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ON THE EFFECTS OF THE SOFT LAYER UPON THE PHASE VELOCITIES OF SURFACE WAVES

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SUMMARY

This paper discusses the effects of the superficial soft ground layer upon the phase velocities of surface waves of earthquake ground motions. In order to investigate the effects of the superficial soft layer, the phase velocities of the surface waves propagating in three kinds of geological structures with different soft-layer thicknesses were obtained by the following two methods. One method is to use earthquake observation data and the other is the Finite Element Method. The main two results are as follows. (1) The phase velocities obtained by the observed data agree reasonably well with the calculated ones. (2) With the increase of the thickness of the superficial soft layer, the phase velocities of surface waves tend to be smaller.

INTRODUCTION

It is recognized that the plane phase difference of ground caused by the surface waves of earthquakes have a significant effect on huge in-ground cylindrical tanks and conduit lines, etc. The phase velocity is a main factor of the phase difference. In this paper the phase velocities of surface waves of earthquake ground motions are examined. From aseismic design point of view, it is advantageous to construct a huge in-ground cylindrical tanks and conduit lines etc. in firm ground. But, these systems are often constructed in weak ground such as reclaimed ground in Japan due to many other location conditions. Therefore, the phase velocity of the surface wave is examined for the following three kinds of ground, i.e. Type 1 - where the superficial soft layer is thick, Type 2 - where the superficial soft layer is thin, and Type 3 - where no soft layer exists. The phase velocity of the surface waves was calculated using data from horizontal plane three point array earthquake observation. The measured phase velocities were compared with the calculated ones by the Finite Element Method (FEM). In addition, we examined the effect of the superficial soft layer upon the phase velocity of surface waves.

EARTHQUAKE OBSERVATIONS

Outline of the earthquake observations (1) Ohgishima in Kawasaki city (Type 1): The thickness of the soft layer on the firm silt stone is shown in Fig.1. The thickness of the soft layer ranges from 60 m to 90 m. The elastic wave velocities of the ground in the earthquake observation site are shown in Fig.2. The observation points are at 120 m depth in the firm silt stone. The plane arrangement of the observation points is also shown in Fig.1. Though the three observation points are independent of one another, the same record time is ensured by an automatic time correction system. Table 1 shows the earthquakes examined in this paper including the cases of Type 1 and 2. Fig.3 shows the time histories of acceleration of a typical earthquake at point A shown in Fig.1. Fig.4 shows examples of the Evolutionary Power Spectra (EPS) (Ref. 1) of the velocities.

(2) Negishi in Yokohama city (Type 2): The thickness of the weak silt layer lying on top of firm silt stone in the earthquake observation site ranges from 5 m to 20 m. The elastic wave velocities of the ground are shown in Fig.5. The earthquake observation points are at 40 m depth in firm silt stone. The plane arrangement of the observation points is shown in Fig.6. The time histories of acceleration of a typical earthquake at the point AG1 shown in Fig.6 are shown in Fig.7. Fig.8 shows an example of the EPS of the acceleration.

(3) Fujimi, Yasuura and Miharu in Yokosuka city (Type 3): The earthquake observation method is shown in Ref.2. In the earthquake observation site, the ground consists of a mud stone only and no soft layer exists. The S-wave velocity Vs and P-wave velocity Vp of the ground are Vs=500 to 850 m/s and Vp=1560 to 1800 m/s, respectively. The three earthquake observation points are at 45 m depth from Tokyo Point.

Phase velocity of the surface waves The phase velocities of surface waves were calculated by a method which uses the EPS of the observed ground motions (Ref.3). In this method, firstly, the EPS of the ground motions at the three points were calculated. Secondly, the arrival times of three peaks of EPS's of designated frequency are determined and the phase velocity is obtained by differences of the arrival times. This method has the following advantage, i.e., the region of frequency and time where surface waves are predominant can be found from the EPS's and then the phase velocity can be obtained in this zone.

(1) Ohgishima in Kawasaki city (Type 1): The phase velocity of the surface wave has dispersion characteristics. As for the dispersion characteristics, the distribution shape of the EPS becomes convex right (Ref.4). In the EPS shown in Fig.4, the dispersions of the surface waves are seen in the following regions. In the epicentral component velocities of the NAGANOKEN SEIBU earthquake, the region is 90 to 100 sec. in time domain, and 0.2 to 0.3 Hz in frequency domain. In the perpendicular component to the epicentral direction of velocities, the regions are 60 to 80 sec. and 0.1 to 0.15 Hz, and 85 to 100 sec. and 0.2 to 0.3 Hz. The phase velocities of other earthquakes shown in Table 1 were obtained by EPS and are shown in Table 2.

(2) Negishi in Yokohama city (Type 2): The phase velocities obtained in the same way as at Ohgishima in Kawasaki city are shown in Table 3.

