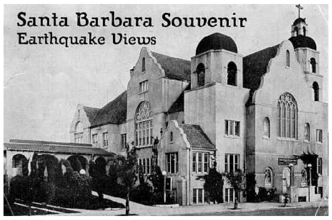

4th IASPEI / IAEE International Symposium:

Effects of Surface Geology on Seismic Motion

August 23–26, 2011 · University of California Santa Barbara

WAVE PROPAGATION ANALYSIS OF A GROUND WITH THREE-DIMENSIONAL IRREGULARITIES BASED ON THE FINITE ELEMENT METHOD

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ABSTRACT

In this paper, a study is presented on the wave propagation in a three-dimensional (3-D) slope ground due to incident surface waves. The objective is to examine the effect of irregularities on the microtremor or ambient vibration wave field. The analysis is based on the 3-D finite element method in conjunction with the 2.5-D thin layered and finite element methods. It was found from the study that wave propagation characteristics change by a great deal when a 3-D irregularity such as a tiny canyon exists in a slope ground with a fundamentally 2-D configuration. The frequency dependency of horizontal to vertical spectral ratios and phase velocities also changes according to the irregularity.

INTRODUCTION

It is essential to know the condition of the ground when considering earthquake disaster mitigation. It is well known that the surface soil condition and micro topography, or landform, influence the seismic intensity of the ground and hence impact structural damage to the buildings and civil infrastructure during earthquakes. However, obtaining information on the ground condition, such as soil profiles, over a wide area is not an easy task from a practical perspective. One of the most popular approaches to estimate the ground condition is to conduct microtremor (ambient vibration) measurements on the ground surface, from which natural frequencies of the ground are obtained (e.g., Nakamura, 1989; Arai *et al*., 2000, 2004). It is also possible to obtain soil profiles from microtremor array measurement results by applying inversion techniques based on the surface wave propagation theory (e.g., Aki, 1957; Capon, 1969; Cho *et al*., 2006). All the approaches proposed so far, however, are based on a parallel layer assumption. The surface wave propagation theory based on the parallel layer assumption is also applied to the problem of traffic induced vibration because of the location of excitation being on the ground surface.

A difficulty arises when the ground has an irregularity, which is often the case in an actual situation. For example, Fig. 1 shows the landform classification of Chiba, the southeastern part of the Kanto plain, or the eastern part of Tokyo metropolitan area, Japan. As can be seen in the figure, this area consists of three major categories of landform, i.e. terrace, lowland and reclaimed ground (Nakai *et al*., 2007). It is also noted that one of the characteristic features of the landform is the existence of a widely distributed narrow river valleys (lowland) that penetrate deep into terrace, which makes the landform of this area very complex. In addition, fairly steep slopes are formed along most of the boundaries between terrace and lowland, meaning that irregular ground is quite popular in this area.

A number of researches regarding wave propagation in an irregular ground have been reported so far (e.g., Hisada *et al*., 1996; Kawase, 1996). Most of them, however, deal with body waves and only a few have looked at surface waves (e.g., Lysmer *et al*., 1972; Nakagawa *et al*., 2010). In addition, a completely flat ground surface assumption for the far field is made in almost all three-dimensional studies (e.g., Bielak *et al*., 1998, 2003).

In this paper, the effect of a three-dimensional ground irregularity on the surface wave propagation is studied. More specifically, a two-dimensional slope ground with a small canyon (hollow) subject to an obliquely incident surface wave is considered, as schematically illustrated in Fig. 2. The analysis method used in the study is a combination of three-dimensional and two-and-a-half-

(2.5-) dimensional finite element methods (Nakagawa *et al*., 2010) in conjunction with a substructure technique (Nakai *et al*., 1985).

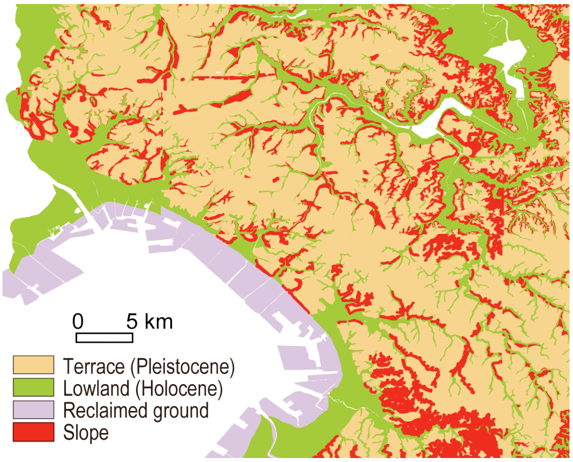


Fig. 1. Landform classification of Chiba area, Japan.

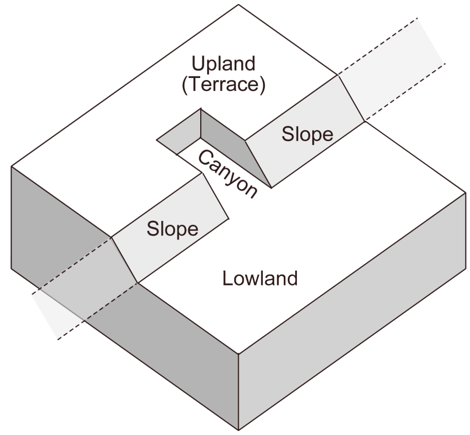


Fig. 2. A slope ground with a tiny canyon.

