after enhancing the records, and the crustal structure under the Akashi Strait could be subsequently derived. The revealed crustal structure was used in synthesis of strong motions recorded in Kobe during the Hyogo-ken Nanbu Earthquake. By using a model with small subfaults in the analysis, the synthetic waveforms may have the same order of amplitudes and frequency ranges as the recorded ones. This model may be useful in the synthesis of strong motions for engineering purposes.

1. INTRODUCTION

The Hyogo-ken Nanbu Earthquake (M_{JMA} 7.2), occurred on January 17, 1995, caused severe damage and loss of life in Kobe and Awaji Island. The hypocenter of the earthquake, according to the Japan Meteorological Agency (JMA)[1], was at 34.607° N latitude and 135.043° E longitude with a depth of 14.3 km. The epicenter was located just about two km east of the Akashi Kaikyo Bridge, which was under construction at the time. The earthquake caused considerably large permanent horizontal and vertical displacements at the anchorages and piers of the bridge. The displacements were induced mainly by creep of the crust, without any significant slips occurred at the bases of the foundations.[2),3)]

The first stage in seismic response analysis of the bridge due to the earthquake is to derive reliable input ground motions at the foundations of the bridge. This is commonly called synthetic seismogram. There are two significant parameters in the synthetic seismogram: the source rupture process and the medium structure.

Key Words: 1995 Keihoku-Seidan explosions, crustal structure, synthetic seismogram

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The characteristics of seismic waves are governed by the elastic properties of the medium where the waves are propagated through. The crustal structure under the bridge have been derived by the same authors[4)], by utilizing a new series of explosion seismic data recorded at the foundations of the bridge. The results are presented briefly in this paper. The application of the revealed crustal information in synthetic seismogram is also presented. The results presented here are the first stage results of on-going studies in deriving the input motions at the foundations of the Akashi Kaikyo Bridge generated by the Hyogo-ken Nanbu Earthquake.

2. CRUSTAL STRUCTURE UNDER THE AKASHI STRAIT

Before the Hyogo-ken Nanbu Earthquake, a number of crustal investigations by utilizing explosion seismic experiments had been conducted along profiles crossing the Akashi Strait. The first one was a series of explosions done in Miboro, Gifu Prefecture from 1957 to 1960.[5),6)] Temporary observatory stations were aligned in three profiles in the central part of Honshu Island, with one of the profiles crossing the Akashi Strait. The Miboro explosion points were located approximately 230 km north-east of

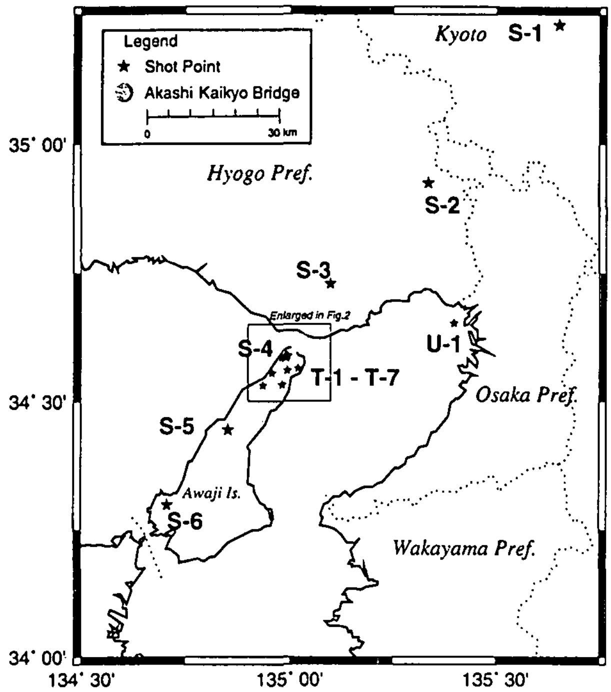

Fig.1 1995 Keihoku-Seidan explosion points.

