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THEORETICAL AND SEMI-EMPIRICAL APPROACHES BY USING NORMAL MODE SOLUTION FOR REPRODUCING SEISMIC MOTIONS AT INTERMEDIATE PERIODS

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SUMMARY

A semi-empirical approach to synthesize intermediate-period strong motions caused by large-scale earthquakes is introduced here. The essence of it is to employ an empirical source-time-function (source spectrum), which are inversely calculated from observed record, instead of source spectra of separated patches on the fault. A reasonable result can be obtained by this approach compared to theoretical ones. Harkrider's Normal Mode solution is used for all these analyses. The method is applied to the analysis of the Kanto earthquake, 1923.

INTRODUCTION

So far, seismic motions at intermediate periods (from 2 or 3 seconds to 20 or 30 seconds) were hardly taken into consideration for the earthquake resistant design, since, in former days, artificial structures with longer natural periods (more than 2~3 seconds) seldom existed. However, due to appearance of large-scale storage tanks and suspension bridges, or planning of super-high-rise buildings, longer period motions became important for the engineering aim. Indeed, unexpected large responses of long-period structures have often been observed even at an epicent-ral distance of more than 100 km. (e.g., the 1983 Akita-Oki, Japan, earthquake, the 1985 Michoacan, Mexico, earthquake, etc.) If a large earthquake happened close to the long-natural-period structures without any proper countermeasures to the longer-period motions, destructive damages would be expected.

Most components of the intermediate-period motions are considered to consist of surface-wave motions. Especially, the great earthquakes whose magnitude scale is ranked around 8 generate many surface waves. The purpose of our research is to estimate these seismic motions reasonably. Before starting synthesis, we should resolve a few difficult problems. The first problem is how to substitute a laterally heterogeneous crustal structure to a pseud horizontally-layered-structure. The second and most important problem is how to express a complicated slippage on the fault plane due to a strength variation, so-called 'asperity' or 'barrier'. In the following sections, we shall show several approaches to resolve these problems in the analyses where we try to synthesize the motions in Tokyo from the 1923 Great-Kanto earthquake. Although the similar analysis was done by Kudo(1978), we analyze it by more reasonable means.

SOUTHERN KANTO EARTHQUAKES

Several great earthquakes in southern Kanto with a recurrence period of around 200 years or more are documented. The last earthquake, which led to severe disasters on the metropolitan area of Japan, is inferred to have happened on an interplate boundary along the Sagami trough in 1923 as shown in Figure 1. Ando's fault model is adopted as the Kanto fault model. Neither of several seismographs succeeded at all to observe complete strong ground motions during the earthquake disturbed by unexpected strong motions. Only two records of Ewing's type and Imamura's type seismographs, installed at Hongo in Tokyo, were partly available on their records. It is convenient to compare the synthesized motions with them to confirm validity of the analysis. In figure 1, the shaded area of the Kanto fault indicates 'near field', where the hypocentral distance from Hongo is less than 2.5 times of the source depth. The remaining part of the plane is designated 'far field'. Tentatively we synthesized motions from far-field sources by the Normal Mode analysis and from near-field sources by the Haskell's formula. It is found the result of the far-field analysis is well similar to that of the entire analysis(far+near) as to the response spectra shown in Figure 1.