PROBLEM UNDER STUDY

As mentioned earlier, the main objective of this study is to examine the characteristics of surface wave propagation in an irregular ground in three dimension in order to evaluate its influence on the soil exploration based on microtremor measurements. As an attempt to address this issue, a simplistic irregular ground that consists of a two-dimensional slope ground with a slit-like narrow canyon that penetrates perpendicularly into the terrace (upland part of the landform), as shown in Fig. 2, has been considered. The problem under study is the microtremor wave field of this landform, which is assumed to be a synthesis of surface waves propagating in a variety of directions. The problem considered in this study is defined by the following statements.

- The ground has a two-dimensional landform, i.e. a slope ground.
- The ground, however, is in three-dimension in that it has a small canyon that penetrates perpedicularly into the terrace (the upland part of the slope ground).
- The soil is two layered throughout the landform.
- The ground is subject to a number of incident surface waves of various modes coming from a variety of directions.

METHOD OF ANALYSIS

The method of analysis is basically a three-dimensional finite element method in conjunction with a substructure technique. It features, however, a couple of points so that it can handle the problem under study. These points include a far field ground with topographic irregularities and surface wave propagation in such a ground.

Substructure Method

There exist a variety of substructure approaches that deal with wave propagation in an elastic medium. The method used in this study follows the following procedures (Nakai *et al*., 1985):

(1) Subdivide the entire ground under study into two parts; a near field that involves three-dimensional irregularities, and a far field which is basically a two-dimensional slope ground.
(2) Compute an impedance matrix $[K_c^*]$ of the far field from which the near field is excavated.
(3) Compute a displacement vector $\{u_c\}$ and traction vector $\{p_c\}$ of an equivalent far field which does not have an excavation and is subject to an incident surface wave.
(4) Compute a driving force vector $\{f_c^*\}$ at the boundary by the following expression:

$$\{f_c^*\} = [K_c^*]\{u_c\} + \{p_c\} \tag{1}$$

(5) Compute a response of the near field by attaching the impedance matrix at its boundary and by applying the driving force to its boundary.

Response of a Far Field: 2.5-Dimensional Analysis

The substructure analysis described above requires a three-dimensional analysis of a two-dimensional slope ground subject to an incident surface wave. This type of analysis is called a 2.5-dimensional analysis (Khair *et al*., 1989; Nagano *et al*., 1985). Since irregularity (slope) is involved in this analysis itself, another sub-structuring is considered, i.e. the 2.5-dimensional thin layered elements and 2.5-dimensional finite elements are combined to obtain the response due to an obliquely incident surface wave to the slope. Fig. 3 illustrates the method of analysis.

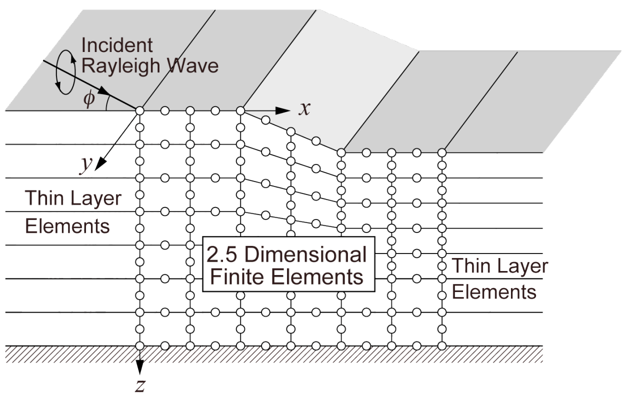


Fig. 3. 2.5-dimensional analysis.

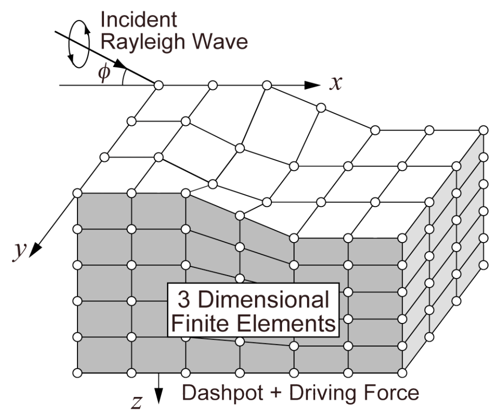


Fig. 4. Three-dimensional analysis.

Response of a Near Field: Three-Dimensional Analysis

The substructure analysis of the target, i.e. a slope ground with a tiny canyon, requires the impedance matrix $[K_c^*]$ and the driving force vector $\{f_c^*\}$ as described earlier. In this study, the impedance matrix $[K_c^*]$ at the boundary of the analysis model is computed as dashpots attached to the boundary. The displacement vector $\{u_c\}$ of the equivalent far field, found in Eq. (1), can be computed from the 2.5-dimensional analysis described in the previous section by the following expression:

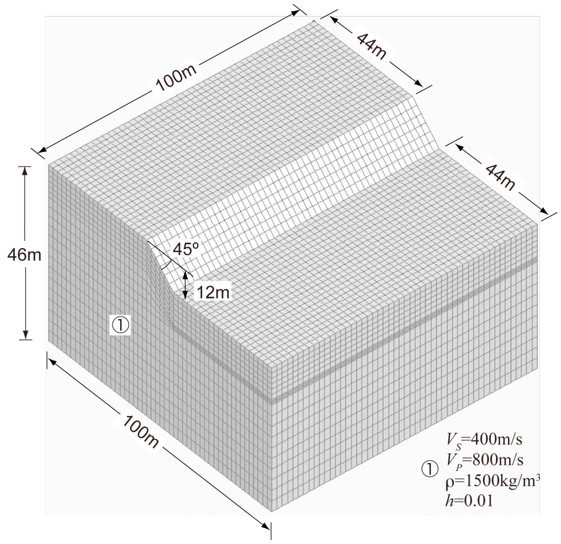
$$\{u_c\} = \{u_{2.5}\}\exp\left(-ik_y^s y\right), \quad k_y^s = k_s \sin\phi \qquad (2)$$

in which, $\{u_{2.5}\}$ is a displacement vector obtained from the 2.5-dimensional analysis. Eq. (2) states that the displacement wave field in the *y*-direction is expressed in an analytic form once the displacements on the *x*-*z* plane are obtained. k_s is the wave number of an incident surface wave of the *s*-th mode, and ϕ is the angle of incidence. Fig. 4 illustrates the three-dimensional analysis.

