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ARRAY MEASUREMENTS OF VERTICAL MICROTREMOR AND SEISMIC MOTIONS FOR EVALUATING LONG-PERIOD GROUND MOTIONS

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SUMMARY

We conducted array measurements of vertical mictrotremors to determine an S-wave velocity structure in Tokyo Metropolitan coastal area in the center of the Kanto district, Japan, for evaluating characteristics of long-period ground motions. Phase velocities of Rayleigh waves were estimated from F-K and SPAC analyses of the array data. We, next, inverted them to S-wave velocity structures of deep sediments from a genetic inversion using existing data on subsurface structure. Furthermore, we investigated characteristics of several earthquake records during shallow earthquakes in the seismic array in the area. Phase velocities of fundamental Love waves and fundamental and first-higher mode Rayleigh waves in a period range from 2 to 7 seconds were determined from semblance analyses of the earthquake array data. The final S-wave profile was selected among the profiles discussed in the microtremor exploration from the constrained condition given from the phase velocities estimated from the earthquake observation. We also discussed on the propagation directions of the surface waves in the earthquake records.

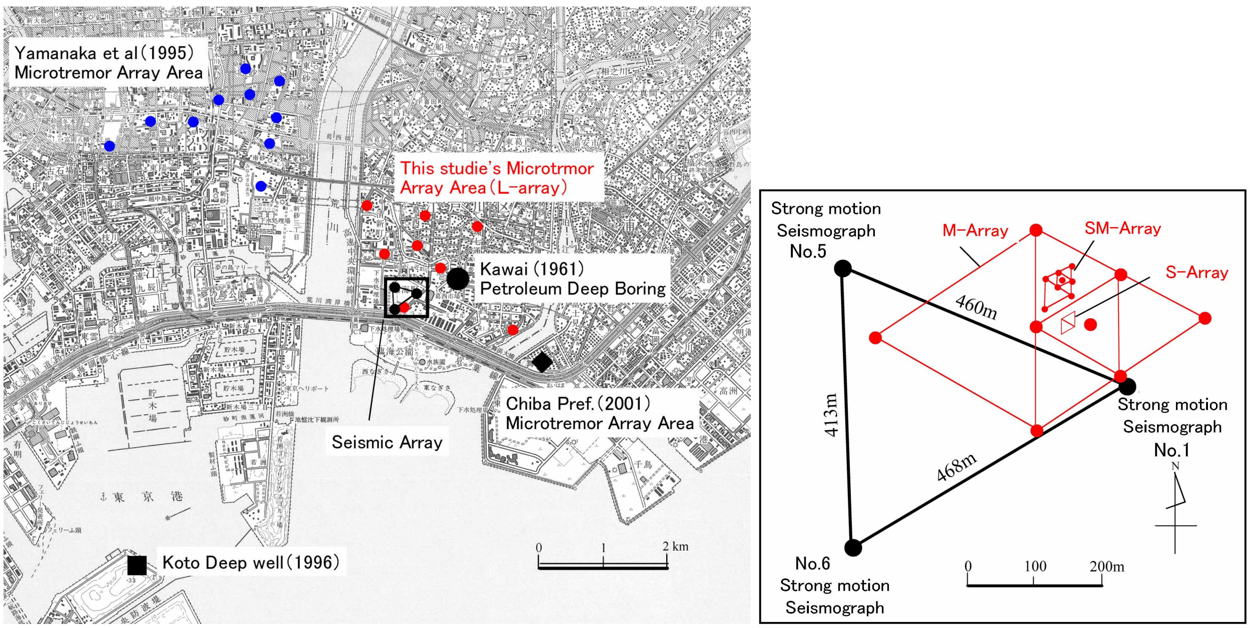
INTRODUCTION

In the recent few decades, a number of large-scale structures, such as high-rise buildings, long-spanned bridges, large oil tanks and base-isolated system buildings of which eigen-periods are laying 2-20 s, has been constructed. Then, there is a becoming important of the intermediate-period for seismic hazard reduction in the construction site. Surface waves make significant contributions to ground motions in the long-period range. In particular, surface waves are generated and amplified with long durations within sedimentary layers by using seismograms array records (Seo *et al.*, 1980) [1]. Most big cities have been developed on the Quaternary sedimentary layers, e.g., Tokyo, San Francisco, Mexico City and so on. Then, long-period ground motions mainly consisted surface waves are deeply related to S-wave profile of sedimentary basin. Therefore, we estimated S-wave structures in the Tokyo Metropolitan coastal area using microtremor array exploration and earthquake records from a tripartite strong motion array with a station spacing of 410 to 470 meters, then, we realized a good relationship between S-wave velocity profile and surface wave dispersion characteristics. Besides, propagation characteristics of Love and Rayleigh wave of which generation and amplification are influenced by the travel path from the basin edge to the site through the deep sedimentary layers.

MICROTREMOR ARRAY EXPLORATION AND INVERTED S-WAVE STRUCTURES AT STRONG MOTION ARRAY SITE

Site Information and Subsurface Soil Conditions

Both seismic array sites are located at Edogawa-ku in Tokyo, from which distance to Tokyo (Japan Railway) station is about 10 km for western direction, geological condition is reclaimed lowland. Fig.-1 shows strong motion array and microtremor array (L-array) site drawing with the past investigated deep bore-hole stations: (Koto Deep Well, (1996)) [2], (Petroleum Deep Boring, (1961)) [3], and array



(a) (b)

Fig.-1 Site Location Map (a) This study's array site and the past existing data station (b) Detail of tripartite seismic array and microtremor M, SM and S-array, as well as denoted a square in Fig(a)

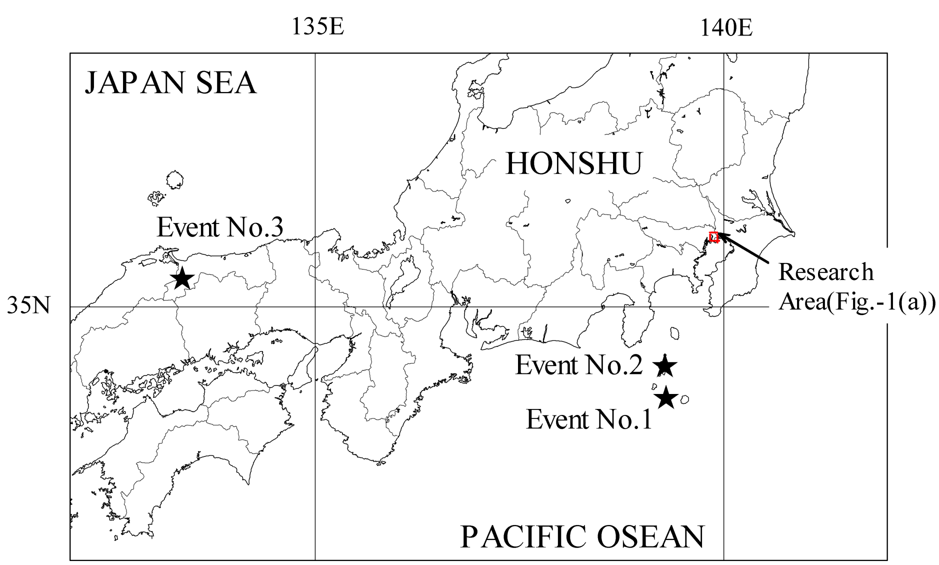


Fig-2 Map showing site location of Japan. Shallow earthquake epicenters of 3-events denoted.