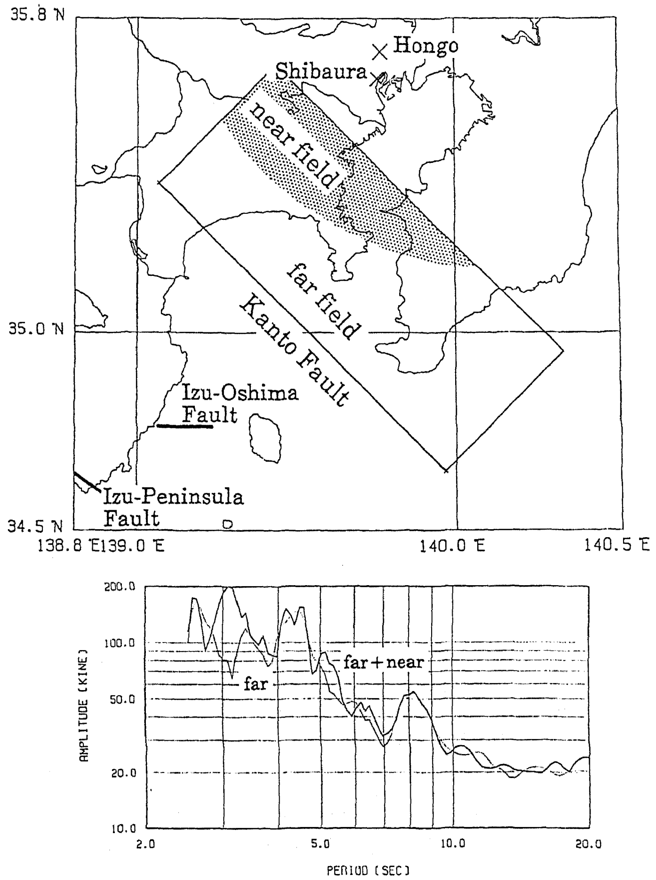

Fig.1. The upper figure shows a map of southern Kanto area. Locations of observation stations in Tokyo and Kanto fault plane as well as two moderate earthquakes are indicated in it. The lower figure shows the response spectra of 'far+near' and 'far' field earthquake.

EQUIVALENT CRUSTAL STRUCTURE

In general, a crustal structure varies from a source to a receiver along a propagating path of surface waves. Before starting synthetic analyses, we should replace a laterally heterogeneous underground with an equivalent horizontally-