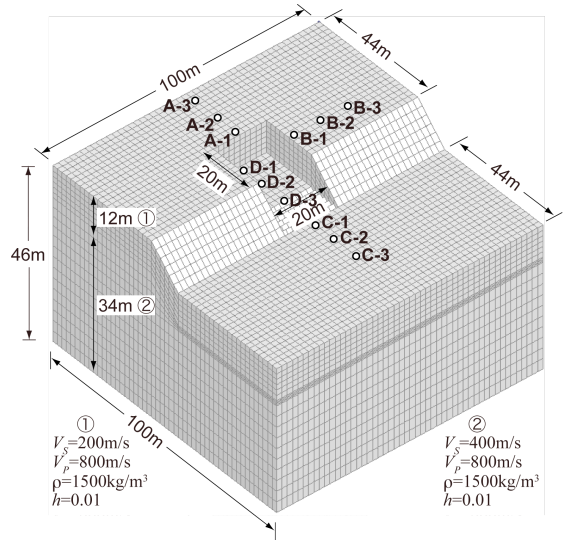
SURFACE WAVE PROPAGATION IN A THREE-DIMENSIONAL IRREGULAR GROUND

Uniform Slope Ground

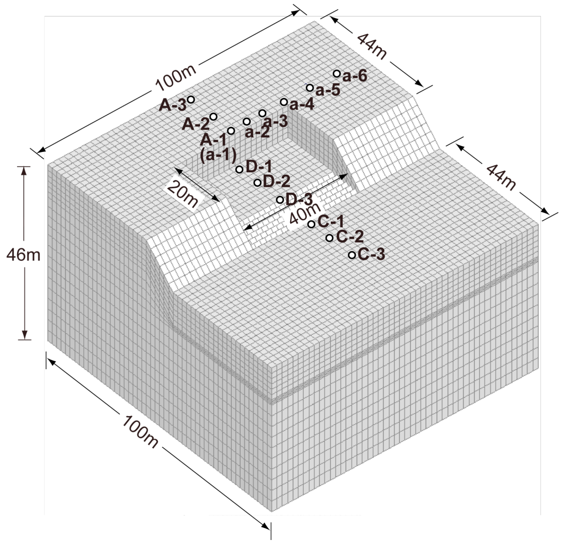
In order to verify the analysis method, a slope ground with uniform soil subject to an incident Rayleigh wave of the fundamental mode has been analyzed. Fig. 5 (a) shows the finite element mesh layout. As shown in the figure, the angle of inclination of the slope is 45° and the height is 12 meters. Eight node linear elements are used in the three-dimensional finite element analysis, while eight node quadratic elements are used in the 2.5-dimensional finite element analysis and three node quadratic elements are used in the 2.5-dimensional thin layered element analysis.



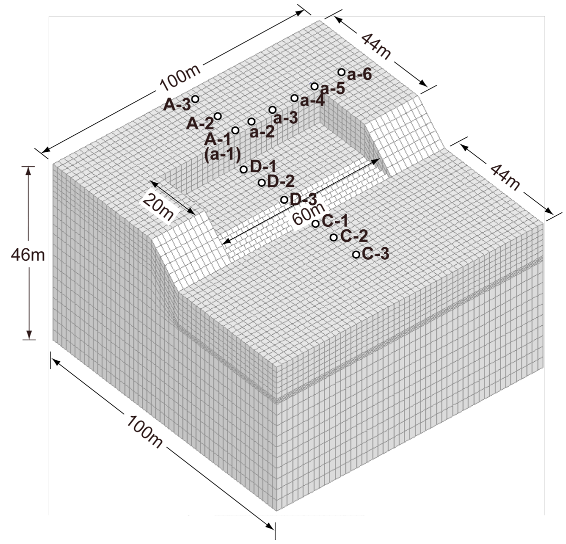
(a) Finite element model of a slope ground.



(b) Slope ground with a canyon of 20 meter width.



(c) Slope ground with a canyon of 40 meter width.