(3) Fujimi, Yasuura and Miharu in Yokosuka city (Type 3): The phase velocities of surface waves obtained by observation data are shown in Fig.11, which is reprinted from Ref.2.

FEM ANALYSES

FEM(Ref.5) was used to calculate the theoretical dispersion curves of the phase and group velocities for the Rayleigh and Love waves. It was confirmed that the FEM solution of phase velocity for the Rayleigh wave has good accuracy by comparison with the solutions of Knopoff's theory and Haskell's model(Ref.6). For the Love wave, the accuracy of FEM solution was confirmed by comparison with Love's theoretical solution and the solution by Haskell's model(Ref.6). As a result, it can be said that the FEM solution for surface waves of up to the 3rd mode has enough accuracy from engineering point of view when the depth, where the displacement of surface wave becomes almost zero, are divided into 50 elements for FEM idealization.

(1) Ohgishima in Kawasaki city (Type 1): The ground depth is taken in a range

from 10 km to 400 km for analyses, according to the frequency and mode number of the surface wave. For depths up to 120m, the P- and S-wave velocities of ground used for analysis are shown in Fig.2. For depths from 120 m to 3 km, we used the P- and S-wave velocities indicated in Ref.7, and for depths from 3 km to 40 km, the elastic wave velocities indicated in Ref.8 were used for analyses. For the depth from 40 km to 400 km, Jeffry-Bullen's distribution of the elastic wave velocity of ground was used for analyses. The FEM model is divided into 50 finite elements. Fig.9 shows the theoretical phase and group velocities for the Rayleigh and Love waves calculated by FEM.

(2) Negishi in Yokohama city (Type 2): For depths up to 120 m, the elastic wave velocities of ground shown in Fig.5 were used for analysis. The elastic wave velocities of ground deeper than 120 m and the FEM idealization are the same as at Ohgishima in Kawasaki city. Fig.10 shows the theoretical dispersion curves of phase and group velocities for the Rayleigh and Love waves.

(3) Fujimi, Yasuura and Miharu in Yokosuka city (Type 3): The theoretical dispersion curves of phase and group velocities for the Rayleigh and Love waves are shown in Fig.11(Ref.2).

The observed phase velocities are shown in Fig.9, 10 and 11 by symbols comparing them with the theoretical dispersion curves. In each case, the agreements are good between observed phase velocities and theoretical dispersion curves.

(4) Effect of the superficial soft layer on the phase velocity: From Fig.9, 10 and 11, the following can be said about phase velocities.

(a) Rayleigh waves : In the frequency range from 0.1 Hz to 0.5 Hz, the variation in the phase velocity is small among the three types of weak layer thickness. In the frequency range from 0.5 Hz to 1.0 Hz, the phase velocity tends to be smaller as the soft layer becomes thicker. In the frequency range from 1.0 Hz to 4.0 Hz, phase velocities approach a constant value when soft layer is thin, but when the soft layer is thick, the velocities tend to be smaller with an increase in frequency.

(b) Love waves : In the frequency range from 0.1 Hz to 1.0 Hz, the effects of the thickness of the soft layer is the same as the effects on the Rayleigh wave. In the frequency range from 1.0 Hz to 5.0 Hz and in any mode higher than 1st, the phase velocities approach constant values when the soft layer is thin, but when the soft layer is thick, phase velocities become smaller with an increase in frequency.

CONCLUSIONS

This study of the phase velocity of surface waves, based on three - point array earthquake observation data and FEM analyses, leads to the following conclusions. (1) The phase velocities of surface waves obtained by earthquake observation data agree well with the theoretical dispersion curves calculated using FEM. Thus the FEM solution can predict the actual phase velocity for surface waves with enough accuracy for engineering purposes. (2) The phase velocities of the surface wave have the tendency to be smaller when a superficial weak layer exists. This tendency becomes stronger as the frequency increases . This fact was proven by earthquake observation data. In case of thick superficial weak layer, it becomes sometimes unsafe for huge in-ground cylindrical tanks, etc., since the wave length becomes shorter when the phase velocity decreases at the same frequency, that is, the plane phase difference of the ground grows.

In the future, the following subjects should be continued:
(a) The accumulation of the earthquake observation data. (b) The clarification of the power of surface wave component in strong earthquake ground motions.

