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Site effects of earthquake ground motions

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ABSTRACT: To elucidate the effects of topography and underground conditions in behavior of ground motions is an important task in earthquake engineering. Until now, several records of earthquakes have been observed by the strong ground motion observation network developed around Toyohashi city, central part of Japan, in 1989. These records were analysed in frequency domain and have brought a reasonable results in comparison with the results of microtremor data and analytical results using one and two dimensional analyses obtained by Kuribayashi et al. (1991). As theoretical study, by using the vector potential presented by Ohhori et al. (1990) and enlarged propagator matrix, A-L method is extended to estimate the behavior of responses of three dimensional arbitrary shaped ground, like the depression or the protrude with some horizontally stratified layers, for incidental P, SV and SH waves in frequency domain.

1. INVESTIGATED AREA

In order to prove the effects of topographical and geological conditions in behavior of ground motions, a strong motion observation network so called TASSEM, Toyohashi University of Technology Array System for Strong Earthquake Motions, has been developed around Toyohashi city that is regarded as one of the most vulnerable areas to destructive earthquakes. Through this area, the Median Tectonic Line extends more than 800 km in the middle part of southwestern Japan dividing it into Inner Zone (Japan Sea side) and Outer Zone (Pacific side).

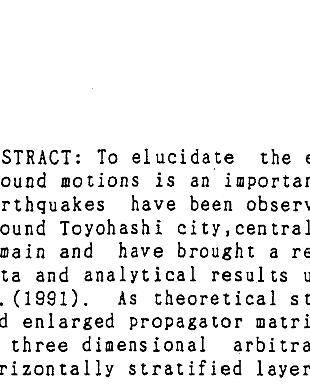

Fig. 1 Distribution of the Epicenters of Past Major Earthquakes

The crustal movement in the area is very complicated and active in Honshu(the mainland of Japan). Movement of oceanic plate is considered that strongly influenced on the Neotectonics of southwestern Japan. Along the Nankai trough, the Philippine seaplate subducts into the crust of Honshu island. In the upper level of the plate, many earthquakes occur frequently. It is likely probable that a fault displacement accompanied with a great earthquake might occur along the central part of the Median Tectonic Line in near future. Fig. 1 shows the investigated area and the distribution of the epicenters of past major earthquakes.

2. ARRAY SEISMIC GROUND MOTION OBSERVATION

The arrangement of the observation points is shown in Fig. 2 and 3. Fig. 4 shows the distribution of standard penetration values, N, at each observation point. Accelerometers were installed in December, 1989. POINT 1 is located on the center of the valley and is covered with the soft alluvial deposit. POINT 2 and POINT 3 locate on the terrace area composed from diluvial layers. Moreover, at POINT 4, supplemental observation is being done there. Observation of base motion has been carried out at the layer composed of gravely sand under ground -60m at POINT 3 as POINT 3B since January, 1991 in present system.

At present time, several ground motion records have been obtained. Maximum acceleration of three events observed by TASSEM is shown in Table 1. These three records are analysed below. Ratio of Fourier amplitude spectrum between the surface and the base, POINT 3B, for the observed data in each observation point is shown in Fig. 5.

In case of POINT 3/POINT 3B, peaks are shown in range from 3 to 4Hz and in case of POINT 1/ POINT 3B and 2/3B, large amplification, order of 20 - 30 times, is shown in high frequency range more than 5Hz. The low-amplitude component of the wave is affected by such large amplification in high-frequency range. However, at POINT 2, large amplification around 0.7 Hz affects the high-amplitude component. Consequently, it is explained that the maximum acceleration, in Table 1, were observed at POINT 2 in spite of its underground condition.

Kuribayashi et al. (1991) carried out the linear response analyses of the model around TASSEM in order to confirm the effects of topographical and geological conditions in amplification characteristics by one-dimensional Multiple Reflection Method and two-dimensional Finite Element Method and as the experimental approach,spectral ratio of microtremor data obtained at investigated area were calculated. Soil properties needed in one and two dimensional analyses are obtained from field tests, soil types and N values, of each observation point. Damping ratio 5 % is used in analyses. S-wave velocity is induced by $V_S = 91.0\ N^{0.337}$. Calculated transfer functions in each point of observation can be obtained in the work of Kuribayashi et al. (1991). From practical results of POINT 3, no peak appears in the frequency range lower than 2 Hz. It differs from the analytical results.

In comparison with the spectral ratio of observed ground motion data and the one of observed microtremor data, value of magnification is differ in absolute ordinate, similar tendency is however shown in frequency domain.