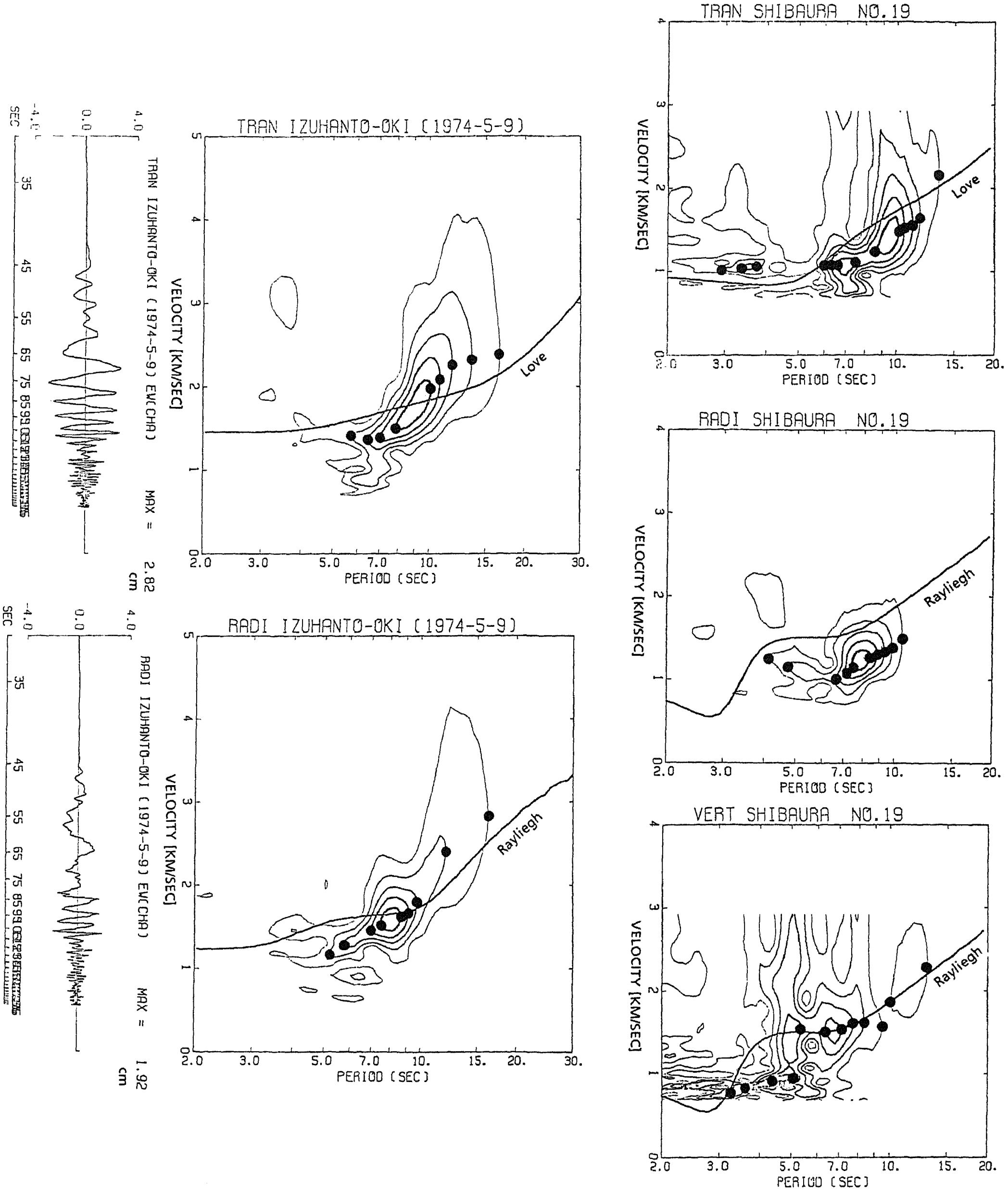

Fig.2. On the left non-stationary spectra of transvers and longitudinal components of the Izu-Peninsula record and dispersion curves of 'B-model' . Non-stationary spectra of transvers, longitudinal and vertical components of the Izu-Oshima record and dispersion curves of 'C-model' are also discribed.

layered-structure whose group velocity of surface waves should be consistent with the real one. To find this equivalent structure, we analyze the intermediate-period records from the recent moderate-size earthquakes occurred in the vicinity of the Kanto fault (see Fig.1). In Figure 3 is shown the record form the 1974 Izu-Peninsula earthquake(M_J=6.9) observed at Hongo, Tokyo. The record is considered to be reliable up to the long period of about 30 seconds. Two horizontal components of the record are transformed to transverse and longitudinal components. Their non-stationary spectra are drawn on the left in Figure 2. The real structure between the source and the receiver is roughly classified to four different structures, i.e., Izu Peninsula(I), Sagami Bay(S), Kanagawa prefecture(K), and Tokyo(T). The equivalent structure, B-model, is determined as rough average of the four structures [$\simeq$(I+S+K+T)/4]. The theoretical group velocities of Love and Rayliegh waves are superimposed on the spectra, where the dispersion curves generally consist with peak trains of the spectra. Kudo's A-model is better for the motions in Tokyo from the Izu-Peninsula earthquake than the B-model, but there is no way to decide the structure for the Kanto earthquake.

It is intuitively suppose that the equivalent structure between Sagami bay and Tokyo(C-model) is better to be decided according to the same process [namely, $\simeq$(S+K+T)/3]. On the right in Figure 3, the dispersion curves of thus decided structure are drawn on the non-stationary spectra of the motion at Shibaura from the 1978 Izu-Oshima earthquake, which occurred close to the Kanto fault. Yet short duration time of the record, weak coherency is recognized. Then, the C-model will be adopted for the analysis of the Kanto earthquake.

SYNTHETIC ANALYSIS

To examine validity of the analytical conditions and limitation of the Normal Mode solution, we synthesize the motion at Hongo from the Izu-Peninsula earthquake. Surface-wave motions $\mathbf{u}(\mathbf{x};\omega)$ at a site $\mathbf{x}$ is formulated as following,

$$\mathbf{u}(\mathbf{x};\omega) = M(\omega)\sum_{j} \mathbf{G}_j(\omega) \qquad (1)$$

where $M(\omega)$, source spectrum, is a Fourier transform of the dynamic seismic moment $M(t)$, and $\mathbf{G}_j(\omega)$ is a complex Green's vector function of j-th modal surface wave excited by an unit double-couple-force. $M(t)$ relates to the source time function $D(\xi;t)$ [for $t\rightarrow\infty$, $M=\mu DS$, where μ: rigidity at the source position, D: average of $D(\xi)$, S: area of the fault, and ξ: position on the fault].

