# A STUDY ON THE CONTRIBUTION OF SURFACE WAVES TO STRONG GROUND MOTIONS

by Kazuyoshi KUDO

## SUMMARY

Most of the transversely polarized strong motion displacements at various source-station azimuths from the 1974 Izu Peninsula earthquake are consistent with the theoretical radiation pattern of Love waves. The two exceptional data in the comparison are satisfactorily explained from the fact that the Love-wave energy is concentrated to the surface when thick and soft sedimentary layers exist under the stations.

## INTRODUCTION

Studies on the strong ground motions in the field of earthquake engineering had been concentrated mostly to seismic body waves, until Trifunac and Brune(1970), Trifunac(1971), Shima(1970), Hasegawa(1974), Anderson(1974) and Hanks(1975) gave arguments on the contribution of surface waves to strong ground motions. Recently, some strong motion recordings were modeled using the normal mode theory (surface waves). Herrmann and Nuttli(1975a,b) suggested that earthquake motions observed at moderate or long distances were well-simulated by the synthetic Love and Rayleigh waves. Boore(1977) verified that the surface waves from the 1906 California earthquake dominated the ground displacements at Mt. Hamilton, through the theoretical modeling both body and surface waves. Swanger and Boore(1978a,b) found the good agreement between the observed displacements at El Centro from the 1968 Borrego Mountain earthquake and the synthetic seismogram using modal superposition up to the second higher mode. Hartzel et al. (1978) modeled successfully the recordings at the epicentral distance of 35km from the 1974 Acapulco earthquake. Kudo(1978) showed that the observed transversely polarized waves at Tokyo from the 1974 Izu Peninsula earthquake, the 1930 North-Izu earthquake and the 1931 Saitama earthquake were well-simulated by the fundamental mode Love waves in the longer period than 5 seconds.

Strictly speaking, the normal mode theory does not give us an exact modeling, but an approximate one. However, the correspondency between the synthetic seismograms obtained from the complete solutions and the one from the modal superposition is excellent, except for the case when the epicentral distance is quite short (Kawasaki,1978; Swanger and Boore,1978a; Herrmann, 1979), and the normal mode solutions have some benefits compared with the other methods, as suggested by Swanger and Boore(1978a).

The radiation pattern of transverse waves observed at various (11) source-station azimuths within 200km from the 1974 Izu Peninsula earthquake is compared with the theory, in the first part of the paper. Short and intermediate period surface-waves are strongly influenced by a shallow underground structure. In some cases, a flat layering assumption is no more valid for modeling the strong motions. Although it may be difficult to deal with the problem exactly, some methods are provided for the approximation. As an example, the applicability of Alsop(1966)'s method is tested through the comparison between the synthetic Love waves propagated across a vertical discontinuity and the observed seismograms at Tokyo.

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## RADIATION PATTERN OF STRONG MOTION DISPLACEMENT

*DATA* The records used in the following were obtained by the strong motion seismograph installed in the stations of Japan Meteorological Agency (J. M. A.). The natural period, damping ratio, static magnification and drum speed of the seismograph are 6.0sec. (horizontal), 8, 1 and 30mm/sec., respectively. The records at 11 stations (see "Table 1" and "Fig.1"), were digitized on a SMAC-READER at every 0.2 or 0.4sec. time interval. The distortions of wave forms due to the finiteness of recording-arm length were removed and the data were interpolated to equal time intervals (0.2 or 0.4 sec.). The instrumental responses were also removed from the originals in the frequency domain and the time history of the motions was acquired by the inverse Fourier transform method (F.F.T.). A cosine-tapered rectangular spectral window (cut-off = 0.06 and 1.0Hz) was used in the computations. Ground displacements thus obtained at 11 stations from the 1974 Izu Peninsula earthquake are shown in "Fig.2". The records obtained by Omori Strong Motion Displacement Meter at Hongo (Tokyo) are also used in the following.

