Beamformed Green Function Synthesizing Procedure for Near-Field Strong Ground Motions

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The Beamformed Green Function (BGF) synthesizing procedure is intended to synthesize multiple seismic inputs for large-scale structures induced by near-field earthquakes. This procedure, based on a set of array records of small events, allows to estimate the strong ground motion at any place into the array's aperture, taking into account the geometrical effect of near-field earthquakes. The reliability of this procedure is discussed using recorded data of the 1995 Hyogo-ken Nanbu Earthquake in Osaka area. Thus, using aftershock records of this earthquake at three stations of CEORKA's array, synthetic strong ground motions are obtained at another two station by both the BGF method and Irikura's synthesizing procedure. It is found that both synthetic signals at these two stations have similar wave shape, but the ones obtained by BGF procedure present smaller amplitudes, specially in the low frequency range. Also, both synthetic signals present some different wave shape than the observed mainshock; however, their Fourier and response spectra acceptably match to that of the observed signal.

Key Words:* *Beamforming algorithm, Green functions, Array aperture, Synthetic strong ground motions.

1.- Introduction

The Beamformed Green Function (BGF) synthesizing procedure presented here, is intended to synthesize strong ground motions signals of near-field earthquakes, based on a set of array records of small events. This method takes advantage of beamforming algorithms to generate the empirical Green functions at any point into the array's aperture, taken into account the geometrical effect of near-field earthquakes; then, the Irikura's semi-empirical synthesizing procedure is used to synthesize the strong ground motions at any specific location.

Formerly this procedure was intended to synthesize multiple seismic inputs for large-scale structures induced by near-field earthquakes, however, it could also be used in broader areas for estimating the representative strong ground motions for seismic hazard assessment. In this sense, the mainshock and aftershocks data of the Hyogo-ken nanbu earthquake recorded by CEORKA's array in Osaka region are used to verify the applicability of this procedure.

2.- Beamformed Green Function Method

The BGF procedure combines the Irikura's semi-empirical Green function method with the Delay-and-Sum beamforming algorithm. Thus, the fault area of the large event is divided into NxN subfaults whose area coincides with the small event's one. Then, assuming the small event is located in each subfault, the empirical Green functions are generated by Delay-and-Sum beamforming algorithm at a given site into the array's aperture (Fig. 1). Finally, these beamformed Green functions are used to synthesize the strong ground motion.

The Delay-and-Sum beamforming algorithm consists in applying appropriate delays to the signals recorded at each sensor of an array, and adding them together to obtain a reinforced signal. These delays are directly related to the lenght of time it takes for the signal to propagate between sensors.

When the source is located in the array's near-field it is assumed the signal *s(t)* spreads spherically into space. Then, by the spherically symmetric solution of the wave equation, the signal $y_m(t)$ recorded by the *mth* sensor has the form

$$y_m(t) = s\left(t - {r_m^0}/{c}\right) \Big/ r_m^0 \qquad (1)$$

where, r_m^0 is the distance from source to the *mth* sensor, and c represents wave propagation velocity. By choosing the delay

$$\Delta_{m,ij} = \frac{r_{ij}^0 - r_m^0}{c} \qquad (2)$$

we can stack the signal replicas captured by all M sensors so that they reinforce each other. Therefore, the beamformer's response to a spherically propagating wave becomes

$$u_{ij}(t) = \sum_{m=0}^{M-1} w_m \frac{r_m^0}{r_{ij}^0} y_m\left(t - \Delta_{m,ij}\right) \qquad (3)$$

where r_{ij} is the distance from the site of interest to the source, and w_m is the mth sensor's weight used for optimizing the array gain.