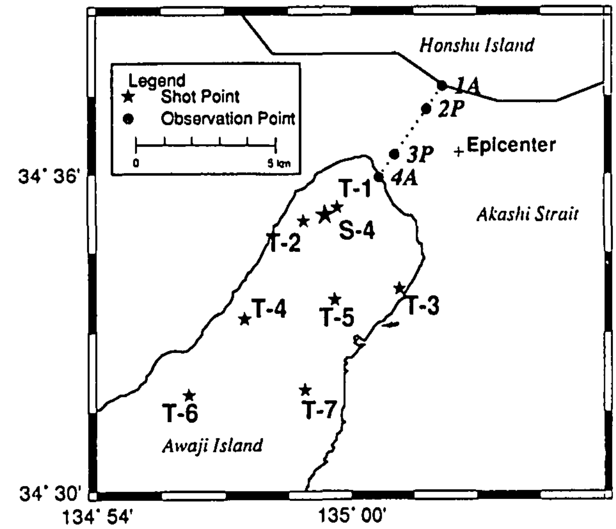

Fig.2 Northern tip of Awaji Island.

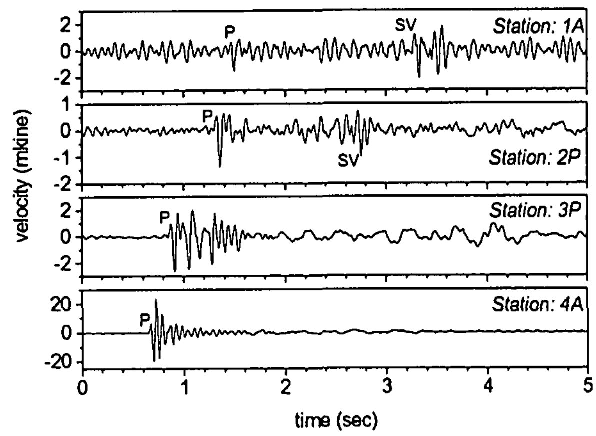

Fig.3 Vertical components recorded during the explosion S-4.

the Akashi Strait. The second one was an explosion done in Toyama, Kochi Prefecture, Shikoku in December 1965.[7),8)] This explosion was intended to be the reverse shot of the Miboro explosions. Eighteen observatory stations were temporarily aligned in a profile starting from Kochi to the north of the Biwa Lake, with intervals of 20 - 30 km. The Akashi Strait was located about 170 km north-east of the Toyama explosion point. With such long epicentral distances, the explosion waves recorded in the vicinity of the Akashi Strait during the two experiments were expected to have refracted or reflected from the basaltic layers of the crust or the upper-mantle layers. Thus, the information of the shallow crustal structure under the Akashi Strait revealed from these experiments was very approximate. In order to study the seismic response of the Akashi Kaikyo Bridge due to the Hyogo-ken Nanbu Earthquake, more detailed crustal structure under the Akashi Strait is necessary.

After the earthquake, a series of explosion seismic experiments were carried out along a profile starting from Kyoto District to the southern region of Awaji Island. These experiments were conducted by the Research Group of Explosion Seismology (RGES) from December 12 to 15, 1995. **Figure 1** shows the map of the profile that was named as the *1995 Keihoku-Seidan Profile*. The star marks indicate the shot points accompanied by the explosion names, and the shaded circle denotes the location of the Akashi Kaikyo Bridge. The length of the profile was about 140 km and a total of fourteen explosions were done during the three days of experiments.

We, as an independent group from the RGES, took part in the experiments to record the explosion signals on the four foundations of the Akashi Kaikyo Bridge. **Figure 2** shows a detailed map of the northern tip of Awaji Island. The dotted line and four solid circles indicate the bridge and its four foundations (1A, 2P, 3P and 4A). A and P denote anchorage and pier, respectively. The star marks indicate the eight shot points carried out in this area. The cross mark points the epicenter of the Hyogo-ken Nanbu Earthquake.