The source parameters of the 1974 Izu Peninsula earthquake are as follows; strike=N55°w, slip angle=14°, dip angle=76°, fault length=20km, fault width=10km, focal depth=10km, rupture velocity=2.5km/sec.(bilateral), rise time=1.0sec., seismic moment=$6.6*10^{25}$dyne-cm (Kawasaki,1978). The S-wave velocity structure in the Izu Peninsula (Model I-3, see "Table 2") was obtained by Kudo et al(1978) so as the dispersion data of Love waves were consistent with the travel time data from the aftershocks of the 1978 Izu-Oshima earthquake. "Fig.3" shows the comparison between the transverse waves observed at MIS and the synthetic Love waves obtained using the above-mentioned source and structure models. Agreement between two is fairly good except for the biginnings. Therefore, one may say that the source and structure models are consistent with the observations, as concerns in the Izu Peninsula.

*SPECTRUM* The synthetic amplitude spectra of Love waves are compared with the transverse waves observed at 11 stations which were equalized at a propagation distance of 100km, as shown in "Fig.4". Most of the theoretical curves fit with the observations in the frequency range from 0.07 to 0.2Hz. Strictly speaking, however, the observed spectra at CHJ, FUN, KOF, and SHZ are small at high frequencies, whereas those at YOK and TOK are very large at low frequencies compared with the theoretical ones. One may understand the above more clearly through the comparison between the synthetic and the observed radiation patterns at every frequency, as shown in "Fig.5". The solid circles away from the theoretical curves are of YOK and TOK. An explanation for the open triangles will be given in the later part.

The above-mentioned discrepancy may be due to the difference of the geological conditions at each site, as can be seen from "Fig.1". Since tall buildings or big oil-tanks have continued to increase in the metropolitan area (TOK and YOK), it is worthwhile to consider quntitatively why spectral amplitudes at TOK and YOK are larger than theoretical or average values in the low frequency.

## EFFCT OF A VERTICAL DISCONTINUITY TO EARTHQUAKE MOTIONS

The environs of Tokyo Metropolis have been well-surveyed by Shima et al.

(1976a,b,1978a,b) and Ohta et al.(1977,1978). A feature of the underground structure in and around Tokyo is that the thick and low-velocity sedimentary layers are found near the surface, and it is quite different from that of the Izu Peninsula. A possible reason why synthetic spectra poorly agree with the observations at TOK and YOK in the preceeding section is due to the disregard of the sedimentary layers. The effect of lateral inhomogeneity on surface-wave propagation might be considerably large. This problem has been of great interest of seismologists related to a continental margin, and some useful methods to evaluate such effects have been proposed. Assuming that there is one plane boundary perpendicular to the line from the epicenter to the station, the transmitted Love waves across the discontinuity will be discussed in the following, adopting the method proposed by Alsop(1966).

*STRUCTURE MODEL* The epicenter, YOK and TOK (or HON) come into line, as shown in "Fig.1". The group-velocity dispersions of transverse waves observed at YOK and HON are obtained using a moving-window, multiple-filter method ("Fig.6"). A true group-velocity of the waves propagated from YOK to HON is given by

$$U_{Y-H} = U_Y U_H ( r_H - r_Y )/( U_Y r_H - U_H r_Y ) \tag{1}$$

where, $U_Y$ and $U_H$ are the group velocities obtained independently from YOK and HON, $r_Y$ and $r_H$ are the epicentral distances of YOK and HON, respectively. Thus obtained group velocities, as a function of frequency, are compared with the theoretical dispersion curves of the fundamental mode Love-wave for the two structure models in and around Tokyo represented by Shima et al(1976a,b). The dispersion curve of Model T-2 (see "Table 2") fits with the observation (solid squares), as shown in "Fig.6". Then a flat layering assumption is valid, as concerns TOK (or HON) and YOK. Whereas, the structure model I-3 is appropriate for the source region. Since any precise underground structure for the whole path has not been clarified, we assume that two multi-layered quater-spaces (Model I-3 and T-2) are in welded contact. The distance from the epicenter to the vertical discontinuity is obtained to be 95km, using the observed group velocities at HON, YOK and MIS and adopting the method represented by Sato(1959). The location of the discontinuity is consistent qualitatively with a feature of the Bouguer gravity anomaly.