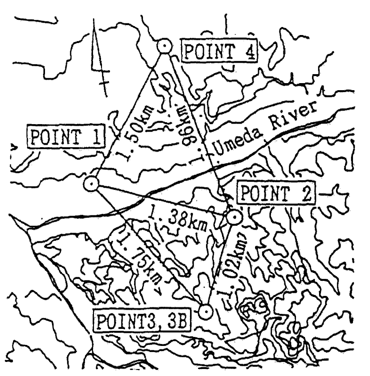

Fig. 2 Arrangement of the Observation Points

Table 1 Maximum Acceleration of Ground MotionsObserved by TASSEM (gal)

Date	Sep. 24, 1990			Apr. 25, 1991			Sep. 03, 1991		
Epicenter Region	Far South off Tokai District			Central Part of Shizuoka			Far South off Tokai District		
Lat.	N33° 6'			N35° 03'			N33° 41'		
Lon.	E138° 38'			E138° 12'			E138° 50'		
Depth	60km			32km			33km		
Magnitude	6.6			4.9			6.3		
Direction	EW	NS	UD	EW	NS	UD	EW	NS	UD
POINT 1	11.2	15.1	3.9	6.8	5.9	1.8	7.2	4.9	1.8
POINT 2	14.9	14.7	6.7	7.5	9.0	4.2	11.0	12.5	3.1
POINT 3	11.1	15.9	5.4	4.7	6.5	3.7	5.1	7.8	2.9
POINT 3B	-	-	-	1.4	2.1	0.7	1.7	2.6	1.4

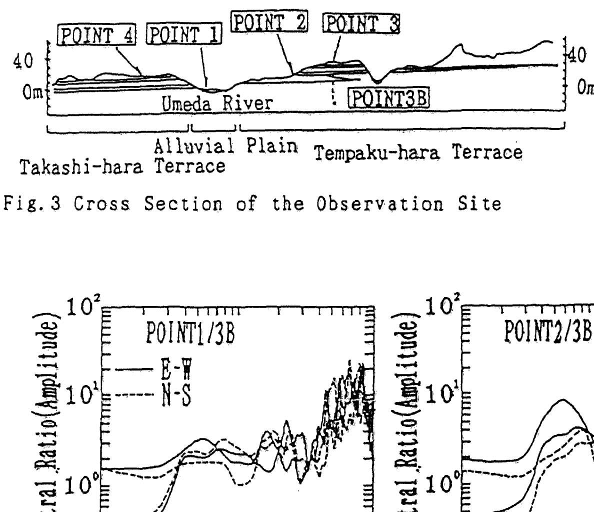

Fig. 3 Cross Section of the Observation Site

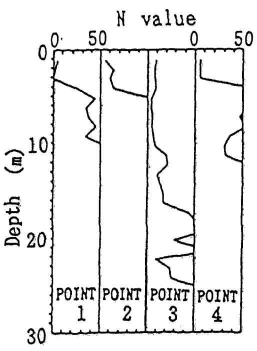

Fig. 4 Distribution of N values at Each Observation Point

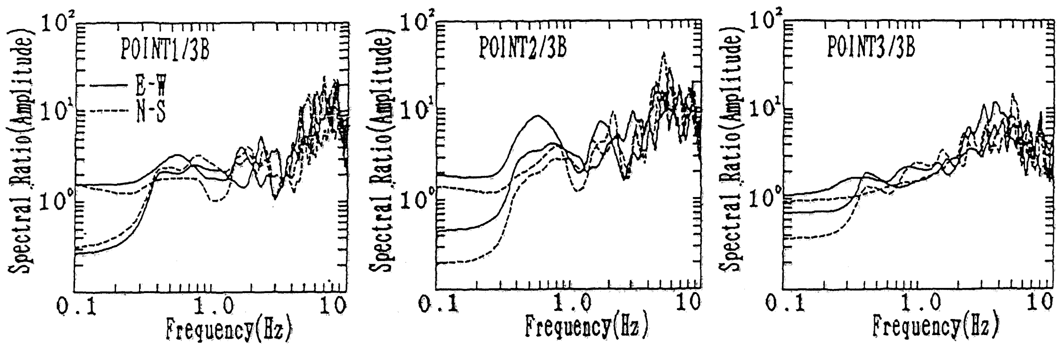

Fig. 5 Spectral Ratio dividing by POINT 3B as Base Motion

3. EXPANSION OF A-L METHOD FOR THREE DIMENSIONAL IRREGULARLY LAYERED STRUCTURES

3.1 Summary of A-L Method

A-L method is a practical method devised by Aki and Larner (1970) to calculate the elastic wave field in a layer-over-halfspace medium with an irregular interface, when plane waves are incident from below. They described the scattered field as a superposition of plane waves,and application of the continuity conditions at the interface yields coupled integral equations. The equations are satisfied in the wave-number domain when the interface shape is made periodic and the equations are Fourier transformed and truncated.