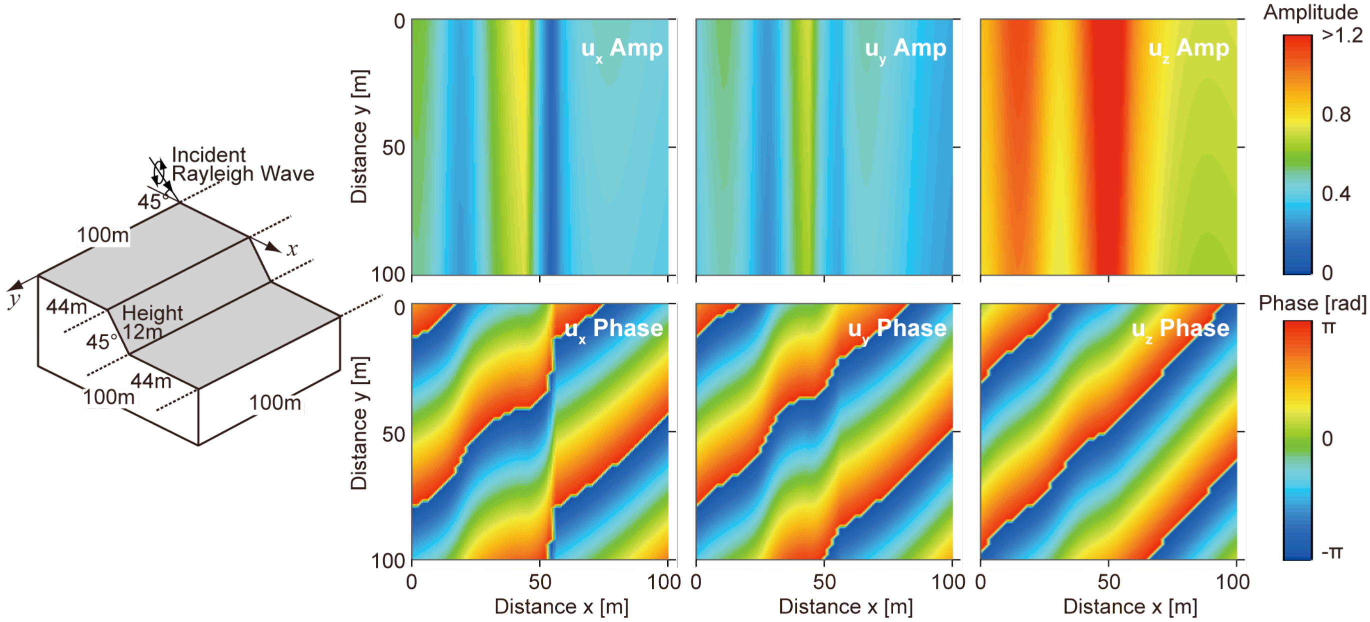
(d) Slope ground with a canyon of 60 meter width.

Fig. 5. Finite element models used in the study.

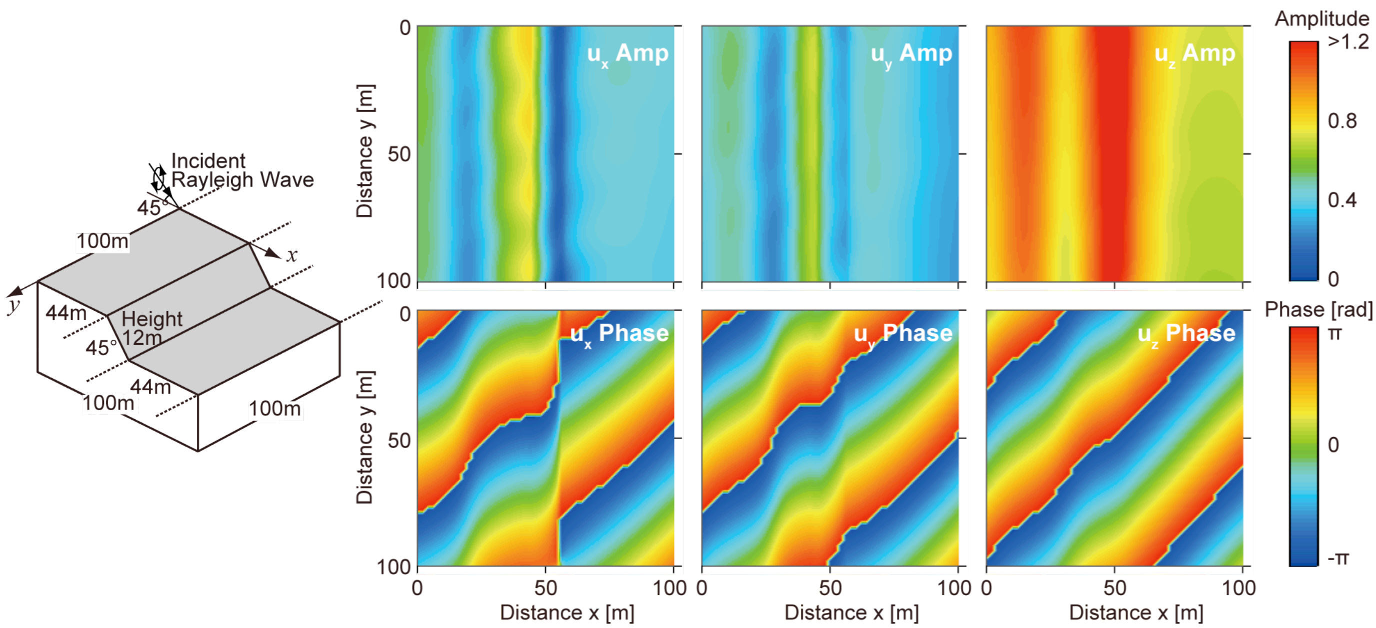
Fig. 6 compares three-dimensional and 2.5-dimensional results of displacement distribution at the ground surface in the case of Rayleigh wave incidence of the fundamental mode of 8Hz with the incidence angle of 45°. The wave is coming from the upland part of the slope ground. Although two analyses must coincide with each other from the theoretical point of view, the three-dimensional analysis result is slightly different from the 2.5-dimensional counterpart especially for displacement amplitudes. A possible reason for this can be addressed to an insufficient accuracy of dashpots as the impedance function of the far field. The fluctuation of displacement distribution found in the three-dimensional results can thus be explained by the interference of the incident wave and waves reflected from the boundary. This fluctuation may be reduced by adopting a more efficient boundary (accurate impedance).