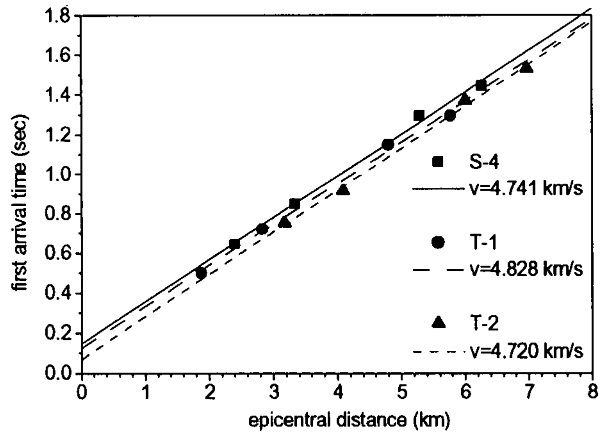

Fig.4 Travel-time curves of the P-waves from the shot points S-4, T-1 and T-2.

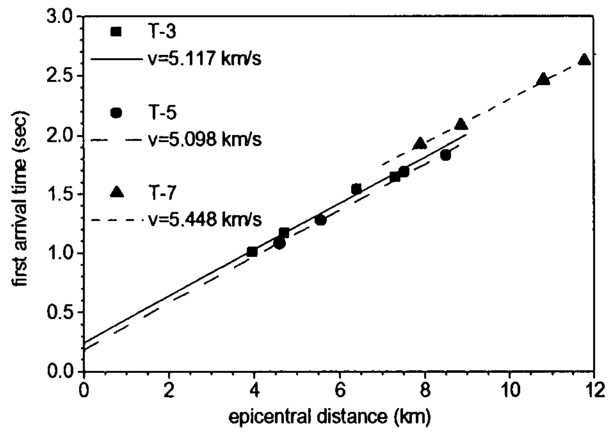

Fig.5 Travel-time curves of the P-waves from the shot points T-3, T-5 and T-7.

Vertical components recorded at 1A, 2P, 3P and 4A during the explosion S-4 are shown in **Fig.3** from top to bottom, respectively. The reference time (0.0 s) is the explosion time. The first arrivals of the P-waves, denoted by P in the figure, could be detected clearly in the four records due to large explosive charge and short epicentral distances. The SV-waves were also detected in the records at 1A and 2P.

Out of the fourteen explosions done during the experiments, only explosion signals from three events, namely S-4, T-1 and T-3, could be clearly detected in the raw records. The data recorded during the other explosions had very poor signal to noise (S/N) ratio. In order to detect the arrivals of the explosion waves in these records, it was necessary to separate the explosion signals from the noise. It could be sufficiently done by band-pass filtering since the explosion signals and

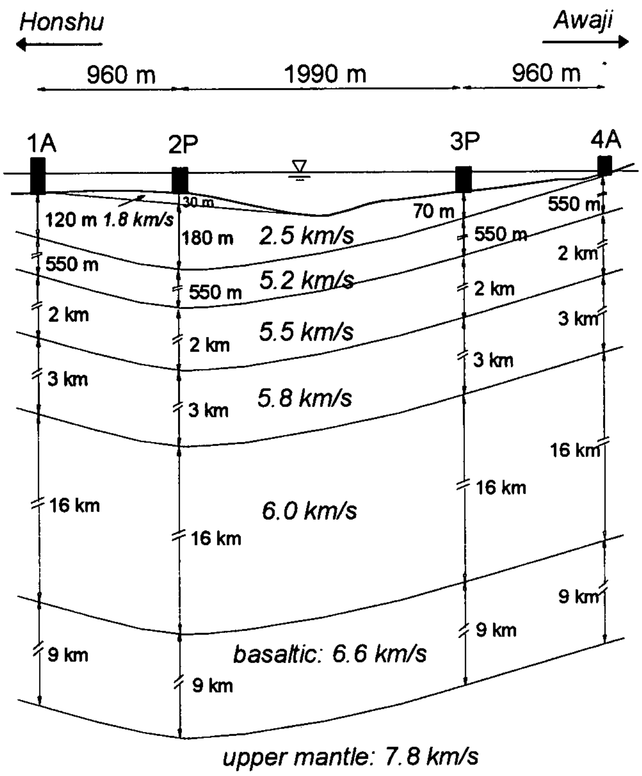

Fig.6 The complete crustal structure under the Akashi Kaikyo Bridge after justifications.

the noise showed distinct frequency bands. After the filtering process, the explosion signals could be detected in almost all records.