exploration sites: (Yamanaka *et al*., (1995)) [4], (Chiba Pref., (2001))[5]. In addition, site location map of larger scale is also shown in Fig.-2. At this site, shallow PS-well logging test was performed down to 100 m as shown in Fig.-3. Subsurface soil layer is almost soft clay down to 35 m with S-wave velocity 120 m/s. The engineering bed rock is appeared almost 50 m in depth. The tripartite seismic array is consisted of 3-component strong motion accelerometers, installed at ground surface as shown in Fig.-1(b).

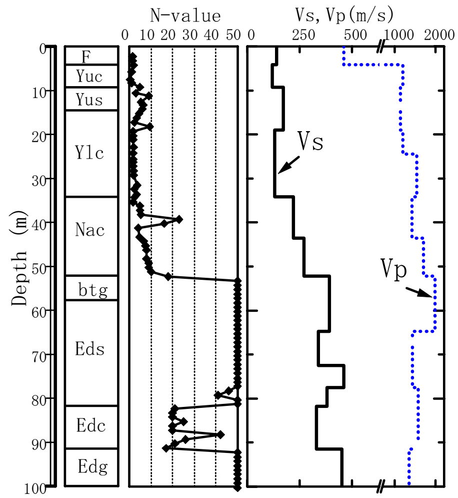


Fig.-3 Shallow PS well logging test and soil profile in this seismic array site

Microtremor Array Exploration and Inverted S-wave Structures

In order to determine S-wave velocity structure in and around the site, we conducted array measurements of vertical microtremor consists of 4-type different size arrays (L,M,SM,S) with spacing 1.7 to 0.3 km as shown in Fig.-1(a),(b). Microtremor array system consists of moving coil type accelerometers and 16 bits data-loggers. Phase velocity dispersion curve of each microtremor array was determined from frequency-wave number spectrum analysis method (hereafter, called as F-K method) [6], [7] and Spatial Auto Correlation Method (hereafter, called as SPAC method) [8]. Then, Fig.-4 shows phase velocity distribution curves computed from both methods using each size array, in which denoted three different theoretical curves derived from the existing investigation data near the site (see Fig.-1(a)).

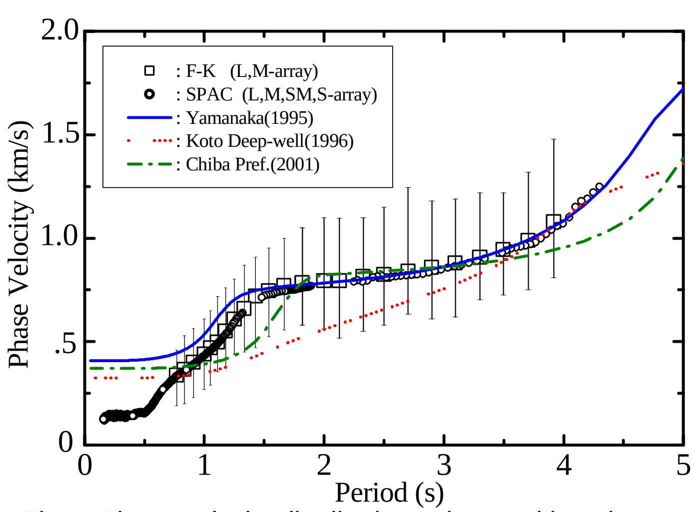


Fig.-4 Phase velocity distributions observed by microtremor arrays and theoretical phase velocities from the existing data.

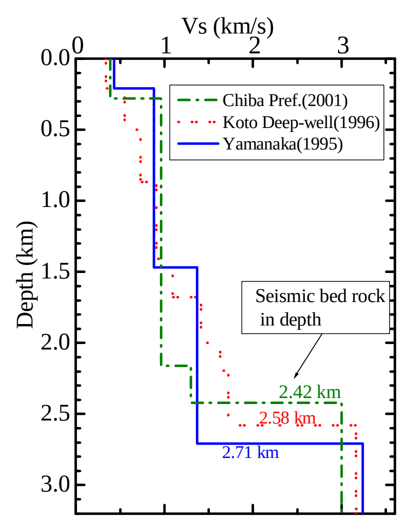


Fig.-5 Comparison of the S-wave velocity models from the existing data

However, these three different theoretical curves cannot explain observed phase velocities from vertical microtremors, then, phase velocities were inverted to an S-wave velocity profile by an inversion based on genetic algorithms (hereafter, called G.A.[9]) assuming a four-layer model. Search area was determined considering the deep boring data [3] and the seismic refraction survey data [4] as shown in Table-1.

Table-1 Search area in phase velocity inversion

No.	Vs (km/s)	H (km)	ρ t (g/cm³)
1	0.40 － 0.70	0.08 － 0.28	2.1
2	0.80 － 1.10	1.30 － 1.50	2.1
3	1.20 － 1.50	0.60 － 1.10	2.3
4	2.70 － 3.40		2.5

Then, Rayleigh wave fundamental mode phase velocities calculated from three different well-fit S-wave velocity models selected among G.A. inversion are shown in Fig.-6. These curves are well-fit to the observed phase velocities of microtremor arrays in a period range of 0.1 to 5.0 s, however, it is realized that 3-curve phase velocities in a period over 5 s are not coincident with each other. This result caused to lack of long period phase velocities over 5 s period due to the trigger power of microtremors, then, three different variations of the 4th layer as well as pre-Tertiary basement layer are realized.