Two-Layered Slope Ground with a Small Canyon

A similar slope ground with two-layered ground is investigated next. The difference from the previous case is that there exists a small canyon that penetrates perpendicularly into the slope, as shown in Fig. 5 (b) through 5 (d). Considered in the study are the three configurations of the canyon: the width of 20 meters, 40 meters and 60 meters. The length (depth) of the canyon is 20 meters. The ground is two-layered. The shear wave velocity of the surface layer is half of that of the underlying layer as shown in Fig. 5. The thickness of the surface layer is 12 meters, meaning that there exists no surface layer in the innermost area of the canyon because the height of the slope is also 12 meters. The rest of the analysis conditions, including the soil properties, are the same as those found in Fig. 5 (a). Displacement wave field and dynamic characteristics of the ground observed at the ground surface are examined below.

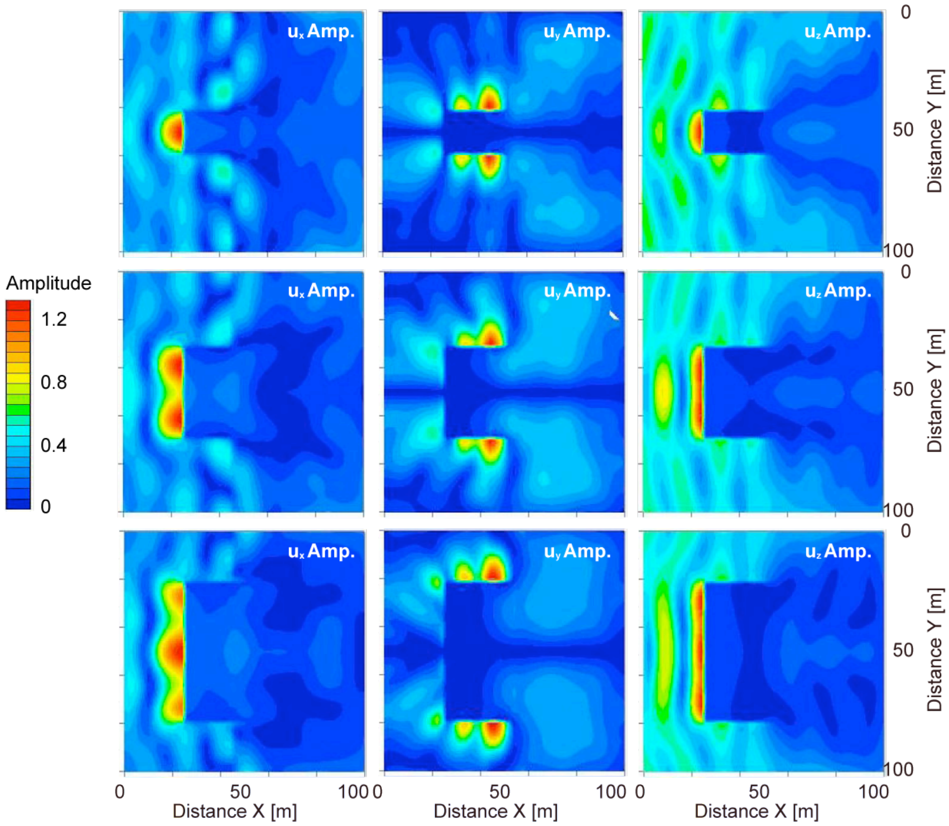


(a) 2.5-dimensional analysis.

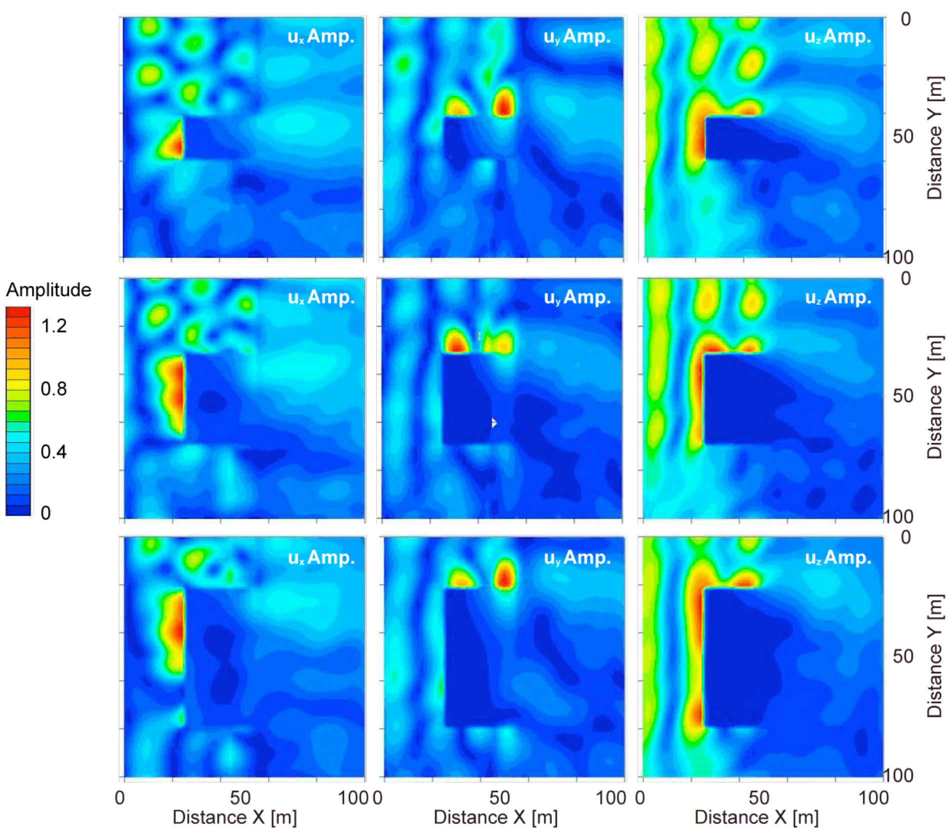


(b) Three-dimensional analysis.