Once the beamformed Green functions at the site of interest, corresponding to each subfaults *(i,j)* are obtained, the synthetic strong ground motion *U(t)* for the large event is given by

$$U(t) = \sum_{i=1}^{N}\sum_{j=1}^{N}\left(\frac{r}{r_{ij}^0}\right) F\left(t - t_{ij}\right) * u_{ij}(t) \qquad (4)$$

where the notation * represents convolution,

$$F(t) = \delta(t) + \frac{1}{n'}\sum_{k=1}^{(N-1)n'} \delta\left[t - \frac{(k-1)\tau}{(N-1)n'}\right] \qquad (5),$$

and

$$t_{ij} = \frac{r_{ij}^0}{V_c} + \frac{\sqrt{\xi_i^2 + \eta_j^2}}{V_r} \qquad (6)$$

The meaning of notations is refered to Irikura (1986).

3.- Application in Osaka Area

Seismic data of the 1995 Hyogo-ken nanbu earthquake, recorded by the CEORKA's array in Osaka area are used to analyze the applicability of this procedure in a broad area. Three stations, Tadaoka (TDO), Fukushima(FKS), and Yae (YAE), are assumed to configure a triangular array, and synthetic signals of the mainshock are obtained by both BGF and Irikura's procedure, at Abeno (ABN), and Sakai (SKI) stations. The location of these stations are shown in Fig. 2, along with the fault plane projection and mainshock (event N001) and aftershocks epicenters.

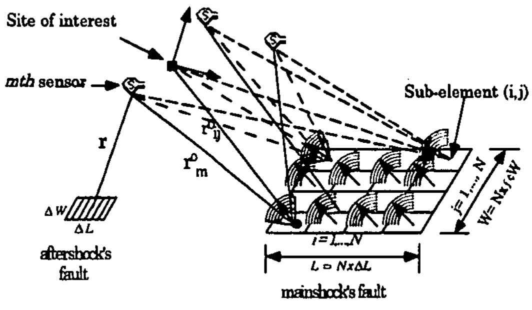

Fig. 1: Empirical Green functions are generated by beamforming algorithm at each sub-element of the mainshock's fault plane.

The source mechanism proposed by Ide et al (1996), consisting in a single fault plane is used in the synthesizing procedure. However, in order to use two events as empirical Green functions, it was divided into two, and in the Kobe area the upper boundary of the fault was considered to be 4 km under the ground surface, as it is shown in Fig. 3. The January 23, M4.5 aftershock (N006), and the October 14, M4.8 aftershock are used in the Awaji and Kobe area of the fault respectively.

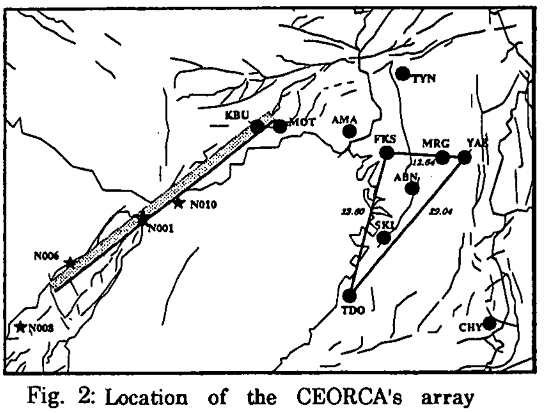

Fig. 2: Location of the CEORCA's array stations along with the mainshock and aftershocks epicenters, and the fault plane horizontal projection.

The energy released from each area of the fault is assumed to be 45% and 55% in the Awaji and Kobe region (Wald,D., 1996), and stress drop ratios between large and small events were estimated to be about 2.0. S wave propagation velocity of 3.2 km/s, and rupture propagation velocity of 2.8 km/s have been used in the analysis.

4.- Results and discussion

Synthetic strong ground motions were obtained by both, BGF method and Irikura's semi-empirical synthesizing procedure, at Abeno (ABN) and Sakai (SKI) stations. While in the BGF procedure, aftershocks data recorded at three station (TDO, FKS, and YAE) were used to obtain the beamformed Green function at ABN and SKI stations, in the Semi-Empirical method the aftershocks signals recorded at these two stations were used as empirical Green functions.