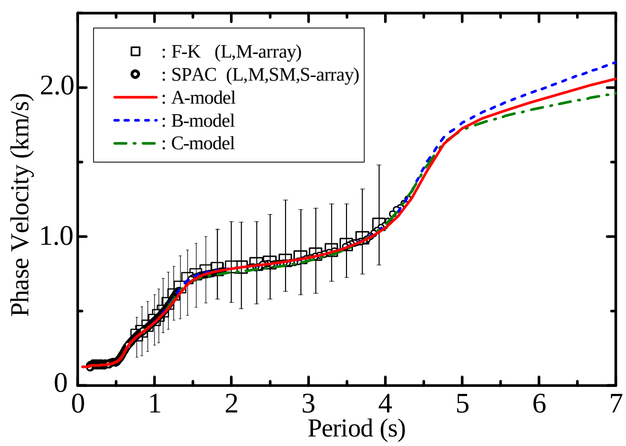


Fig.-6 Comparison of observed phase velocities and fundamental mode Rayleigh wave phase velocities of three different well-fit models selected among G.A. inversion

Table-2.1 A-model selected among G.A. inversion

Depth (km)	Vs (km/s)	ρ t (g/cm³)
0.10 - 0.33	0.60	2.0
0.33 - 1.66	0.92	2.1
1.66 - 2.34	1.29	2.3
2.34 -	3.01	2.5

Table-2.2 B-model selected among G.A. inversion

Depth (km)	Vs (km/s)	ρ t (g/cm³)
0.10 - 0.26	0.67	2.0
0.26 - 1.65	0.90	2.1
1.65 - 2.42	1.43	2.3
2.42 -	3.38	2.5

Table-2.2 C-model selected among G.A. inversion

Depth (km)	Vs (km/s)	ρ t (g/cm³)
0.10 - 0.21	0.58	2.0
0.21 - 1.56	0.88	2.1
1.56 - 2.35	1.49	2.3
2.35 -	2.73	2.5

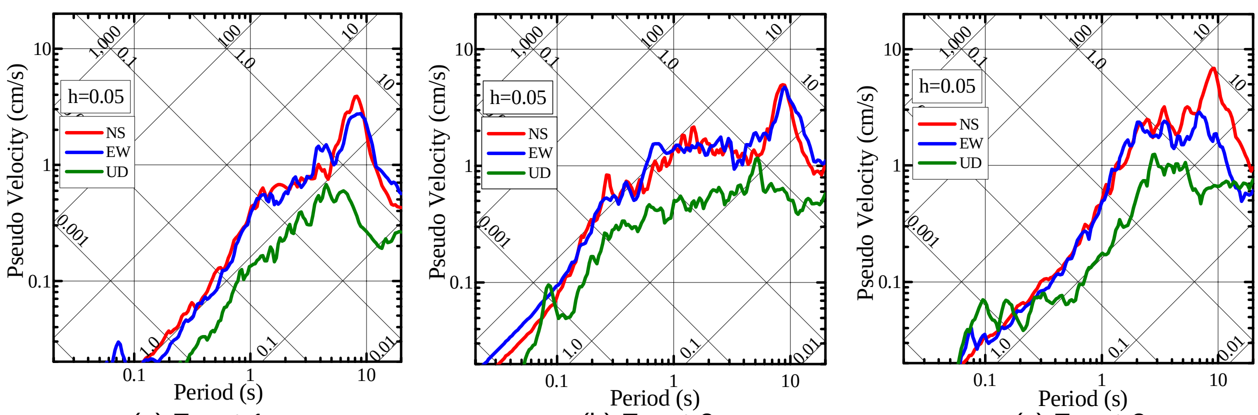
Spectral Analyses and Surface Wave Propagation Characteristics of Shallow Earthquakes

The tripartite strong motion array has been started observation since 1997, several earthquake records obtained. Then, three earthquake records of shallow hypocenter are selected as apparent appearance of surface wave motions (Table-3). Epicenter of the two events earthquake of No.1 and 2 are the Near Niijima Island located Kanto district of Japan, Event-3 is a far distance earthquake from Tokyo named the 2000 western Tottori Pref. (Japan) earthquake with Mj=7.3 as shown in Fig.-2.

Table-3 Three event earthquakes analyzed in this study

Event No.	Date	Region	Lat. (deg.)	Lon. (deg.)	Depth (km)	Mj	Hyp.Dis. (km)
1	9,July,2000	Near Niijima Is. of Japan	34.10	139.30	14	6.1	168
2	15,July,2000	Near Niijima Is. of Japan	34.42	139.25	5	6.3	148
3	6,October,2000	Western Tottori Pref. of Japan	35.28	133.35	11	7.3	591

We calculated 5% damped pseudo velocity response spectra of recorded accelerograms with three components as shown in Fig.-7(a),(b),(c). In those records, a sharp peak of each horizontal component in a period range of 8 to 10 s can be seen, also, a peak of UD component in a period range of 3 to 6 s can be seen.



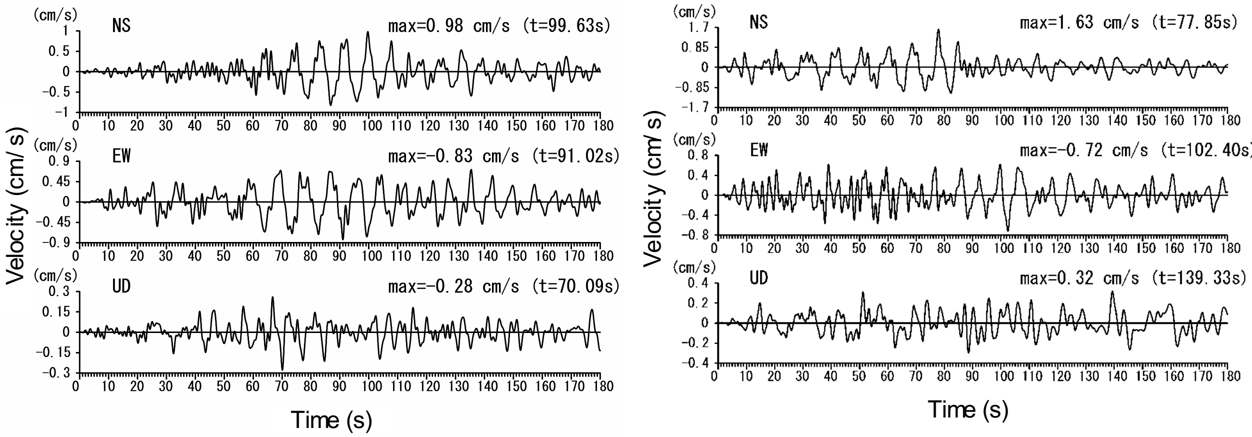
(a) Event-1 (b) Event-2 (c) Event-3

Fig.-7 Pseudo velocity response spectra with 5% damping of 3-event earthquake records

On the other hand, time histories of velocity wave motions integrated from accelerometer seismograms are shown in Fig.-8(a),(b) of which wave motions are high-cut filter treated (cutoff frequency 1 Hz). Also, displacement horizontal particle motions (1 Hz high-cut filtered) also shown in Fig.-9(a),(b).