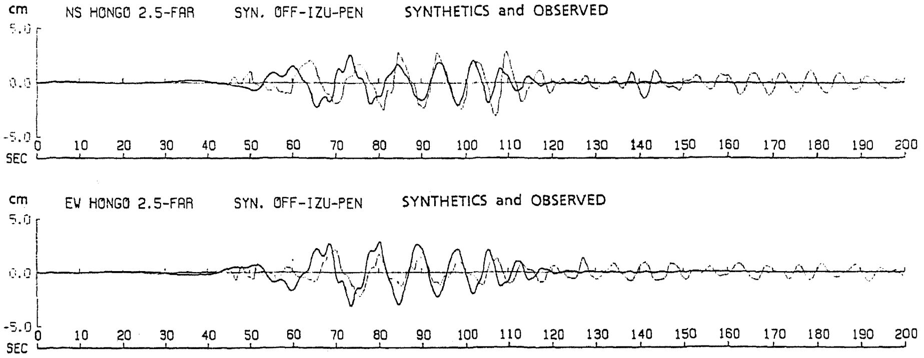

Fig.3. Comparison of the synthetic seismograms under smooth slippage (thick) and the observed (thin) which were recorded by Omori's type seismograph at Hongo, Tokyo duaring the 1974 Izu-Peninsula earthquake. The observed is shifted 25 seconds to connect with the synthetic.

Figure 3 shows the synthesized seismograms, which are calculated by assuming smooth slippage, and the observed ones. The major parts of the two seismograms agree very well, though the first portion caused by body waves and the low-amplitude coda part caused by refractive and reflective waves can not be expressed well by the analysis. This good agreement seems to be referred to the size of the earthquake. Short-period motions are originally generated by a non-uniform slippage owing to a strength variation on the fault. If an earthquake size were small, we would be able to regard it as a single event (i.e., smooth slippage) for estimating intermidiate-period motions. The Kanto earthquake, however, is too large to be regarded as a single event. Really, the smooth slippage model led the result of the trial calculation to a much less displacement amplitude than the observed. We should determine source time function $D(\xi;t)$ including such a complicate slippage for reproducing intermediate-period motions, but it is unknown for the Kanto earthquake. The $D(\xi;t)$ of the 1968 Tokachi-Oki earthquake(M_J=7.9) resolved by Mori and Shimazaki(1984) was tentatively applied for the Kanto calculation, but the result is yet too small.

As mentioned above, it is very difficult to determine the real slippage of the great earthquake. Then, the empirical source spectrum $M_a(\omega)$, which is derived from the record $\mathbf{u}_a(\mathbf{x};\omega)$ of the moderate-size earthquake occurred near the mainshock, is employed in stead of submitting $D(\xi;t)$ for the analysis. The theoretical motion $\mathbf{u}(\mathbf{x};\omega)$ from the great earthquake is expressed as,

$$\mathbf{u}(\mathbf{x};\omega) = \sum_k \left[M_k(\omega) \sum_j \mathbf{G}_{jk}(\omega) \right] \tag{2}$$

where $M_k(\omega)$ is a source spectrum of the k-th fraction(patch) of the fault plane. $\mathbf{G}_{jk}(\omega)$ is a Green's function of j-th mode from the k-th patch. It is considered that roughness of a slippage of a small event is similar to that of a mainshock if these two events occurred in the same crustal area. Therefore it may be allowed to use $M_a(\omega)$ of the observed earthquake instead of the k-th source spectrum $M_k(\omega)$ of the great earthquake, when each patch size is consistent with the small event. The ratio of the seismic moments of the two events is employed as the separation number of the main fault. The final formula is shown below.

$$\mathbf{u}(\mathbf{x};\omega) \simeq \mathbf{u}_a(\mathbf{x};\omega) \sum_k \left[\frac{\sum_j \mathbf{G}_{jk}(\omega)}{\sum_j \mathbf{G}_{ja}(\omega)} \right] \tag{3}$$

The value of [ ] in Equation (3) means combination of excitation correction due to the source depth, time-lag correction due to the wave propagation, and radiation pattern correction. It is danger to rely on this correction coefficient entirely. For example, since radiation pattern is not so clear especially for short-period motions, the calculated value will be overestimated if the receiver is located in the nodal direction of the small event. Also, correction of source depth sometimes leads to overestimation, because seismic waves are not generated from only one point by a small event. To prevent these misleading estimation, the amplitude of the correction coefficient is restricted to less than ten for each discrete frequency number, while its phase is not restricted at all. The synthesized motion of the Kanto earthquake and its response spectra are drawn in Figure 4. Comparing the spectra with a spectrum of the observed record, the synthesized value is thought to be relatively large.