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Table 1 Earthquakes

Earthquake	M	KAWASAKI Type 1	YOKOHAMA Type 2	YOKOSUKA Type 3
IBARAKIKEN OKI 57. 7. 23	7.0			O
IZUOOSHIMA KINKAI OKI 57. 8. 12	5.7			O
NIHONKAI CHUBU 58. 5. 26	7.7			O
KANAGAWAKEN SEIBU 58. 8. 8	6.1		O	O
TOUKAIDO HARUKAOKI 59. 1. 1	7.4	O	O	
KANAGAWA·YAMANASHI KEN KYO 59. 2. 24	5.4	O	O	
TORISHIMA KINKAI 59. 3. 6	7.9		O	O
NAGANOKEN SEIBU 59. 9. 14	6.9	O	O	O
BOUSOUHAN TOU OKI 59. 9. 19	6.7	O	O	
IBARAKI·CHIBA KENKYO 60. 10. 4	6.2	O	O	
CHIBAKEN CHUBU 60. 11. 6	5.1		O	

M : Magnitude

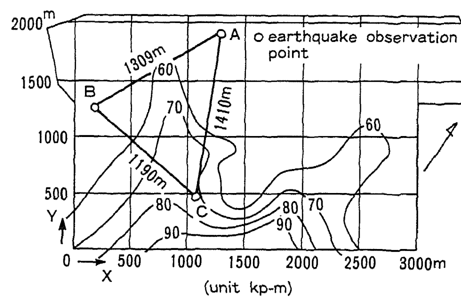


Fig.1 Depth of Soft Layer and Earthquake Observation Points

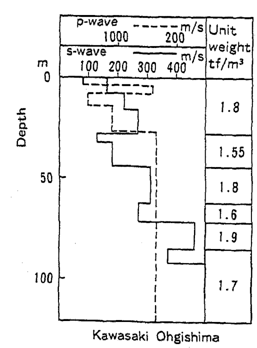


Fig.2 Elastic Wave Velocities at Ohgishima

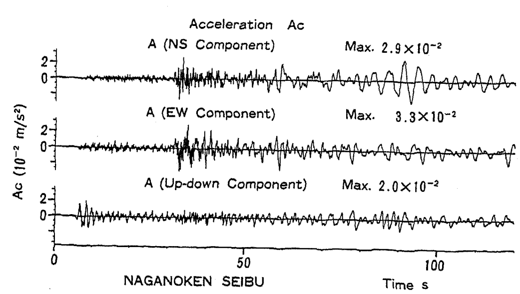


Fig.3 Observed Accelerations at Ohgishima

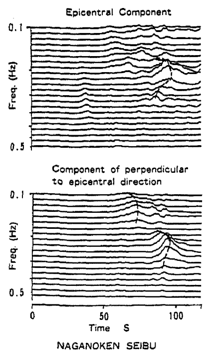


Fig.4 Evolutionary Power Spectra of Velocities

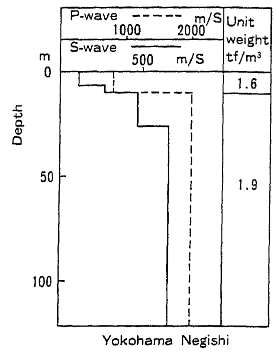


Fig.5 Elastic Wave Velocities at Negishi

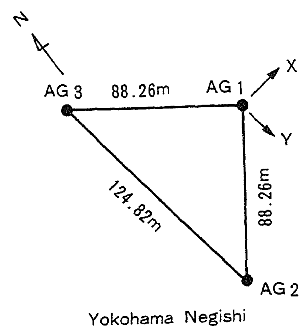


Fig.6 Earthquake Observation Points at Negishi

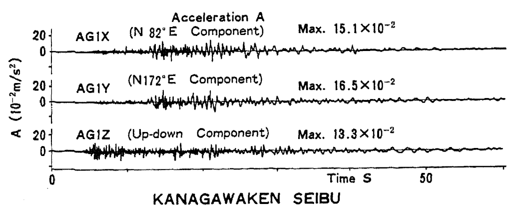


Fig.7 Observed Accelerations at Negishi

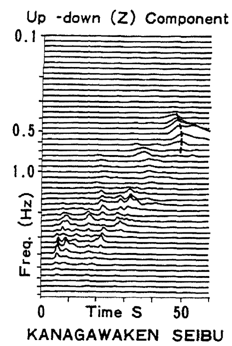


Fig.8 Evolutionary Power Spectra of Acceleration

Table 2 Observed Phase Velocities of Surface Waves at Ohgishima

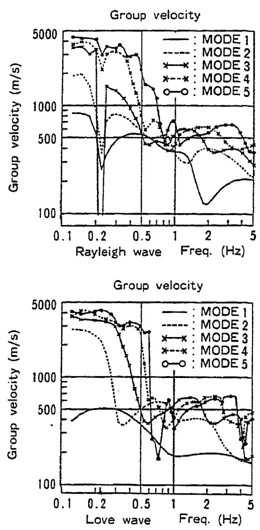
Earthquake	Rayleigh wave f Hz C m/s	Love wave f Hz C m/s
TOUKAIDO HARUKA OKI	0.209(1) 781 0.229(1) 809 1.096(2) 532 1.096(5) 951 1.445(1) 422	0.12 (1) 1330
KANAGAWA·YAMANASHI KENKYO	0.8 (3) 763	0.273(2) 2051
NAGANOKEN SEIBU	0.209(1) 1341	0.120(1) 1052 0.132(1) 930 0.135(1) 1110
BOUSOUHANTOU OKI	0.191(1) 719 0.225(1) 748	0.11 (1) 1182
IBARAKI·CHIBA KENKYO	0.191(1) 621 0.209(1) 638 0.60 (4) 1576	

f : frequency, C : phase Velocity ( )mode No.