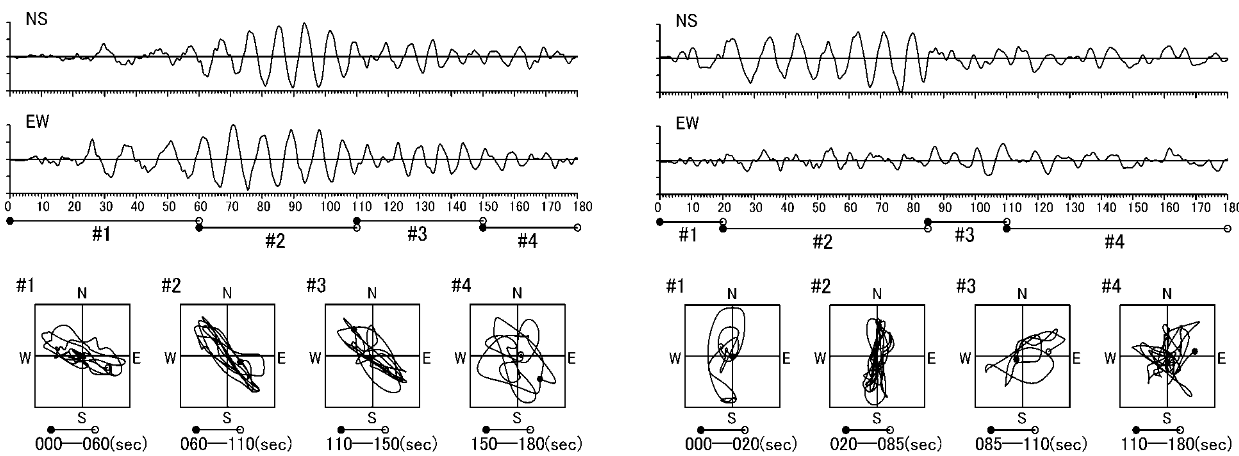
Regarding to velocity motions of each horizontal component of Event No.2, long period motions in a period range of 8 to 10 s appeared at 20 seconds and peak amplitude can be seen at 90-100 seconds in time domain. Besides, long period wave motion of Event-3 can be seen almost as NS component from 20 to 90 seconds in time domain.

Then, it is supposed that long period wave motions of horizontal components could be Love waves of which propagating from each epicentral direction. As regard to Event No.2, first arrival of long period wave motions of 0-60 durations are propagating from N200E direction (see Fig.-9(a) #1) as well as the direction to the epicenter, while, the later phase wave motions are arrived from N235E direction (see Fig.-9(a) #2), inclined to western direction. Furthermore, as regard to Event-3, first arrival (0–85 seconds) of surface wave motions (as well as NS component) are appeared from western direction (see Fig.-9(b)), almost the epicentral direction of a far distance earthquake (the 2000 western Tottori Pref. EQ., Japan).



(a) Event No.2 (b) Event No.3

Fig.-8 Time histories of velocity wave motions (1 Hz high-cut filtered)



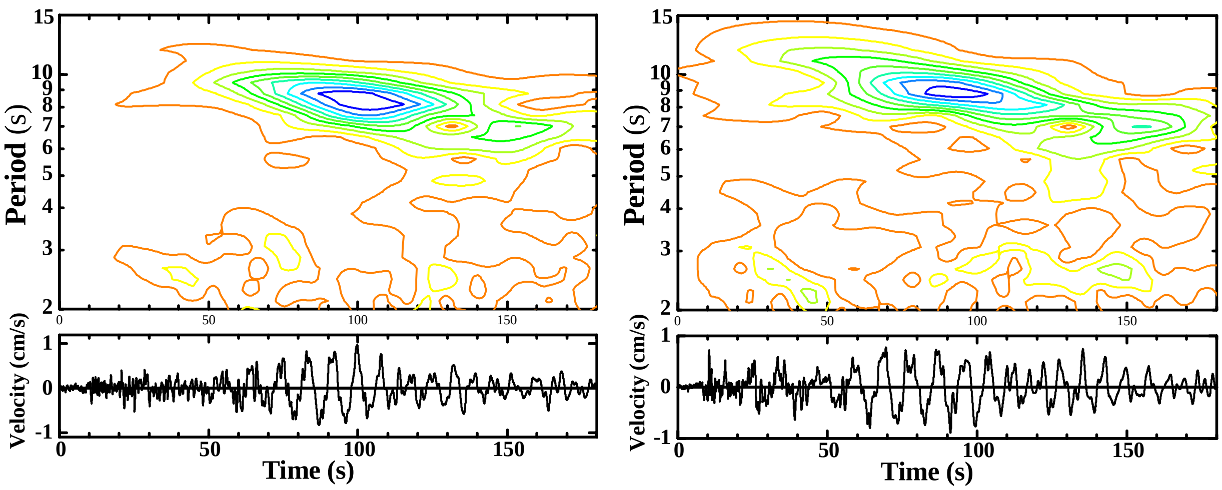
(a) Event No.2 (b) Event No.3

Fig.-9 Displacement particle motions of horizontal components (1 Hz high-cut filtered)

PROPAGATION CHARACTERISTICS OF SURFACE WAVES OF RECORDED EARTHQUAKES

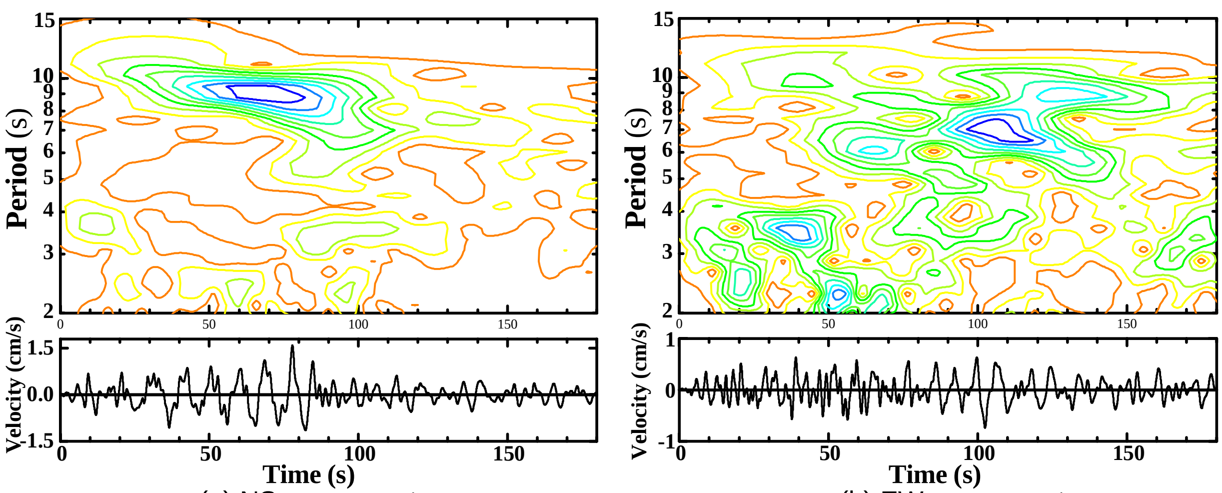
Propagation Characteristics of Love Wave Motions