CONCLUSIONS

Short-period motions are considered to be caused by incoherent dislocations on an earthquake source. In general, it is difficult to estimate real source dislocations. Then, it is also difficult to predict intermediate-period motions for a great earthquake by the theoretical method even if multiple-event mechanism is taken into consideration for synthetic analyses. Meanwhile, the proposed semi-empirical approach is available for these periods, though some improvements are still necesary.

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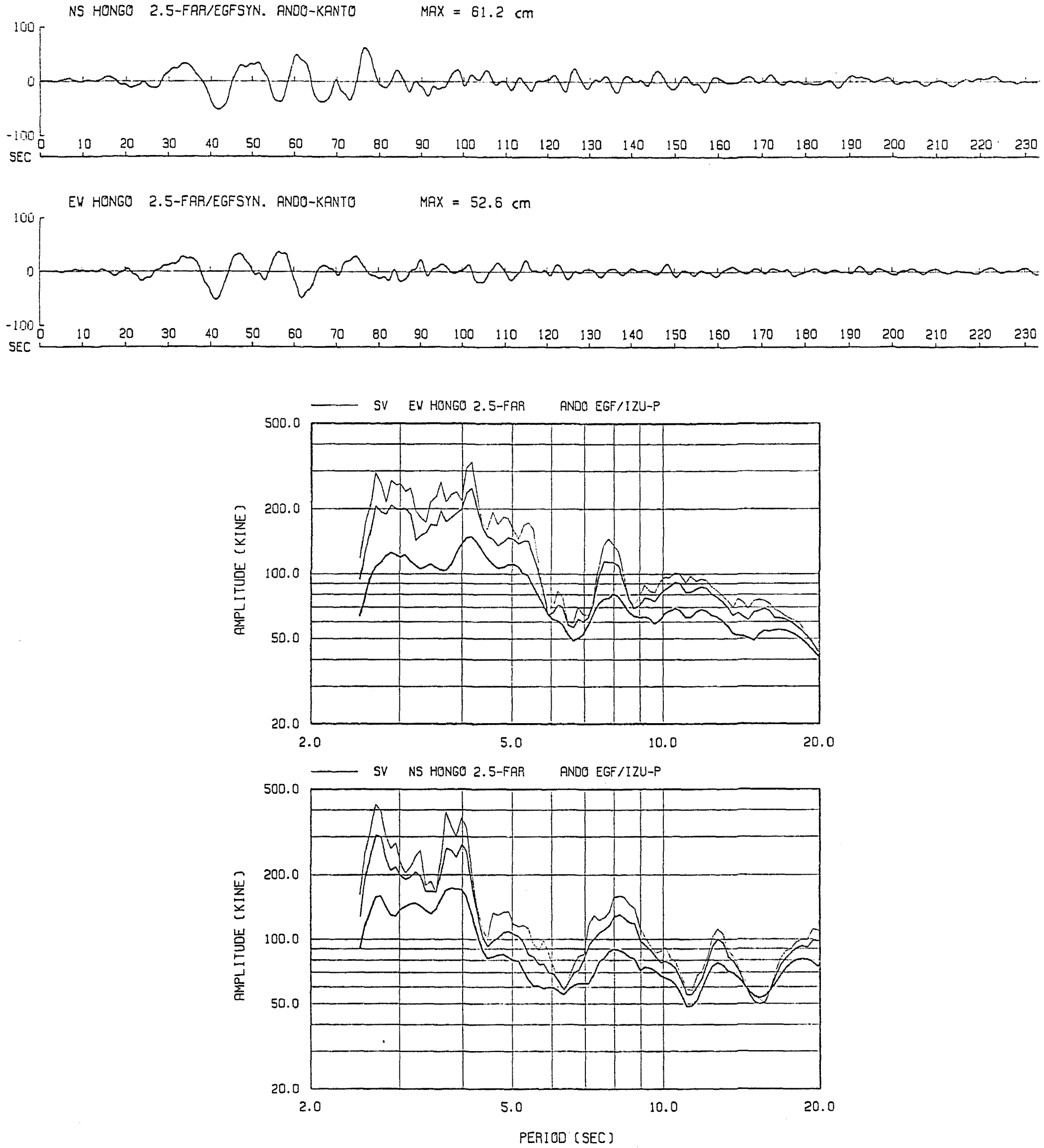

Fig.4. Synthetic motion of Kanto earthquake by semi-empirical method and its response spectra of three different damping factors(1%, 2%, 5%).