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ANALYSIS OF GROUND MOTIONS ON ALLUVIAL DEPOSIT CONSIDERING SURFACE WAVES

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SUMMARY

An approximate method to calculate ground motions considering Love waves on a layered ground which has a topographical discontinuity at a lateral side subjected to vertically incident SH waves is presented. Responses of the ground are assumed as the sum of one-dimensional waves and Love waves. The coefficients of Love modes are determined from the approximate boundary conditions at the discontinuity. Using the method, a strong ground motion observed on an soft alluvial deposit during the 1983 Mid-Japan Sea earthquake is simulated. The calculated waveform considering Love waves represents well the feature of the observed waveform.

INTRODUCTION

Recently, strong ground motion records observed on extremely soft grounds, for example, records on the reclamation dike at Hachirogata during the 1983 Mid-Japan Sea earthquake and some records in Mexico City during the 1985 Mexico earthquake, have attracted great attention of earthquake engineers because of their singular features. These records have showed monotonous sinusoidal waveforms with large amplitudes at the later part of the records and so had very long durations. These features of the ground motions are considered to be caused by the local topographical irregularity from the comparison of the waveforms with those observed at the neighbouring sites.

In this paper, presented is an approximate method to analyze ground motions considering surface waves on a layered ground with a topographical discontinuity at the lateral side of the ground. Using the method, moreover, a simulation analysis of strong ground motions recorded on an extremely soft deposit during the 1983 Mid-Japan Sea earthquake is conducted.

METHOD OF ANALYSIS

Step-Shaped Ground Model Fig. 1 shows a two dimensional ground model, in which two layered grounds, I and II, are in contact at x=0 and plane SH waves are incident vertically. Responses of the two grounds, U^I and U^{II}, are assumed as follows, omitting the time factor, $\exp[i\omega t]$.

$$U^I(\omega,x,z)=f^I(\omega,z)+\sum_{n=1}^{N} a_n(\omega)\Phi_n^I(\omega,z)\exp[i\bar{k}_n^I x] \quad ; \quad x\le 0 \tag{1.a}$$

$$U^{II}(\omega,x,z)=f^{II}(\omega,z)+\sum_{m=1}^{M} b_m(\omega)\Phi_m^{II}(\omega,z)\exp[-i\bar{k}_m^{II} x] \quad ; \quad x\ge 0 \tag{1.b}$$

where

- f ; 1-D response of layered ground Φ ; mode shape of Love wave
- k ; wave number of Love wave $\bar{k} = k(1-h)$
- h ; damping factor of ground a,b ; amplitude coefficients of Love waves

The responses are expressed as the sum of of "one-dimensional response of layered ground to incident SH waves" and "Love waves which are generated at the discontinuous plane of contact of the two grounds and propagate laterally". These are approximate solutions in the sense that body waves scattered at the discontinuity are neglected. To simplify the calculation, moreover, the velocity and mode function of Love wave are calculated neglecting the damping of the ground. Damping effect is approximately taken into account in the term of wave number $\bar{k}$.

Unknown amplitude coefficients, a and b, are determined from the boundary conditions at the discontinuous plane of contact of the two grounds. First, a following relation between the coefficients can be obtained from the stress condition and the orthogonality of the mode functions of Love waves.

$$a_n = -\sum_{m=1}^{M} b_m P_{nm} \qquad (2)$$

where $P_{nm} = k_m^{II}\int_0^\infty \mu^{II}\Phi_n^I\Phi_m^{II}dz / k_n^I\int_0^\infty \mu^I(\Phi_n^I)^2dz$

Next, the boundary condition of the displacement is approximately satisfied so as to minimize the difference between the displacements of the two grounds at the contact (Ref. 1). The integrated squared error along the vertical plane of the contact, J, is as follows, in which $[\ ]^*$ represents the conjugate complex.

$$J = \int_0^{\bar{z}} \bar{U}\bar{U}^* dz \qquad (3)$$

where $\bar{U} = U^I(\omega,0,z) - U^{II}(\omega,0,z)$

From the condition that minimizes J in Eq. (3), the following linear simultaneous equations for the unknown coefficients b's are available.

$$\sum_{s=1}^{M} b_s\Big[\sum_{n=1}^{N}\sum_{r=1}^{N} P_{nm}P_{rs}S_{nr} + \sum_{n=1}^{N}(P_{nm}T_{ns}+P_{ns}T_{nm}) + V_{ms}\Big] = \sum_{n=1}^{N} P_{nm}X_n + Y_m \quad, m=1\sim M \qquad (4)$$

where $S_{nr} = \int_0^{\bar{z}}\Phi_n^I\Phi_r^I dz$, $T_{nm} = \int_0^{\bar{z}}\Phi_n^I\Phi_m^{II}dz$, $V_{ms} = \int_0^{\bar{z}}\Phi_m^{II}\Phi_s^{II}dz$,