Non-stationary spectrum analysis using multiple filtering techniques [10] was carried out to estimate dispersion and amplitude characteristics of surface wave motions for the recorded seismograms. We conducted these analyses for horizontal components of 2-event velocity seismograms to investigate Love wave motions as shown spectral contour in Fig.-11 and Fig.-12. It can be seen that each horizontal component spectral peak contours of Event-2 expresses continuous wide range dispersion trend in a period range of 7 to 13 s during long duration from 0 to 150 seconds in time domain. While, NS component spectrum of Event-3 has almost same dispersive trend as well as Event-2, however, EW component has another trend of partially peak contours in a period range of 5 to 7 s and of 2 to 4 s These differences to dispersive characteristics of period and continuous peak contours for two Events are due to surface wave propagation path trapped or generated at the edge of deep sediment layers in the Kanto (included Tokyo area) basin.



(a) NS component (b) EW component

Fig.-10 Non-stationary spectra of horizontal component velocity motions (Event-2)

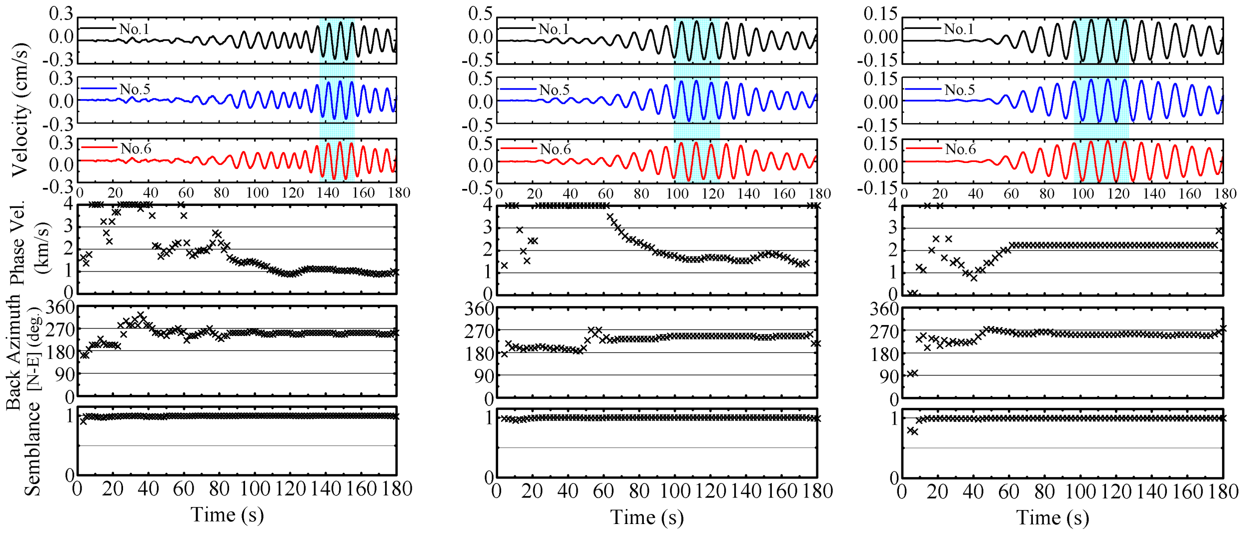


(a) NS component (b) EW component

Fig.-11 Non-stationary spectra of horizontal component velocity motions (Event-3)

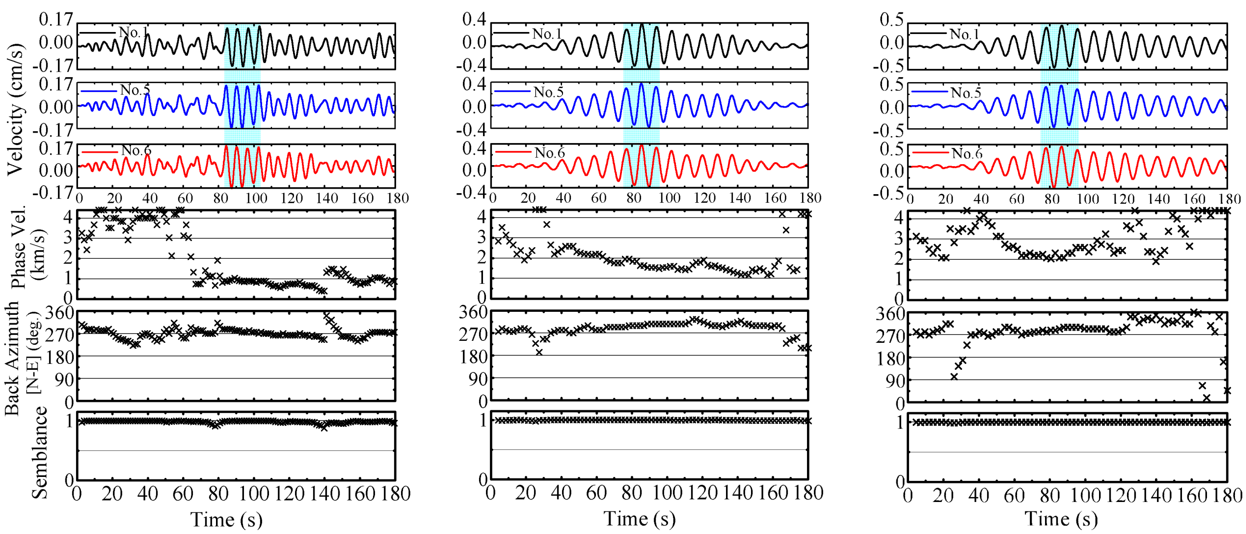
With considering continuous wide range dispersive periods (6-10 s) and peak motions of Love wave, semblance analyses were carried out to determine surface wave travel direction and phase velocities as shown in Fig.-12 and Fig.-13. In those figures, semblance value equal 1.0 means well-fit determination to the 3 different band-pass filtered wave motions decided to be a properly propagating direction and phase velocity. Then, three transverse component waves of Event-2 were polarized to N135E revolved, while, transverse components of Event-3 were regarded as NS component.