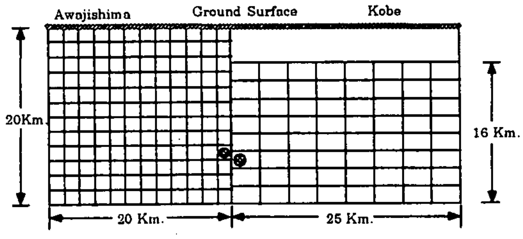

Fig. 3: Fault rupture model, and locations of rupture starting points (Modified after Ide et al, 1996)

The EW component of observed and synthetic velocity time histories at ABN station are shown in Fig. 4, and Fig. 5 shows their acceleration and velocity response spectra.

As it can be seen in these figures, the synthetic signals obtained by both procedures present lower amplitudes in the low frequency range. This characteristic is also observed in the other components of the signal. Fig. 6 and Fig. 7 depict the corresponding velocity time histories, and response spectra for the signal at SKI station. They also show low amplitudes in the low frequency range.

Fig. 8 shows the Fourier spectra of synthetic and observed signal at ABN and SKI stations. Here also can be observed that they fit better in the high frequency range. The synthetic signals present lower amplitudes for frequencies around 1 Hz, however for frequencies less than 0.1 Hz their amplitudes are larger than that of the observed ones. Since the synthetic signals obtained by both procedures present the same patterns, it is possible that the difference with the observed signal is owing to local site effects.

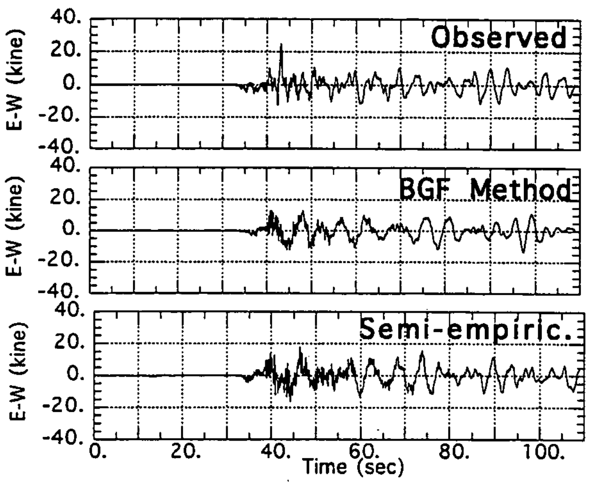

Fig.4: Velocity time histories of Observed and and Synthetic signals of the mainshock at Abeno Station. Component E-W.

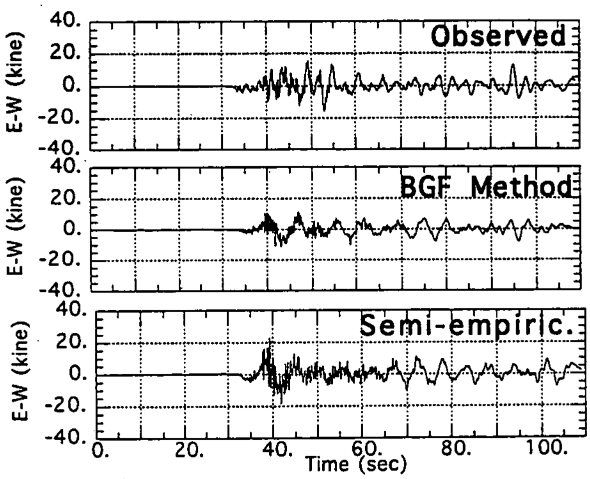

Fig.6: Velocity time histories of Observed and and Synthetic signals of the mainshock at Sakai Station. Component E-W.