Figure 4 shows the travel-time curves of the P-waves originated from the explosion points S-4, T-1 and T-2, which were located closest to the bridge. All the sources were located south of the bridge, thus the P-waves arrived at 4A (southern anchorage) first and propagated subsequently to the north. The linear regression lines for the three events are also shown in the figure. The apparent velocities of the P-waves from these events, which correspond to the slope of the regression lines showed similar values. These waves may be assumed to have propagated through the same layer that has the same velocity.

Figure 5 shows the P-wave travel-time curves for the explosions T-3, T-5 and T-7. The shot points of T-3 and T-5 were located about 4 km south of 4A, and the shot point of T-7 was about 8 km. The apparent velocities of the P-waves from T-3 and T-5 were in the order of 5.1 km/s and that from T-7 was 5.448 km/s. These velocities were higher than those of the previous three events (S-4, T-1 and T-2). These results suggest that the apparent velocities increased

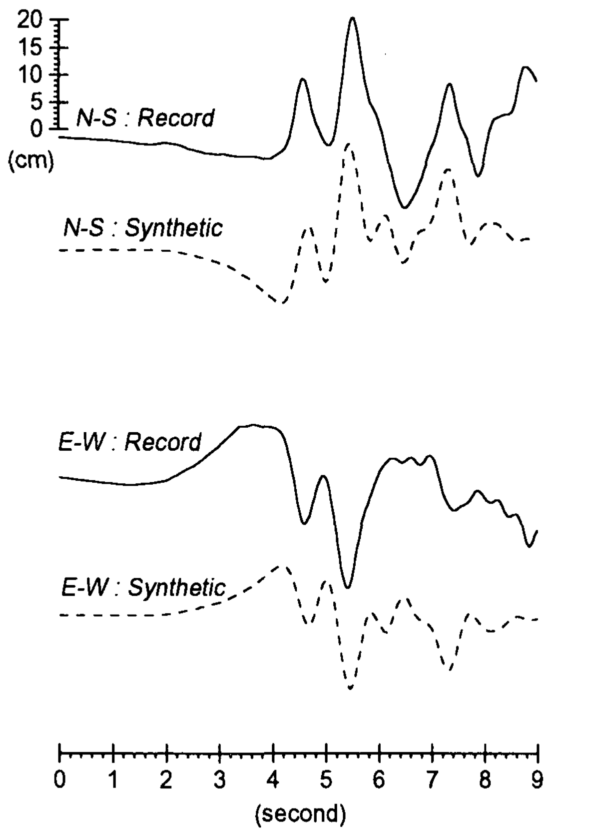

Fig.7 recorded and synthetic displacement waveforms at Kobe-JMA

with the increase of the epicentral distance. This is reasonable because the P-waves originated from sources located farther may propagate through deeper layers that are generally harder and have higher velocities. Thus, the P-waves from T-3 and T-5 were assumed to propagate through the same deeper layer, and that from T-7 propagated through yet deeper layer.

The P-waves from the explosion S-6, which was located 43.5 km south-west of 4A showed an apparent velocity of 5.897 km/s. Thus, it was consistent with the above findings.

The crustal structure under the Akashi Kaikyo Bridge was derived from the travel time of the explosion signals by assuming a structure with dipping interface between the sediment layer and the crustal layer below it.[4] The complete crustal structure, shown in **Fig.6** , was obtained after several justifications. The velocity values shown in the figure are the P-wave velocities of the corresponding layers. The thin sediment layer under 2P, with P-wave velocity of 1.8 km/s, was