As a result, regarding to Event-2 (see Fig.-12(a),(b),(c)), first arrival of surface waves of 0-40 seconds duration are from almost N200E direction as well as the epicenter with high phase velocity, later phase motions are from N260E direction with a velocity range 1.0 to 2.2 km/s (Kinoshita *et al* (1992)) [11]. With regard to Event-3 (see Fig.-13(a),(b),(c)), there are no apparent earlier phase motions as well as Event-2, then, Love wave peak amplitude motions are realized from almost N270E to N290E direction, inclined to north-west direction comparing to its epicenter, with a velocity range of 0.9 to 2.1 km/s (see blue color shadowed).



(a) 6.5 s (b) 8.5 s (c) 9.5s

Fig.-12 Semblance analyses of transverse component wave motions (Event-2)

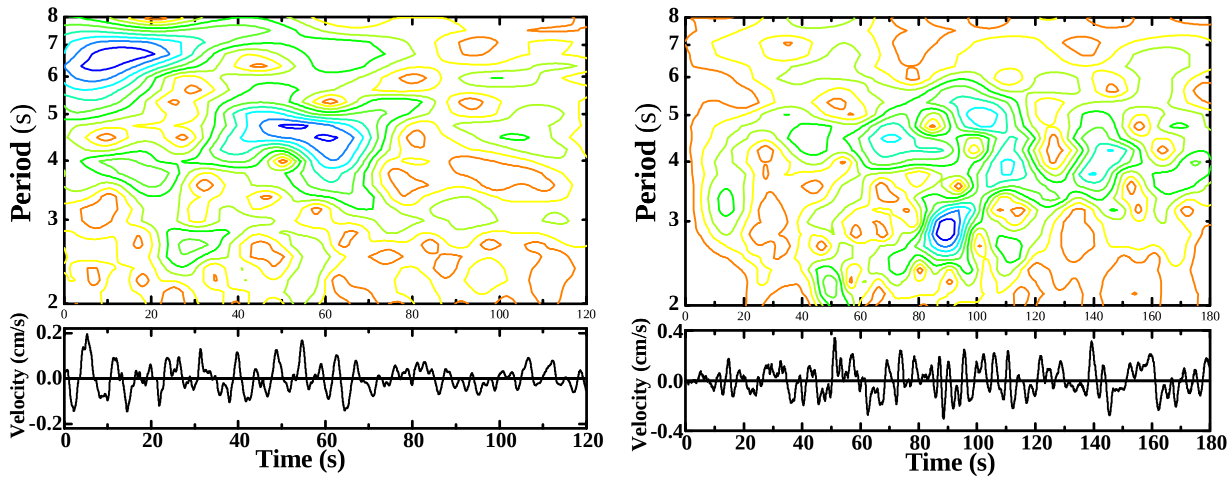


(a) 5.5 s (b) 8.5 s (c) 9.5s

Fig.-13 Semblance analyses of transverse component wave motions (Event-3)

Propagation Characteristics of Rayleigh Wave Motions

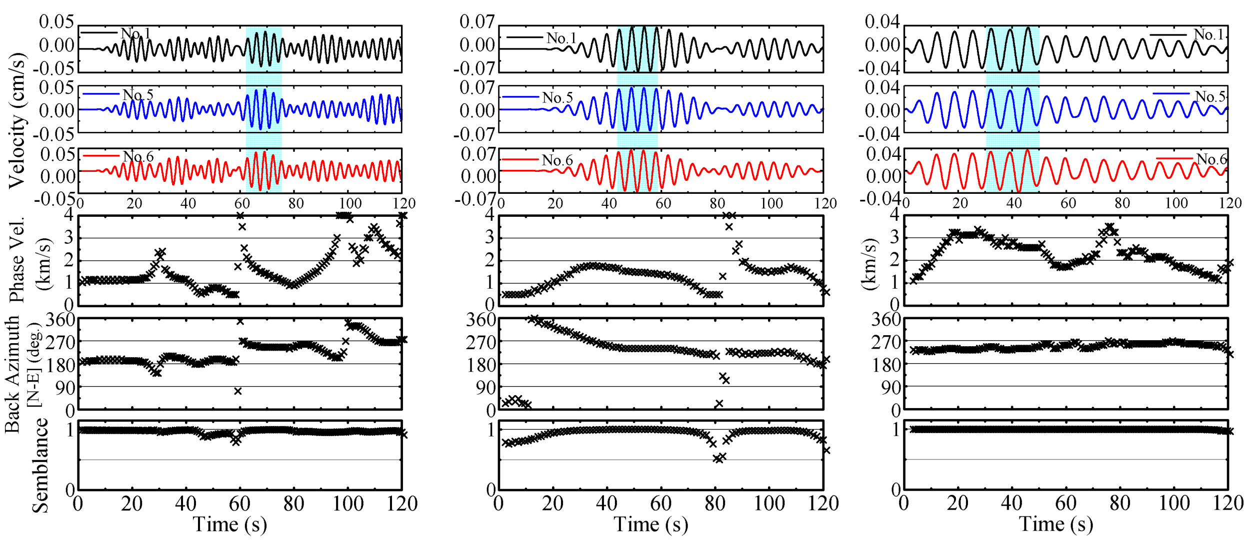
Non-stationary spectrum analyses were carried out for vertical components of 2-event velocity seismograms to investigate Rayleigh wave dispersive characteristics as shown in Fig.-14. It can be seen that spectral peak contours of each event express no continuous wide range dispersion trend in a period range of 2 to 8 s, however, Event-1 has a partially generation trend in a period range of 6 to 7 s and 3.5 to 5 s during short duration from 0-30 seconds and from 40-70 s in time domain, respectively. While, it can be seen that Event-3 has different shape spectral contours with Event-1 as short range peak contours in a period range of 2.5 to 6.0 s, individually.