*TRANSMITTED LOVE WAVE* The method proposed by Alsop(1966) is that the reflection coefficients are obtained by minimizing the differences of eigenfunctions of Love waves between two quarter-spaces and the transmission coefficients are given by satisfying the continuity of the stress at a discontinuity. "Fig.7-A" shows the S-wave velocity structure models of the Izu Peninsula (Model I-3) and Tokyo (Model T-2). The source and the stations ( TOK and YOK) are located in the medium I and II, respectively. The transmission coefficients at the surface (surface ratio) [a], the coupling coefficients [b] and the percentage of energy not accounted for [c] are computed and shown in "Fig.7-B".

First, the surface displacements of forward going Love waves at the discontinuity are given by the following equation in the frequency domain,

$$U^I(\omega) = M_0\, G(\omega)\, e^{-i\frac{3\pi}{4}}\, A^I \sqrt{k^I}\, D(\omega) \int_{d_1}^{d_2} \chi(\theta,z)\,dz\; e^{-ik^I r^I} / \sqrt{2\pi r^I} \tag{2}$$

where, $M_0$ =seismic moment, $G(\omega)$ =time transformed source time function, $A^{I}$ = amplitude response factor of Love waves in the medium I, $k^{I}$ = wave number of Love wave in the medium I, $D(\omega)$ = directivity function (Ben Menahem,1961), $\chi(\theta,z)$ =radiation pattern function, $d_1$ and $d_2$ =top and bottom depth of the fault, $z$ =depth, $r^{I}$ =distance between a source to a vertical discontinuity and $\theta$ =azimuth measured from the fault strike to the station anticlockwise (Harkrider,1970). Next, the displacements at the station in the medium II are given by multiplying the transmission coefficients $Sr(\omega)$ at the surface,

$$U^{II}(\omega) = U^{I}(\omega)\ Sr(\omega)\ e^{-ik^{II}(r^{II} - r^{I})} \ /\ \surd(r^{II} / r^{I}) \qquad (3)$$

where, $k^{II}$ =wave number of Love waves in medium II and $r^{II}$ =distance from the epicenter to the station.

The amplitude spectra observed at TOK and HON are compared with the theoretical ones thus obtained (fundamental mode Love wave), as shown in "Fig.8". Broken and solid lines show the amplitude spectra corrected by the "Eq.3" and those obtained assuming medium I only, respectively. Thin and thick lines correspond to the spectra when rupture velocities are 2.5km/sec. and 2.0km/sec., respectively. The adaptability of the theoretical amplitude spectra to the observations is improved, by taking the effects of vertical discontinuity into consideration. The rupture velocity of 2.0km/sec is appropriate for the present study. The open triangles in "Fig.5" show the amplitudes at TOK and YOK thus corrected. The correspondency between theoretical and observed radiation pattern is also improved.

*SYNTHESIS* Synthetic Love waves by means of the inverse Fourier transform of $U^{II}(\omega)$ are compared with the observations (the first and the second traces) in "Fig.9". The fourth and fifth traces show the fundamental and the first higher mode Love waves, respectively. The third trace is the sum of the fourth and fifth traces. Good agreement between observed and synthetic seismograms is obtained in both amplitudes and phases, except for the beginnings of the S-wave arrival and the coda. "Fig.10" shows the fundamental mode Love waves at Tokyo given by assuming the medium I only (broken line) and those obtained by employing both medium I and II (solid line). A significant contribution of sedimentary layers (in medium II ) to surface-wave motion can be found. Generally speaking, tall buildings and large scale structures have long natural periods and small damping coefficients. Therefore, the existence of thick sediments should be taken into consideration for the anti-seismic designing of such buildings.