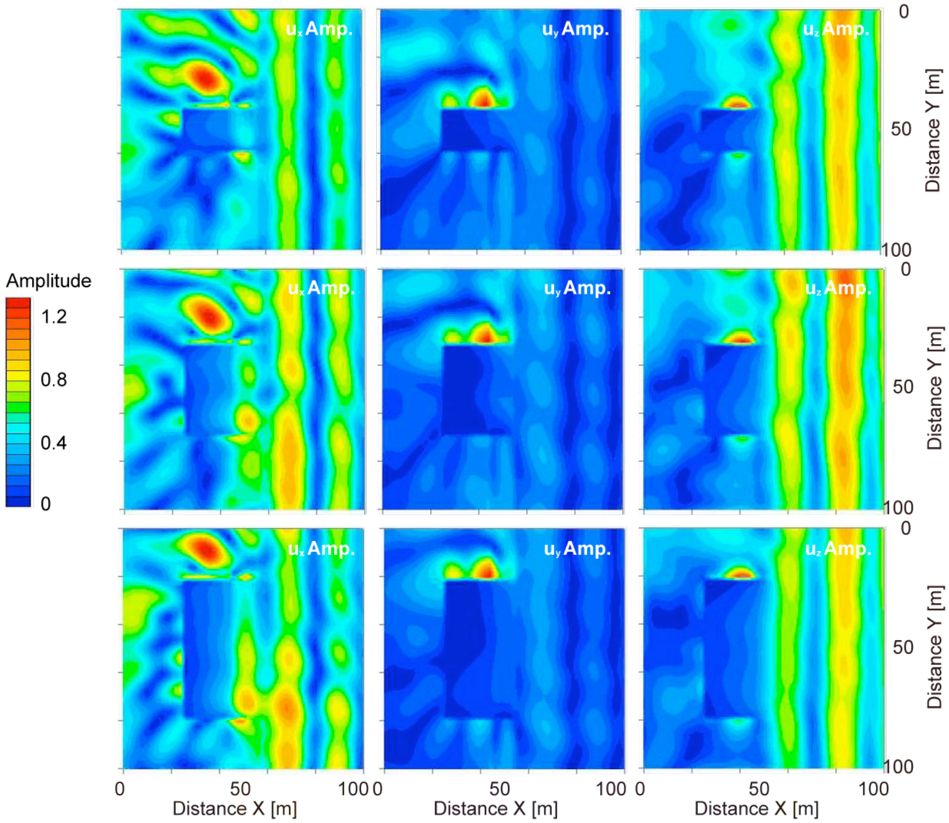
Fig. 6. Wave field of a uniform slope ground due to an incident Rayleigh wave of fundamental mode of 8 Hz.



(a) Incident angle of 0º.



(b) Incident angle of 45º.



(c) Incident angle of 135º.

Fig. 7. Wave field of a two-layered slope ground with a canyon due to an incident Rayleigh wave of fundamental mode of 8 Hz.

<u>Displacement wave field</u>

Fig. 7 shows the displacement wave field for the frequency of 8 Hz. Results for the incidence angles of 0º (coming from left, perpendicular to the slope), 45º and 135º are given. From the figure, it can be pointed out that:

- Due to the existence of a canyon, the displacement field is very complex.
- Amplitude of displacement is large in the area located upstream with respect to the canyon and is small in the back.
- The affected area is fairy large when compared to the size of the canyon.
- Variation of the displacement amplitude is large on the upland part of the ground but the influence on the displacement field is observed in a wide-ranging area of the lowland as well.
- Amplitude of displacement at the ground surface inside the canyon is fairly small.

If we take a closer look at the results, it is possible to add that:

- In the case of incident waves coming from the upland part of the slope ground, the displacement amplitude in the upland part becomes large but that in the lowland part is fairly small. This is due to the reflection of the incoming wave at the slope.
- On the contrary, the incoming wave from the lowland part gets transmitted to the upland part to some extent.
- The displacement amplitude in the *x*-direction, u_x, is very large along the cliff at the end of the canyon, but its intensity varies with the location along the cliff.
- There exists an area close to the upstream side of the valley where u_x is large when the wave comes from the lowland part of the ground.
- The displacement amplitude in the *y*-direction, u_y, is large along the cliff at the side of the canyon, and its intensity varies with the location.
- The vertical displacement amplitude tends to become large along the cliff at the end and the side of the canyon.

Although these characteristics vary depending on the frequency, hence the wavelength, the influence appears over large areas even in the low frequency range.