Table 1 elastic properties of medium

Layer no.	v_p (km/s)	v_s (km/s)	ρ (g/cm^3)	Depth (km)	Q_p	Q_s
1	1.80	0.80	2.00	0.00	60	30
2	2.50	1.00	2.10	0.07	60	30
3	5.20	2.90	2.50	0.17	200	100
4	5.50	3.20	2.60	0.72	400	200
5	5.80	3.30	2.60	2.72	500	250
6	6.00	3.46	2.70	5.72	600	300
7	6.60	3.81	2.80	21.72	800	400
8	7.80	4.50	3.20	30.72	1000	500

adjusted from soil data obtained from bore holes done prior to the construction of the bridge. The basaltic and upper-mantle layer was adjusted from the travel-time data of the Miboro and Toyama explosions.[8]

3. SYNTHETIC SEISMOGRAM

Many studies have been done in analyzing the source rupture process of the Hyogo-ken Nanbu Earthquake by inverting the strong motion alone[9], and with the teleseismic and geodetic data in unison.[10),11] Although these studies were conducted in different ways, the results showed many similar features. The results of the inversions indicated that the largest slips occurred in the northern, shallow part of the Nojima Fault and around the hypocenter.

The synthesis of horizontal displacement, recorded at a JMA station in Kobe, was done. The Kobe-JMA station is located 15.4 km north-east of the epicenter. The station is founded on middle Pleistocene Period deposit, which is approximated to have a P-wave velocity of 1.8 km/s. The crustal structure under the station was assumed to be the same as that found under the Akashi Strait **(Fig.6)**, and its elastic properties are given in **Table 1**.

The synthesis was done for the first 6.0 s of the main rupture occurred around the hypocenter, according to the rupture history derived from joint inversion.[10] The moment of the rupture was estimated to be 7.2 x 10^{18} Nm (about 36% of the total seismic moment). The size of the subfaults used in the synthesis was 1 km x 1 km, and rupture velocity was set to be 2.8 km/s (about 80% of local shear velocity). The rise time was approximated to be 0.72 s. The large slip in the shallow part of the Nojima Fault was excluded in the analysis since it did not generate large ground motion in Kobe.[11] This could be explained that the rupture in the Nojima Fault was directed away from Kobe, thus radiating more energy away from the city, and the rate of the slips was slow.

Figure 7 shows the recorded and synthetic horizontal ground displacement at the Kobe-JMA. The displacement records were obtained by integrating twice the original accelerograms. Time-axis linear trend have been removed from the records, but no filtering was applied to them. The synthetic displacements in both directions agree quite well with the recorded ones in order of amplitude and frequency. The source rupture process[10] used in the synthesis was derived from low frequency band (lower than 1.0 Hz) waveforms, with large subfaults (4 km x 4 km) and consequently long rise time (3 s). **Figure 7** shows that by using smaller subfaults and shorter rise time, the synthetic waveform may have the same order in amplitude and frequency range as the recorded waveform.

4. CONCLUSION

In the seismic response analysis of the Akashi Kaikyo Bridge, the crustal information under the bridge is very significant because the elastic properties of the crust govern the propagation characteristics of the seismic waves. The *1995 Keihoku-Seidan* explosions provided sufficient data to reveal the detailed shallow crustal structure under the bridge.

Although the source rupture history that was used in the analysis was derived from low frequency band waveforms, it is applicable in the synthesis of seismograms in the frequency ranges of engineering interest. By dividing the ruptured fault plane into many smaller subfaults (dimension of 1 km x 1 km or less) and consequently assigning shorter rise time, the synthetic waveforms may have the same order in amplitudes and frequency ranges as the recorded ones. This model may synthesize the strong motions that would be useful for engineering purposes.

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明石海峡大橋下での地殻構造及び近地地震動の合成への適用に関する研究

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一連の爆破実験が 1995 京北―西淡測線に沿って行われた。明石海峡大橋の土台に於いて、実験の間に取られた殆どの記録は大変 S/N 比が悪いものであった。しかしながら、記録にフィルターをかけた後では爆破の信号をうまく捉える事が出来、それにより明石海峡での地殻構造が導かれた。明らかになった地殻構造は神戸で記録された強震動との合成に使われた。解析で小さい副断層を含めたモデルを使う事によって、合成波形は記録されたものと同じオーダーの振幅と周波数領域になった。このモデルは工学目的における強震動との合成に有用である。