$X_n = \int_0^{\bar{z}}\Phi_n^I(f^I - f^{II})dz$, $Y_m = \int_0^{\bar{z}}\Phi_m^{II}(f^I - f^{II})dz$

<u>Basin-Shaped Ground Model</u> Fig. 2 shows a two dimensional ground model of a basin shape, which has two vertical discontinuities at the both lateral sides of the ground II. Based on the same assumption as in the step-shaped model, responses of the grounds are expressed as follows, considering the symmetry of the shape.

$$U^I(\omega,x,z) = f^I(\omega,z) + \sum_{n=1}^{N} a_n(\omega)\Phi_n^I(\omega,z)\exp[i\bar{k}_n^I x] \quad ; \ x<0 \qquad (5.a)$$

$$U^{II}(\omega,x,z) = f^{II}(\omega,z) + \sum_{m=1}^{M} b_m(\omega)\Phi_m^{II}(\omega,z)\cos\bar{k}_m^{II}(x-L) \quad ; \ 0<x<L \qquad (5.b)$$

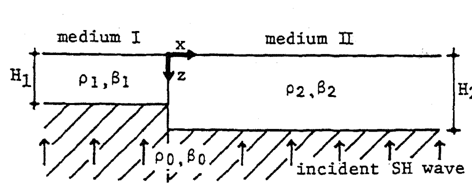

Fig. 1 Step-shaped ground model

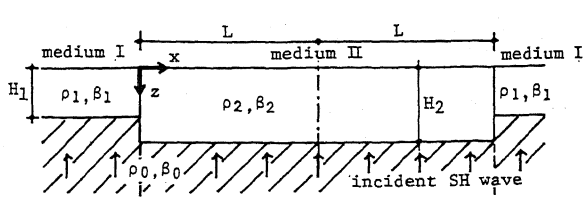

Fig. 2 Basin-shaped ground model

Unknown amplitude coefficients of Love wave, a and b, are determined by the almost same manner as in the previous problem. Following relations are available from the boundary conditions at the discontinuous plane of contact.

$$a_n = -\sum_{m=1}^{M} b_m s_m P_{nm} \tag{6}$$

$$\sum_{s=1}^{M} b_s \left[s_m^* s_s \sum_{n=1}^{N} \sum_{r=1}^{N} P_{nm} P_{rs} S_{nr} - i \sum_{n=1}^{N} \left(s_m^* c_s P_{nm} T_{ns} - c_m^* s_s P_{ns} T_{nm} \right) + c_m^* c_s V_{ms} \right] = -i s_m^* \sum_{n=1}^{N} P_{nm} X_n + c_m^* Y_m \ , \ m=1 \ M \tag{7}$$

where $c_m = \cos \bar{k}_m^{II} L$, $s_m = \sin \bar{k}_m^{II} L$

FUNDAMENTAL PROPERTIES

Fundamental properties of ground motions containing Love waves are discussed from the numerical example of a simple ground model shown in Fig. 3. Damping factor of the ground is taken as 2%.

Fig. 4 shows the dispersion curves of Love waves for the soft ground II . It is found that the minimum group velocity of the fundamental mode is about 60% of the shear wave velocity of the surface layer. Fig. 5 shows the one-dimensional responses of the two layered grounds, regarded to be independent each other, subjected to incident harmonic SH waves. Fig. 6 shows the responses of the two grounds on the surface at the contact taking the interaction of the two grounds into account. From the Figs. 5 and 6, it is considered that the degree of approximation of the boundary condition at the vertical discontinuity is good.

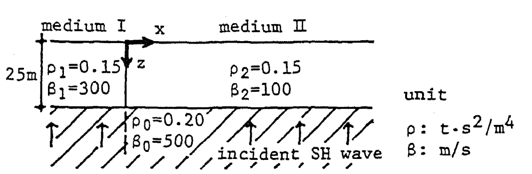

Fig. 3 Ground model for numerical example.

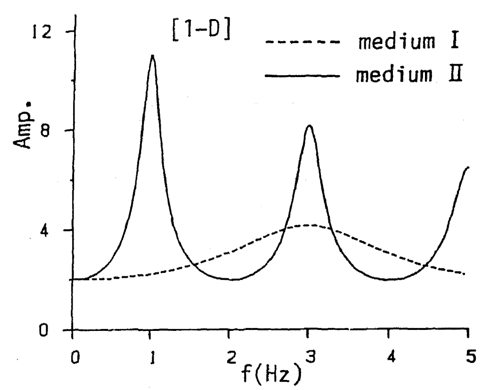

Fig. 5 Harmonic 1-D responses of the two grounds.