Afterward, A-L method was applied to solve the problem of the irregular surface and the incident P and SV waves by Bouchon (1973), in time domain by Bard and Bouchon. Kohketsu(1987) introduced enlarged propagator matrix and extended A-L method to 2-D multilayered media.

Recently Ohhori et al. (1990) extended the method to three-dimensional irregular subsurface structures by using displacement potential.

3.2 Formulation

We consider the three-dimensional problem that has the homogeneous isotropic elastic half-space and the layers have laterally irregular shape. The problem is to find the displacement and traction at the free surface and any points in the medium upon incidence SH wave same as the past studies and incidental P, SV wave. Displacement vector can be presented by using scalar potential ϕ and vector potential $\vec{\Psi}$;

$$\vec{U} = \mathrm{grad}\,\phi + \mathrm{curl}\,\vec{\Psi} \qquad (1)$$

We assume the potential taking by Ohhori et al. *(1990) as follows;*

$$\phi = {}_1\chi , \quad \vec{\Psi} = ({}_2\chi , {}_3\chi , 0) \qquad (2).$$

Then, transform the potential into the frequency wavenumber (ω-k) domain, ${}_1\chi$, ${}_2\chi$, ${}_3\chi$ should have the form;

$$\begin{aligned}
{}_1\chi_i &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} [{}_1A_i(Kx,Ky)\exp(+j\nu_{pi}Z) + {}_1B_i(Kx,Ky)\exp(-j\nu_{pi}Z)] \exp(j(KxX+KyY))dKxdKy \\
{}_2\chi_i &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} [{}_2A_i(Kx,Ky)\exp(+j\nu_{si}Z) + {}_2B_i(Kx,Ky)\exp(-j\nu_{si}Z)] \exp(j(KxX+KyY))dKxdKy \qquad (3) \\
{}_3\chi_i &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} [{}_3A_i(Kx,Ky)\exp(+j\nu_{si}Z) + {}_3B_i(Kx,Ky)\exp(-j\nu_{si}Z)] \exp(j(KxX+KyY))dKxdKy
\end{aligned}$$

Here, Kx,Ky= horizontal discrete wavenumber, $j=\sqrt{-1}$, ν =vertical discrete wavenumber, A,B= coefficients. p and s mean the relation to P-wave and S-wave respectively.

From (1) and (2), then displacement as:

$$[u_x, u_y, u_z] = [\partial_1\chi/\partial x - \partial_3\chi/\partial z , \; \partial_1\chi/\partial y + \partial_2\chi/\partial z , \; \partial_1\chi/\partial z + \partial_3\chi/\partial x - \partial_2\chi/\partial y] \quad (4).$$

Consider an irregular interface between two layers, the condition of continuity of displacement and traction must be imposed along the interface. Equations (3) are truncated by N, truncation number of infinite integrals, to reform them into infinite-sum equations.

3.3 Examples

To verify the expanded method, the results were compared the results with similarly obtained for the models,two-dimensional model of sediment-filled valley including two horizontal layers analysed by Bravo,M.A. et al.(1988) by using A-L method and three dimensional model of sediment-filled valley analysed by Sánchez-Sesma et al. (1984) using A-L method and Jiang and Kuribayashi(1988) using B.E.M. and show reasonable agreement.

As example cases, two and three dimensional model of horizontally stratified N deposits on the half-space under the incidence S-waves were analysed. Model of 2-D is the stratified parabolic deposit of Fig.6. In the depression, there are n(= 1,2,3) horizontal layers. Soil properties are shown in Table 2. 3-D model is shown in Fig.7 and given by, $h=2.5*(1-3\xi^2+2\xi^3)$, where $0 \leqq \xi \leqq 1$, h= height of the ridge, and $\xi=(x^2+y^2)^{1/2}/a$. Soil properties are shown in Table 3. Incidence angle is 0° and incidence wave are P and S wave. Analysed frequency is decided to correspond to normalized frequency $\eta=1.0$. These model take the general dimensions, half-width of the deposit a= 5.0 km, maximum depth H= 2.5 km, periodic length of irregularity Lx,Ly= 30 km. When we decide the truncation number of infinite integrals Nx and Ny, in calculated frequency, f , the maximum *horizontal discrete wavenumber should be* chosen more than the wave number of surface wave that has the shortest wave length. For that reason, Nx and Ny must be satisfied following equation;

$$Nd \geqq 1.1*f*Ld/Vs_{min} \quad (d=x,y) \qquad (5)$$

where Vs_{min} is S-wave velocity of the softest medium and Ld is periodic length of irregularity. In numerical computation, as N increases,capacity of memory storage and time to calculate increase rapidly.

From the results as shown in Fig.8 and 9, amplitudes of horizontal displacement at the surface become large, as the number of layers are increased. Especially, it is influenced by the softest layer that is the top of stratified deposits. Vertical displacement have the tendency same as horizontal displacement. As the interesting phenomenon in 3-D analyses, displacements, Radial and Azimuthal direction, are differ in comparison with Model 1 and Model 2.