(a) Event-1 (b) Event-3

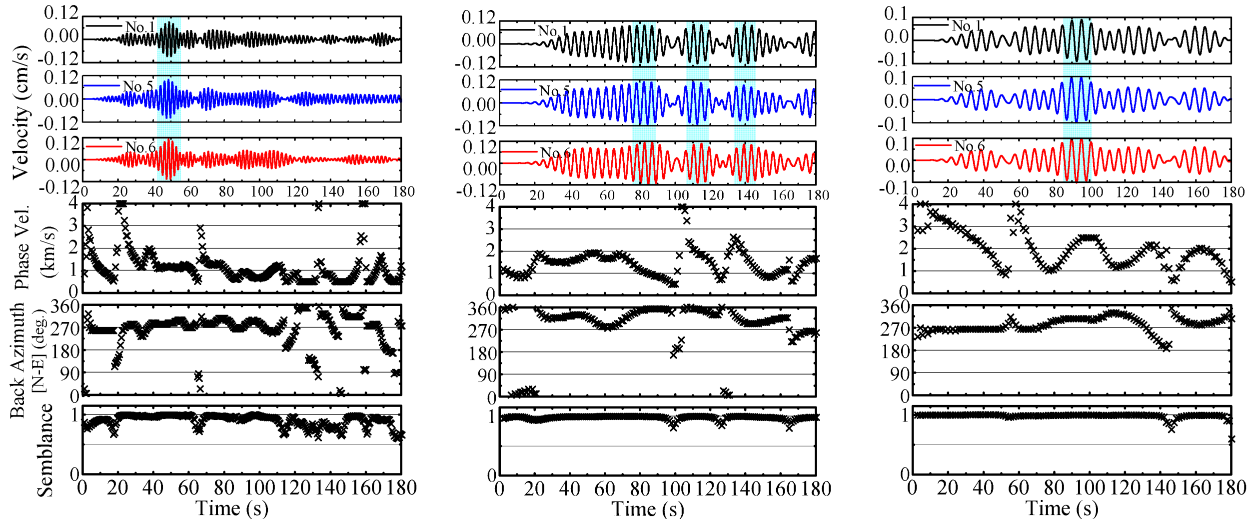
Fig.-14 Non-stationary spectra of UD component velocity motions

With considering partially recognized short range dispersion characteristics of surface wave motions in term of peak spectral contours of 2-events vertical wave motions, semblance analyses were carried out to determine Rayleigh wave travel direction and phase velocities as shown in Fig.-15 and Fig.-16.



(a) 3.2 s (b) 4.8 s (c) 6.8s

Fig.-15 Semblance analyses for UD component filtered velocity motions (Event-1)



(a) 2.2 s. (b) 4.4 s (c) 5.7s

Fig.-16 Semblance analyses for UD component filtered velocity motions (Event-3)

As a result, regarding to Event-1 (see Fig.-15(a),(b),(c)), peak amplitude of wave motions (blue color shadowed) of UD component time histories indicate arrival from almost N225E direction with variant velocities, such as 1.5, 1.3, and 2.6 km/s. In case of Event-3 (see Fig.-16(a),(b),(c)), when peak velocity appeared, wave motions of UD component are arrived from variant direction, such as N280E (a), N350E (b), and N300E (c), with a velocity range of 1.2 to 2.4 km/s. In those cases, it is realized that Rayleigh wave generation and propagation direction are short ranged dispersion and complex characteristics rather than Love wave motions are simple and wide ranged dispersions.

CHARACTERISTICS OF SURFACE WAVES BASED ON THE SUBSURFACE STRUCTURES

S-wave Velocity Structures Derived from Microtremor Array and Strong Motion Array Records

From above described semblance analyses, we obtained phase velocity value for each second period (band-pass filtered) case when amplitude of each filtered wave motion showed peak value (blue color shadowed).

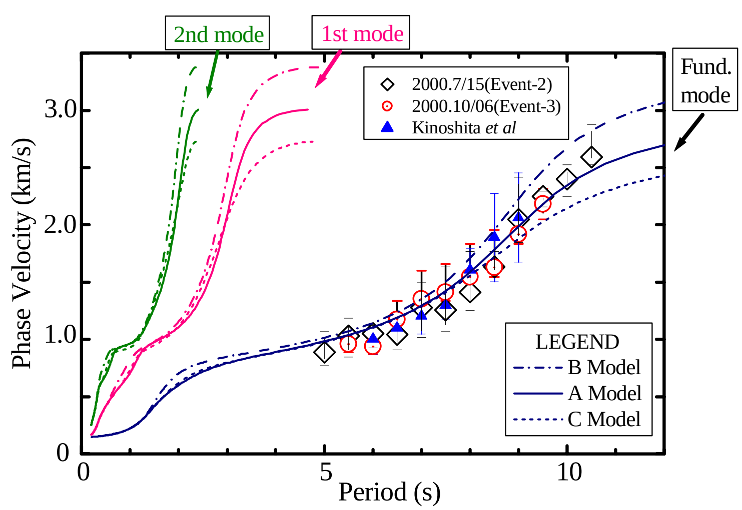


Fig.-17 Phase velocity distributions by semblance analyses with drawing theoretical higher mode Love wave phase velocities of well-fit 3 models selected among G.A. inversion

Then, phase velocities of transverse components regarded as Love wave were obtained with wide range periods of 5 to 10.5 s as shown in Fig.-17 drawing with theoretical (included higher mode) phase velocities of 3 well-fit inversion models. From semblance analyses for UD components, we obtained Rayleigh wave phase velocity value of each period and showed phase velocity distributions with theoretical higher mode phase velocities from 3 well-fit inversion models in Fig.-18.

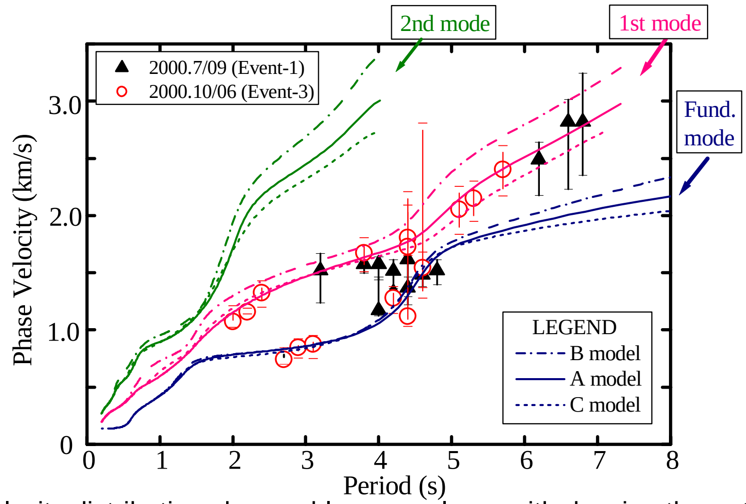
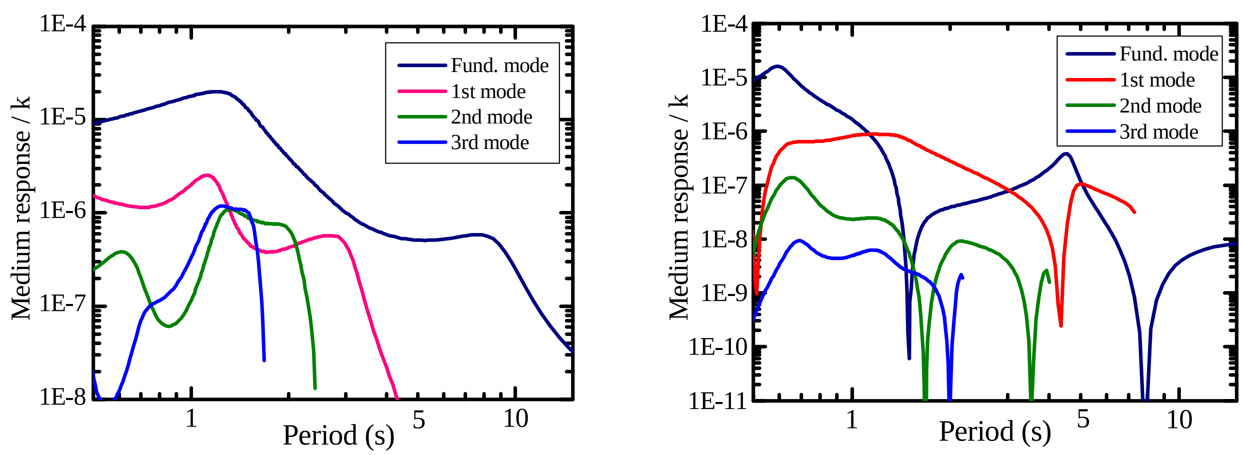