## DISCUSSION AND CONCLUSION

The adequacy of the normal mode theory in modeling for the observed ground motion displacements at moderate distance was examined by comparing the theoretical radiation patterns as well as seismograms with the observations. The radiation patterns of transverse waves observed within an epicentral distance of 200km agreed with those of Love waves in the frequency range from 0.07 to 0.2Hz. This may give an insight into the study of earthquake source mechanism. Among the observations, however, the spectral amplitudes at TOK and YOK were considerably large compared with the theoretical or average ones. This is due to the geological conditions which are different from the others. In other words, the surface displacement amplitudes at

TOK and YOK were magnified when Love waves transmitted from "hard" to "soft" medium. A numerical examination for our problem was made by using the method proposed by Alsop(1966), and good agreement was obtained between the syntheses and the observations. Alsop's method does not necessarily give us good approximations as can be seen from "Fig.7-B,c", but it is adequate for its simplicity.

Kudo(1978) gave a good fit between the synthetic Love waves and the observation at HON from the 1974 Izu Peninsula earthquake, assuming a flat layering medium, even though virtual. His method is applicable to predict the motions at Tokyo from the future Izu Peninsula earthquake. However, it may not be powerful for the cases of different epicentral distances or azimuths. This difficulty was eliminated by the present study.

## ACKNOWLEDGEMENTS

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Table 1 Station Data

| Sta. Name | Code | Long. E | Lat. N | Alt.(m) | Dist.(km) | Azimuth(θ)* |
|---|---|---|---|---|---|---|
| Tateyama | TAT | 139.868° | 34.983° | 6 | 105.8 | 57° |
| Yokohama | YOK | 139.655° | 35.437° | 38 | 119.7 | 84° |
| Tokyo | TOK | 139.758° | 35.687° | 21 | 147.1 | 88° |
|  | (HON) | 139.762° | 35.716° | 20 | 150.0 | 89° |
| Kumagaya | KMG | 139.385° | 36.147° | 30 | 177.6 | 107° |
| Mishima | MIS | 138.930° | 35.112° | 20 | 56.1 | 111° |
| Chichibu | CHJ | 139.082° | 35.992° | 218 | 154.4 | 115° |
| Maebashi | MAE | 139.065° | 36.402° | 112 | 199.2 | 117° |
| Kawaguchiko | FUN | 138.763° | 35.498° | 860 | 97.6 | 129° |
| Kofu | KOF | 138.558° | 35.665° | 272 | 118.1 | 136° |
| Shizuoka | SHZ | 138.407° | 34.973° | 14 | 53.5 | 168° |
| Hamamatsu | HMM | 137.723° | 34.708° | 32 | 99.3 | 210° |

* measured from the negative strike (S55°E) of the fault

Table 2 Structure Models

Model I-3

| Layer | S-Velocity (km/sec) | Density (g/cm$^3$) | Thickness (km) |
|---|---|---|---|
| 1 | 1.45 | 2.2 | 1.0 |
| 2 | 2.3 | 2.5 | 1.0 |
| 3 | 2.5 | 2.5 | 2.0 |
| 4 | 3.7 | 2.8 | 15.0 |
| 5 | 3.9 | 3.0 | ∞ |

Model T-1

| Layer | S-Velocity (km/sec) | Density (g/cm$^3$) | Thickness (km) |
|---|---|---|---|
| 1 | 0.7 | 2.0 | 1.0 |
| 2 | 1.5 | 2.3 | 1.6 |
| 3 | 3.0 | 2.5 | ∞ |

Model T-2

| Layer | S-Velocity (km/sec) | Density (g/cm$^3$) | Thickness (km) |
|---|---|---|---|
| 1 | 0.58 | 1.8 | 0.2 |
| 2 | 0.7 | 2.0 | 0.47 |
| 3 | 1.5 | 2.3 | 1.84 |
| 4 | 3.0 | 2.5 | 3.5 |
| 5 | 3.4 | 2.6 | ∞ |