4. CONCLUSIONS

Aichi prefecture is regarded as one of the most vulnerable area to destructive earthquakes. Several earthquakes were recorded by present observation system. The amplification characteristics in frequency domain around TASSEM are proved from analytical results and consequences in strong motion observations.

By using the vector potential presented by Ohhori et al. and enlarged propagator matrix, A-L method is extended to estimate the behavior of responses of three dimensional arbitrary shaped ground, like the depression or the protrude with some horizontally stratified layers,incidental P,SV and SH waves in frequency domain. Comparison of results with those obtained by other researchers shows reasonable agreement.

As example cases, two and three dimensional model of horizontally stratified deposits on the half-space under the incidence S waves were analysed. From the results, effects of the softest layer near the surface were confirmed.

It is clear that A-L Method is an effective tool to estimate the behavior of responses in three dimensional irregularly layered structures subjected to incidental P,SV,SH waves. Hereafter, three-dimensional analyses of the investigated area, around Toyohashi, will be done by using the present expanded A-L method.

ACKNOWLEDGEMENTS

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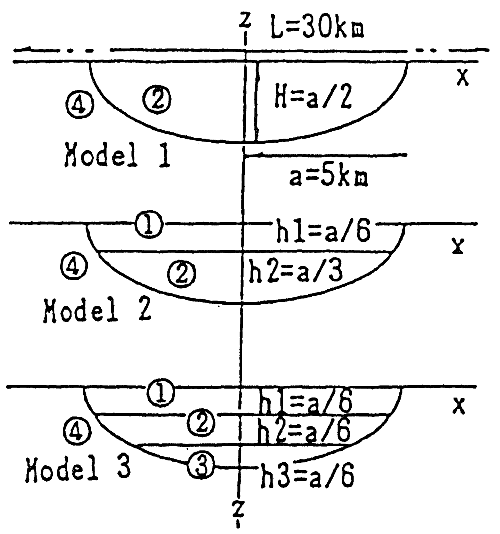

Fig.6 2-D Model

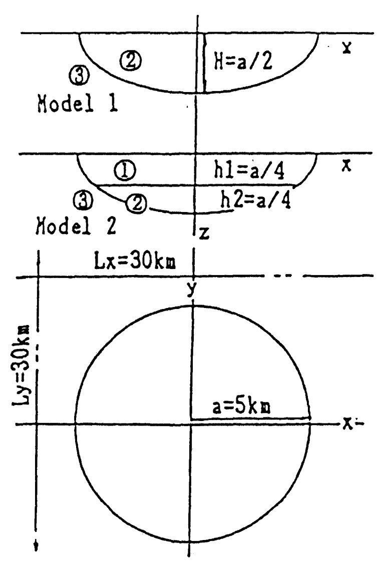

Fig.7 3-D Model

Table 2 Soil Properties used in 2-D Analyses

Soil Type	Vp (km/s)	Vs (km/s)	Density ρ (t/m³)	Damping
1	1.87	1.0	2.25	0.05
2	3.74	2.0	2.55	0.02
3	4.68	2.5	2.85	0.01
4	5.20	3.0	3.00	0.00

Table 3 Soil Properties used in 3-D Analyses

Soil Type	Vp (km/s)	Vs (km/s)	Density ρ (t/m³)
1	1.50	0.8	1.80
2	1.87	1.0	1.80
3	3.00	1.73	2.40

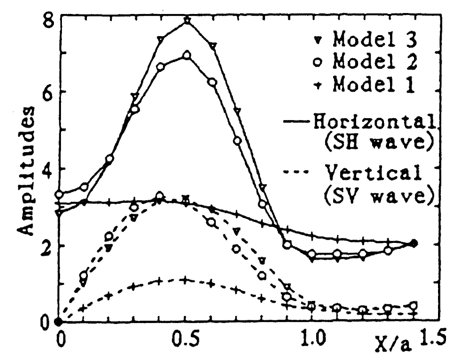

Fig.8 Displacement Amplitudes on the surface in 2-D Model Incidence S wave's Angle=0°

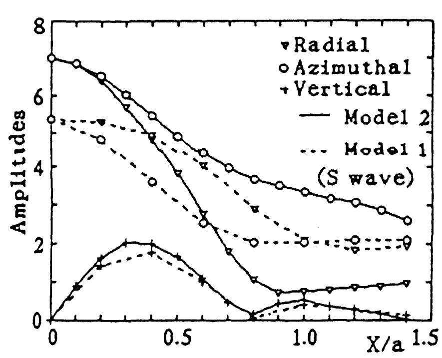

Fig.9 Displacement Amplitudes on the surface in 3-D Model Incidence S wave's Angle=0°