Table 3 Observed Phase Velocities of Surface Waves at Negishi

Earthquake	Rayleigh wave f Hz c m/s	Love wave f Hz c m/s
IBARAKI-KEN OKI		0.12 (1) 1050 0.30 (2) 1435 0.45 (2) 1000 1.07 (5) 1850
IZUOOSHIMA KINKAI OKI	1.20 (4) 1000	
KANAGAWA-KEN SEIBU	0.187(1) 1461 0.471(2) 769	
NIHONKAI CHUBU	0.182(1) 1248 0.218(1) 1249 0.239(1) 588	0.126(1) 1765
TORISHI-MA KINKAI	0.178(1) 1396 0.198(1) 1471 0.572(4) 1974 0.636(4) 1471	0.094(1) 1471 0.707(4) 1973
NAGANOKEN SEIBU	0.174(1) 1471 0.229(1) 736 0.525(2) 1224	0.120(1) 987

f : frequency C : phase Velocity
( )mode No.



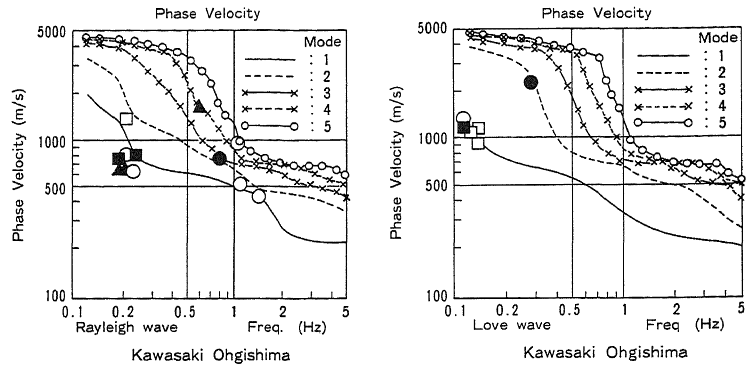
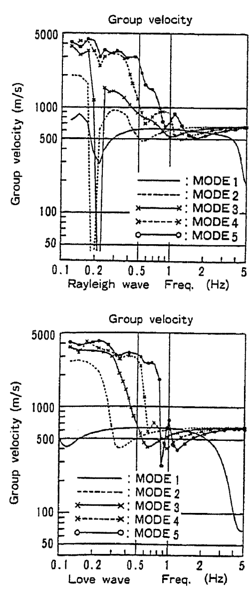


Fig.9 Velocities of Surface Waves at Ohgishima. Lines show Theoretical Dispersion Curve. Symbols show Observed Values.



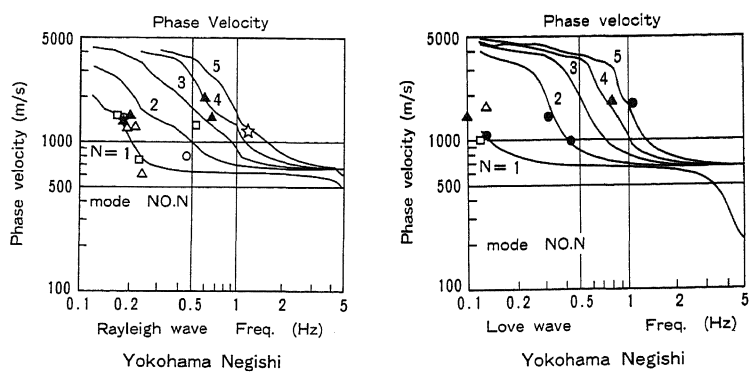


Fig.10 Velocities of Surface Waves at Negishi. Lines and Symbols are the Same as Fig.9.

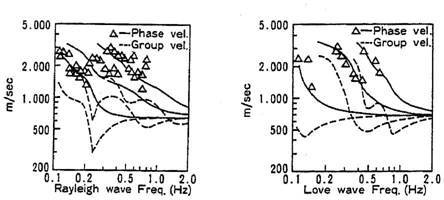


Fig.11 Velocities of Surface Waves at Fujimi 'etc. Lines and Symbols are the Same as Fig.9.