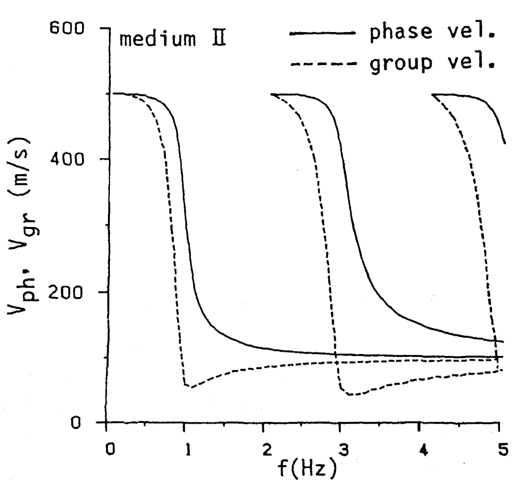

Fig. 4 Dispersion curves for Love waves of ground II.

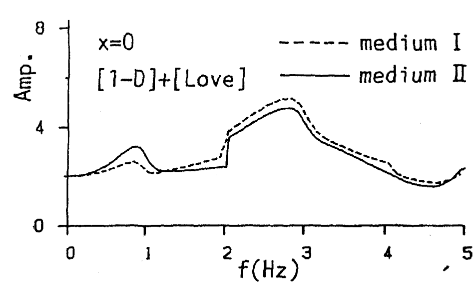

Fig. 6 Comparison of harmonic responses of two grounds at the contact.

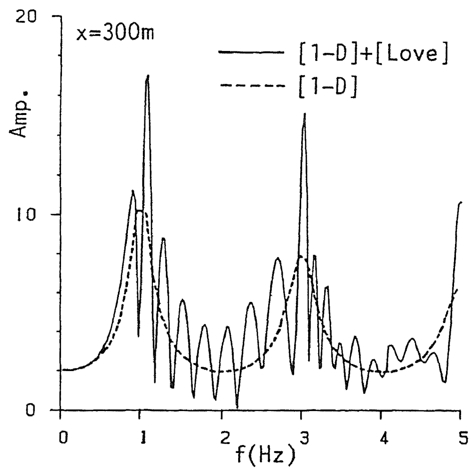

Fig. 7(a) Harmonic response at x=300m.

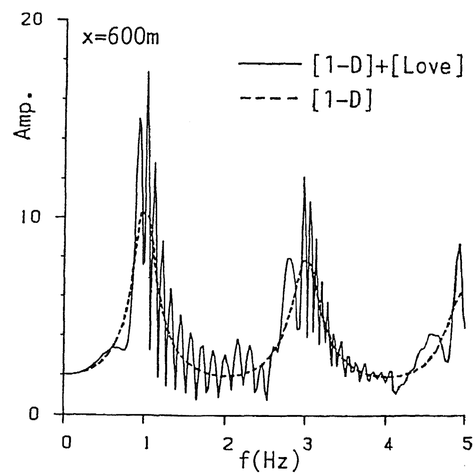

Fig. 7(b) Harmonic response at x=600m.

Solid lines in Fig. 7 show the harmonic responses containing Love waves at the distances of 300m and 600m from the contact. Broken lines in the figure are one-dimensional responses. Significant fluctuation can be seen in the response containing Love waves accompanied by the increase in the distance from the contact.

Fig. 8 shows time history responses of the ground II subjected to pulse-like incident SH wave. The top figure is a waveform consisting of only one-dimensional response. The middle and bottom figures are responses containing Love waves at the distances of 300m and 600m, respectively. It is found that the duration of the ground motion containing Love waves are prolonged by Love waves propagating laterally from the discontinuity with the low group velocity. Period of dominant Love wave is about 1 sec, which coincides with the period at which the group velocity of Love wave of the fundamental mode is the minimum.