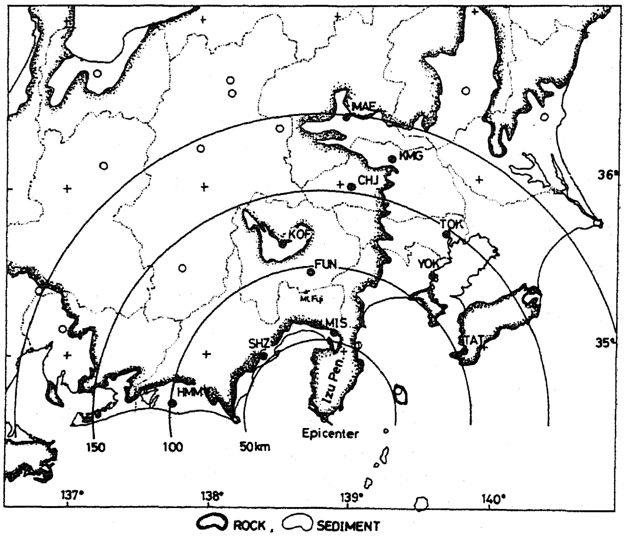

Fig. 1 Map showing the epicenter of the Izu Peninsula earthquake and the locations of the J.M.A. stations (open and solid circles) in the central Japan. The records at 11 stations (solid circles) are analyzed in the present study.

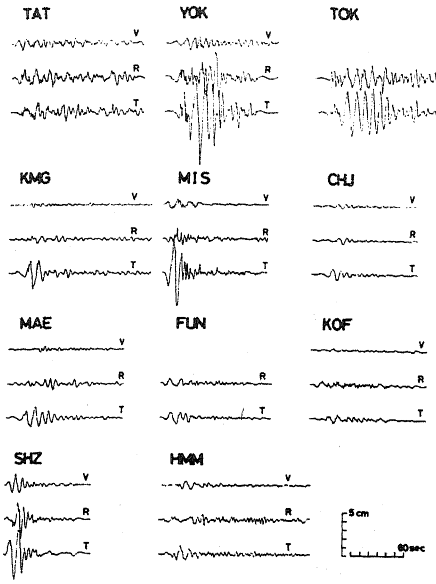

Fig. 2 Seismograms after the instrumental responses were removed. R: radial, T: transverse, V: vertical.

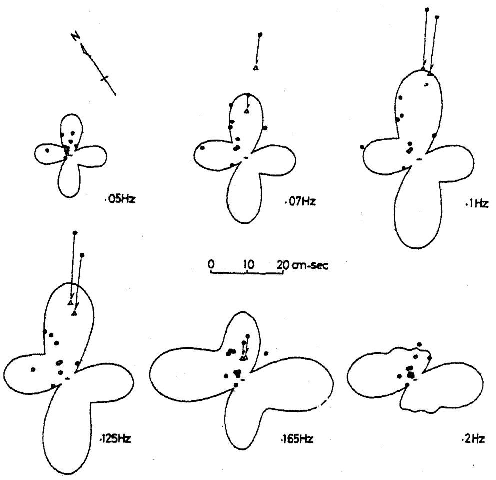

Fig. 5 Radiation pattern of Love waves at every frequency compared with the observation. Solid circles: Observations without correction Open triangles: with the correction of transmission at a vertical discontinuity.

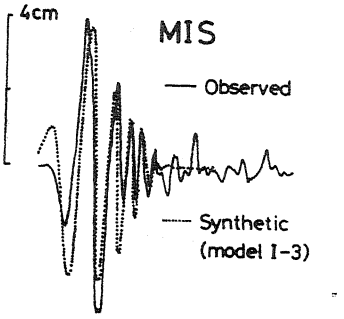

Fig. 3 Synthetic Love waves compared with the transverse waves observed at MIS.

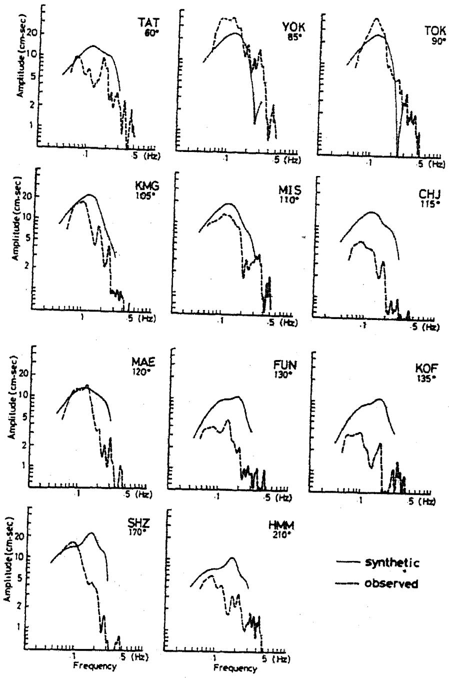

Fig. 4 Comparison between the observed and the synthetic Love wave spectra.