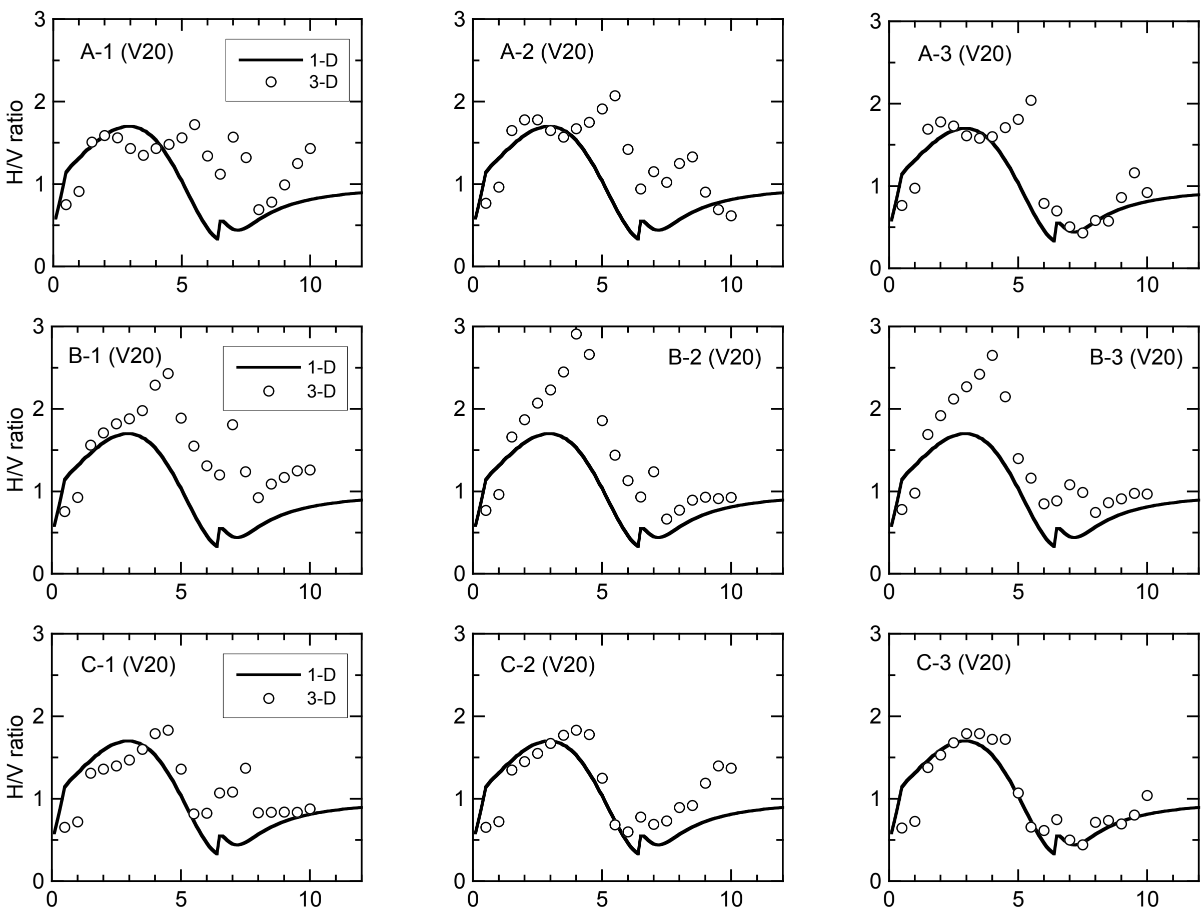
H/V spectra and phase velocity dispersion curves

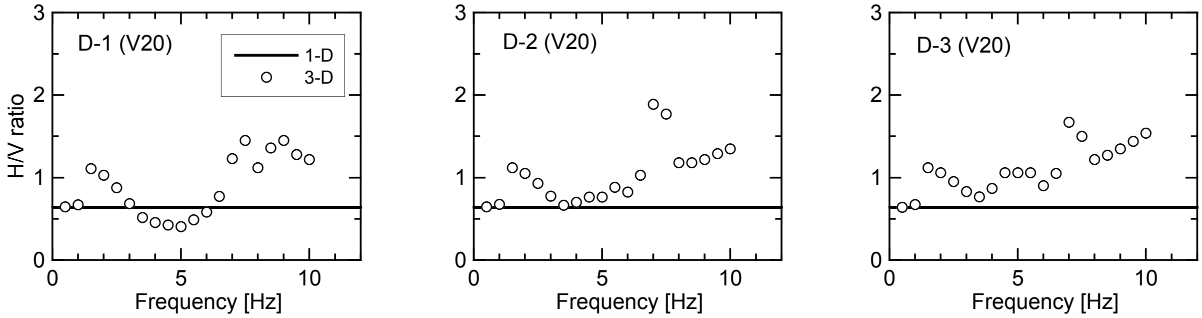
Based on the widely accepted hypothesis that microtremors are a synthesis of various surface waves travelling from a variety of directions, the microtremor wave field has been simulated by aggregating different kinds of surface waves (i.e. Rayleigh and Love waves), higher modes in addition to the fundamental mode, and a number of incident (azimuth) angles for each frequency. The incident angles considered in the study are −135º, −45º, 0º, 45º, 135º and 180º, where the incident angle of 0º corresponds to the case in which the wave is coming from left perpendicularly to the slope.