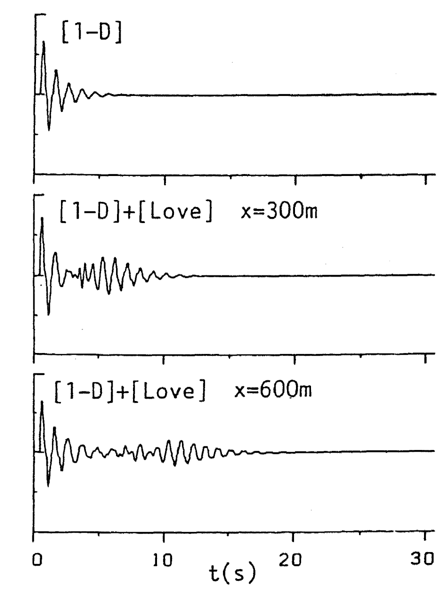

Fig. 8 Time history responses

SIMULATION ANALYSIS

Fig. 9 shows strong ground motion records obtained at Akita, Hirosaki and Hachirogata sites during the 1983 Mid-Japan Sea earthquake (Ref. 2). The sites of Akita and Hirosaki are on the relatively hard ground. The site of Hachirogata is on the reclamation dike of which ground condition is extremely soft. Durations with large amplitude in the Akita and Hirosaki records are about 60 sec. On the other hand, in the Hachirogata record, monotonic sinusoidal waves with large amplitudes appear in the later part of the record, from 60 to 120 sec. This characteristic feature of the Hachirogata record is considered to be caused by the local topographical effect around the observation site. In the following, presented is a simulation analysis of the Hachirogata record using the proposed method.

Fig. 10 shows the topography of the site of Hachirogata and the location of the accelerograph (SMAC). Contours in the figure show the depth of the bottom of the soft alluvial deposit. Fig. 11 shows the topographical section along the line A-A in Fig. 10. The thickness of the alluvial layer at the observation site is about 40m, but it decreases rapidly in the west of the site.

Fig. 12 shows a ground model used in the analysis. The thickness of the soft surface layer is taken as 40m. The discontinuity of the ground in the west side is located at the distance of 1.6km from the observation site, considering the topography shown in Fig. 11. The discontinuity of the ground in the east side is located at the distance of 2.8km from the observation site after some trial-and-error analyses. Soil parameters are shown in the figure.

For the incident waveform, the NS component of the strong ground motion record in Akita site shown in Fig. 9, of which amplitude is multiplied by 0.5, is used. High damping factor of 10% for the one-dimensional response is used to reduce high frequency components in the Akita record used as an input wave. Low damping factor of 0.5% for Love wave is used.

Fig. 13 shows the comparison of the calculated and the observed waveforms. An envelope of the calculated waveform consisting of only one-dimensional response decays rapidly after the time of 20 sec. In the calculated waveform considering Love waves, dominant waves appear at the time of about 60 and 90 sec after the waves of one-dimensional response. The dominant waves at the time of 60 sec are Love waves travelling from the western discontinuity and those at the time of 90 sec are Love waves travelling from the eastern discontinuity of the model. The calculated waveform simulates well the feature of the observed waveform.