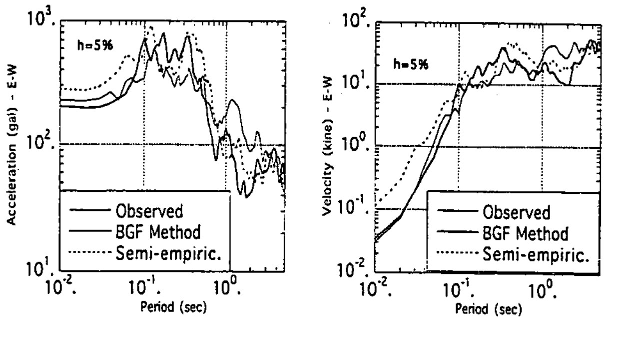

Fig.5: Acceleration and velocity response spectra of Observed and Synthetic signals of the mainshock at Abeno Station. Component E-W.

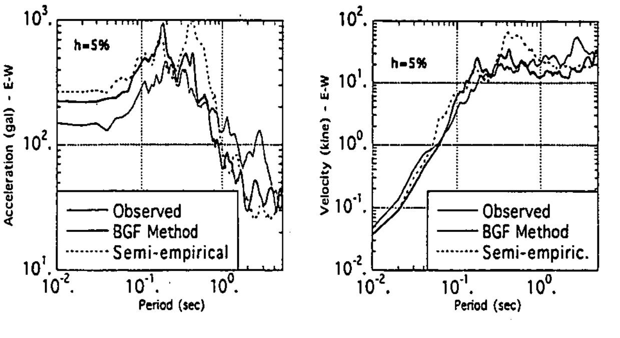

Fig.7: Acceleration and velocity response spectra of Observed and Synthetic signals of the mainshock at Sakai Station. Component E-W.

Since the synthetic signals obtained by BGF method are similar to those obtained by Irikura's semi-empirical procedure, and also they match quite well with the observed signal at each station, it shows that this procedure can be useful to estimate strong ground motios in sites were even no small event records are available.

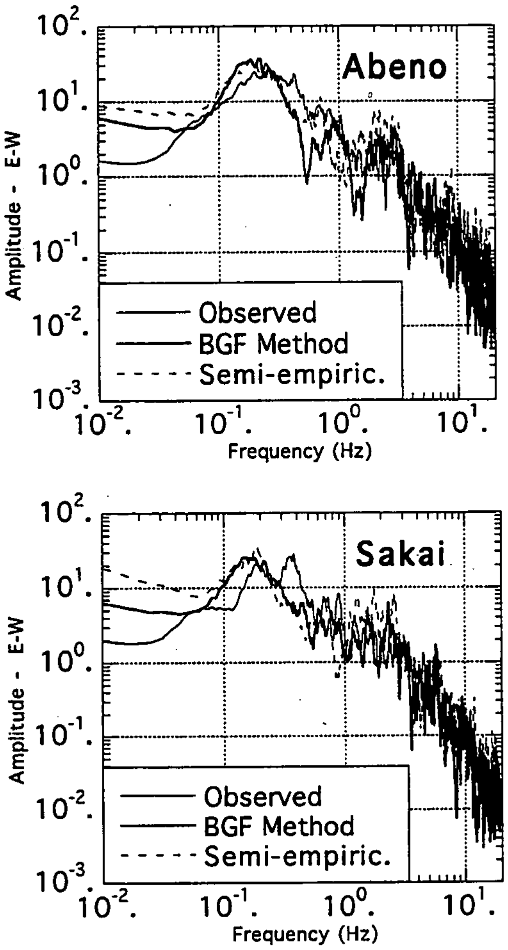

Fig.8: Velocity Fourier spectra of Observed and Synthetic signals of the mainshock at Abeno and Sakai Stations. Component E-W

5.- Conclusions

- The Beamformed Green Function method for synthesizing strong ground motions induced by near fields earthquakes, is presented. This procedure allows to estimate the strong ground motions even in locations where no data is available.

- Even though the mainshock records present very complex waveforms, the synthetic signals obtained by both, BGF method and semi-empirical procedure, show good agreement with the observed ones.

- Since the beamforming algorithm reduces the wave's high frequency content, the waveform of synthetic signals obtained by Irikura's procedure show much better fitting with the observed ones than those obtained by beamformed Green functions. However, the BGF procedure shows its advantages when no small event data is available at a site of interest.

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