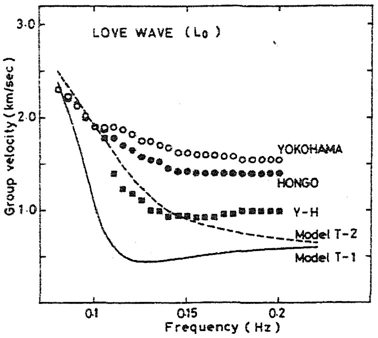

Fig. 6 Comparison between the observed and the theoretical group velocity dispersion curves.

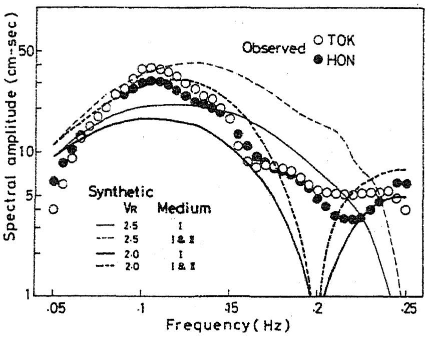

Fig. 8 Synthetic amplitude spectra compared with the observations.

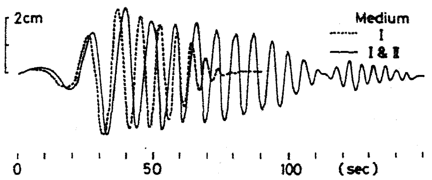

Fig. 10 Comparison of synthetic Love waves with (solid line) and without (broken line) medium II.

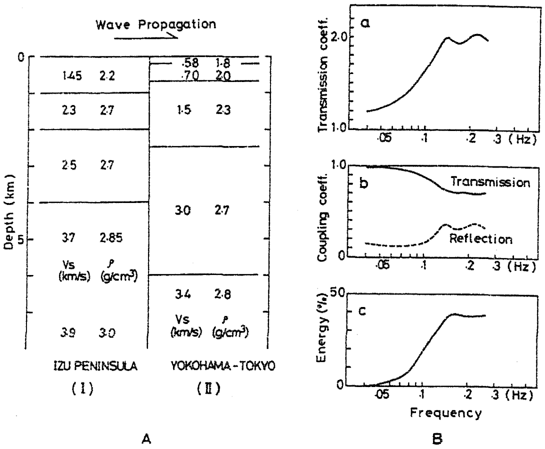

Fig. 7 Structure model with a vertical discontinuity [A]. Transmission coefficient at the surface (a), coupling coefficient at the discontinuity (b) and the percentage of energy not accounted for (c), [B], computed following Alsop(1966).

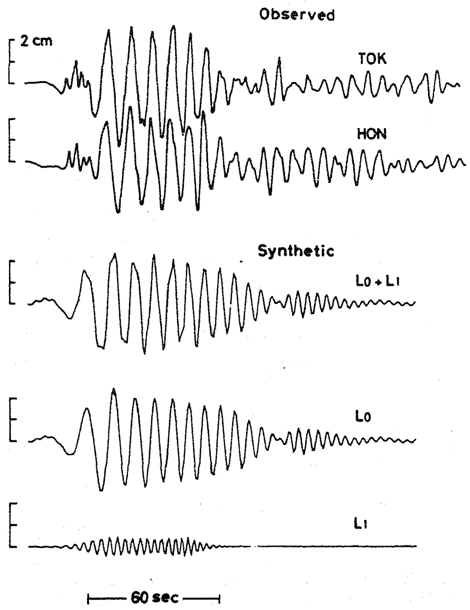

Fig. 9 Synthetic Love waves compared with the observed transverse waves at TOK and HON.