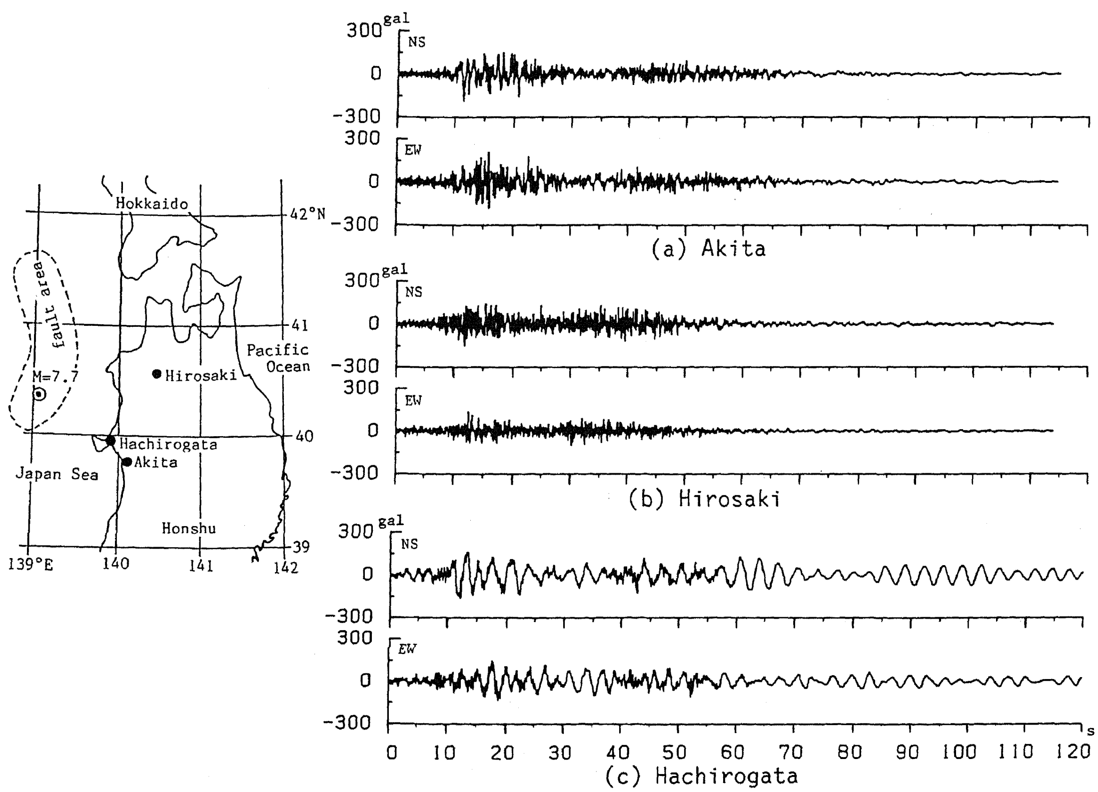

Fig. 9 Strong ground motion records during the 1983 Mid-Japan Sea earthquake

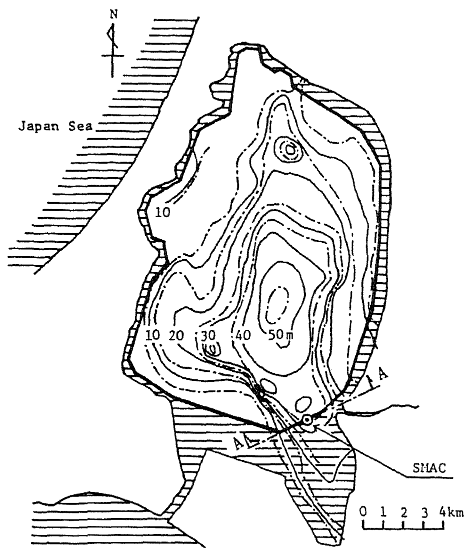

Fig. 10 Topographical map of Hachirogata and location of accelerograph(SMAC).

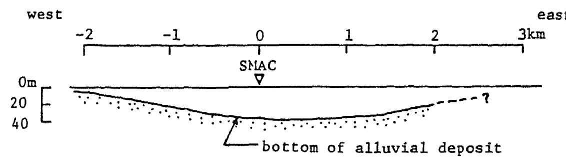

Fig. 11 Section along line A-A in Fig. 10

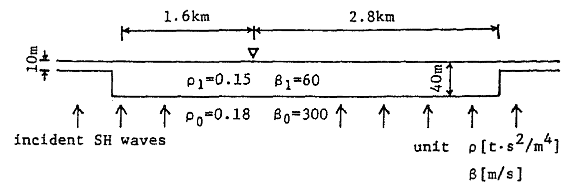

Fig. 12 Ground model for the Hachirogata site.

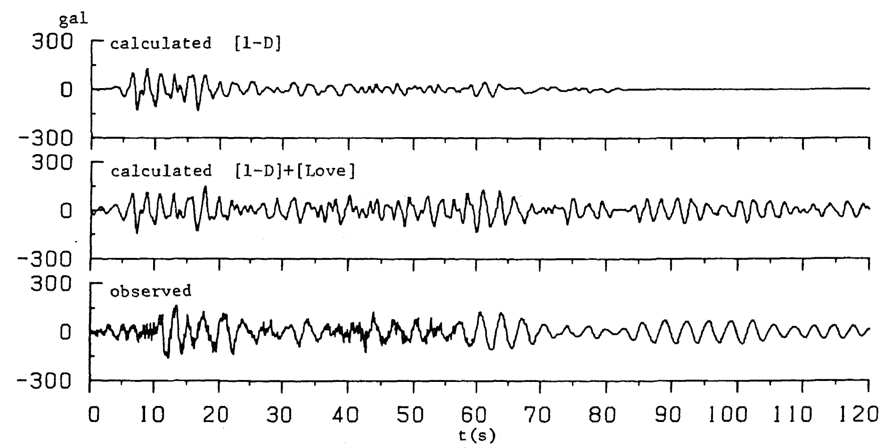

Fig. 13 Comparison of the calculated and the observed waveforms

CONCLUSIONS

A simple approximate method to calculate ground motions considering Love waves which are generated by the topographical discontinuity is proposed. It is illustrated that the ground motions on an extremely soft ground may have dominant surface waves caused by the local topographical discontinuity through the simulation analysis of the strong ground motions.

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