Fig.-18 Phase velocity distributions by semblance analyses with drawing theoretical higher mode Rayleigh wave phase velocities of well-fit 3 models selected among G.A. inversion

Therefore, we recognized that A-model was best-fit model, of which good relationship realized between phase velocities of transverse component selected from semblance analyses and Love wave fundamental mode phase velocities. Also, it was cleared that A-model played best-fit role among 3 models, of which good relationship realized between UD component phase velocities from semblance analyses and theoretical Rayleigh wave fundamental and first higher mode phase velocities.

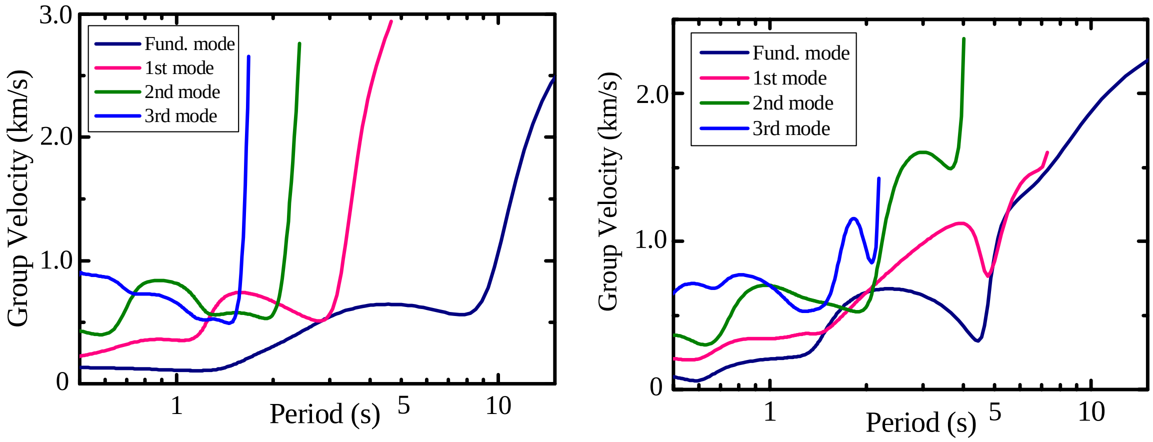
Then, we tried to estimate amplitude characteristics with calculating Medium response divided by wave length (λ) [12] as regard to be amplitude spectra as shown in Fig.-19(a),(b). It is realized that Love wave fundamental mode Medium response predominated, while, Rayleigh wave 1st higher mode Medium response predominated in a period range of 1.1 to 3.0 s and 5.0 to 7.0 s, Rayleigh wave fundamental mode Medium response in a period of the other residual range predominated (see Fig.-19(b)).



(a) Love waves (b) Rayleigh waves

Fig.-19 Theoretical spectral amplitude of A-model with each higher mode

Medium response / λ as well as spectral amplitude of predominant periods are well concordant with Love waves and Rayleigh waves phase velocities from semblance analyses. Furthermore, we calculated theoretical group velocities of Love waves and Rayleigh waves of A-model as shown in Fig.-20(a),(b). It can be seen that good relationship between Love wave airy phase in a period 8.0 s and wide dispersion characteristics in a period range 7.0 to 13 s of Non-stationary spectra above described in Fig.-10 and -11. Besides, it can be explained that good relationship between Rayleigh wave airy phases in a period of 4.0 of fundamental mode and 5.0 s of 1st higher mode group velocities and partially dominated short ranged spectral contour of Non-stationary spectra as well as dispersion trend in a period range of 4.0 to 6.0 periods, as above described in Fig.-14(a),(b).



(a) Love waves (b) Rayleigh waves

Fig.-20 Theoretical group velocities of A-model with each higher mode

CONCLUSIONS

In this study, vertical microtremor array measurements were conducted in the seismic array site of Tokyo Bay coastal area, and long period surface wave motions were recognized in the strong motion array observation records by the shallow earthquakes. From using these results, it was obtained well-fit S-wave velocity profile and was cleared surface wave propagation and amplitude characteristics as above described. Conclusion remarks are as follows;

(1) In Tokyo Metropolitan coastal area in Japan, it was obtained well-explained S-wave structure model conducting microtremor array measurement and several analyses using 3 events of shallow earthquake records in a horizontal strong motion array.

(2) In generally, the difficulties exist due to its trigger power of long period Microtremor is limited up to approximately 5.0 s, however, it was cleared that a possibility could be existed, of which phase velocities of wide ranged period over 5.0 s obtained using microtremor array and shallow earthquake records in a seismic horizontal array. Therefore, the records of strong motion observation station owned by government are widely opened now, where if we obtain earthquake records by conducting array measurement with temporary installing seismometers, it would be estimated a reliable S-wave velocity model than a simple station observation of strong motions.

(3) In this site, it can be clearly explained that long period motions of the shallow epicentral earthquakes are surfaces waves. Then, its propagation characteristics are well explained from an S-wave velocity structure, such as surface waves travel with fundamental mode Love waves and fundamental and 1st higher mode Rayleigh waves.

(4) In shallow earthquakes, it is clearly appeared that wide ranged dispersion of a period 7 to 13 s for horizontal components, as regarded Love waves. The first arrival of Love wave motions are from the direction of the epicenter, then later phase long period wave motions of Love waves are from south-west direction, inclined to western direction as well as reference [12]. While, Rayleigh waves have short ranged dispersion characteristics in a period 4.0 to 6.0 s, then, it is dominated spectral contour as complex shape and irregular appearance with considering Non-stationary spectra of UD components. Rayleigh wave motions propagate from almost the direction of the epicenter, but a little inclined to south-west to west direction for Event-1, and travel from west or north-west direction for Event-3.

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