The horizontal to vertical spectral ratios, or H/V spectra, at selected locations have been computed by summing up the displacements due to various waves. Summation was done in terms of the power of displacement amplitude as shown in the following expression:

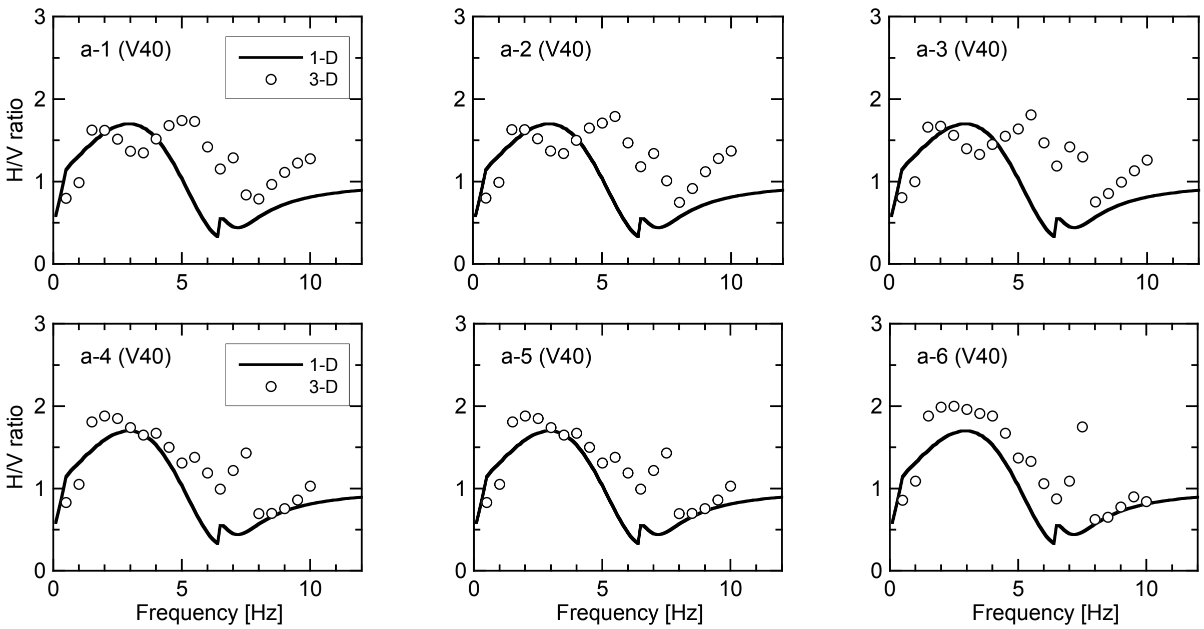
$$H/V = \sqrt{\sum_{l=1}^{W} |u_x|_l^2 + \sum_{l=1}^{W} |u_y|_l^2} \Bigg/ \sqrt{\sum_{l=1}^{W} |u_z|_l^2} \qquad (3)$$

in which W is the number of incident surface waves. In the above expression, u_i ($i=x$, y, z) is computed as a weighted summation of different kinds of surface waves and modes. The weighting factor was set to the medium response for different modes and the constant value of 0.7 was assumed as the ratio between Raleigh and Love wave components (Arai et al., 2004). The phase velocity dispersion curves have been computed from the vertical component of the microtremor wave field based on the centerless circular array (CCA) method (Cho et al., 2006) by assuming an array of hypothetical censors that correspond to neighboring nodes located at the ground surface of the finite element model. Fig. 8 shows H/V spectra, while Fig. 9 shows the phase velocity dispersion curves at various locations near the canyon in this slope ground as shown in Fig. 5. From these figures, it is possible to say the followings.

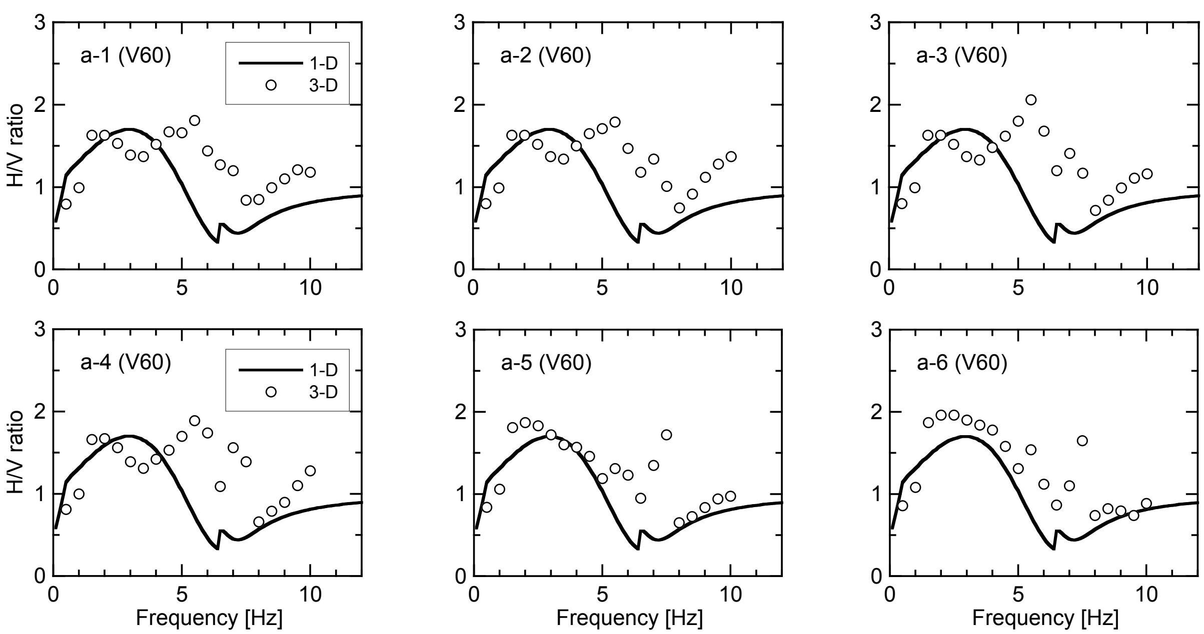




(a) Slope ground with a canyon of 20 meter width



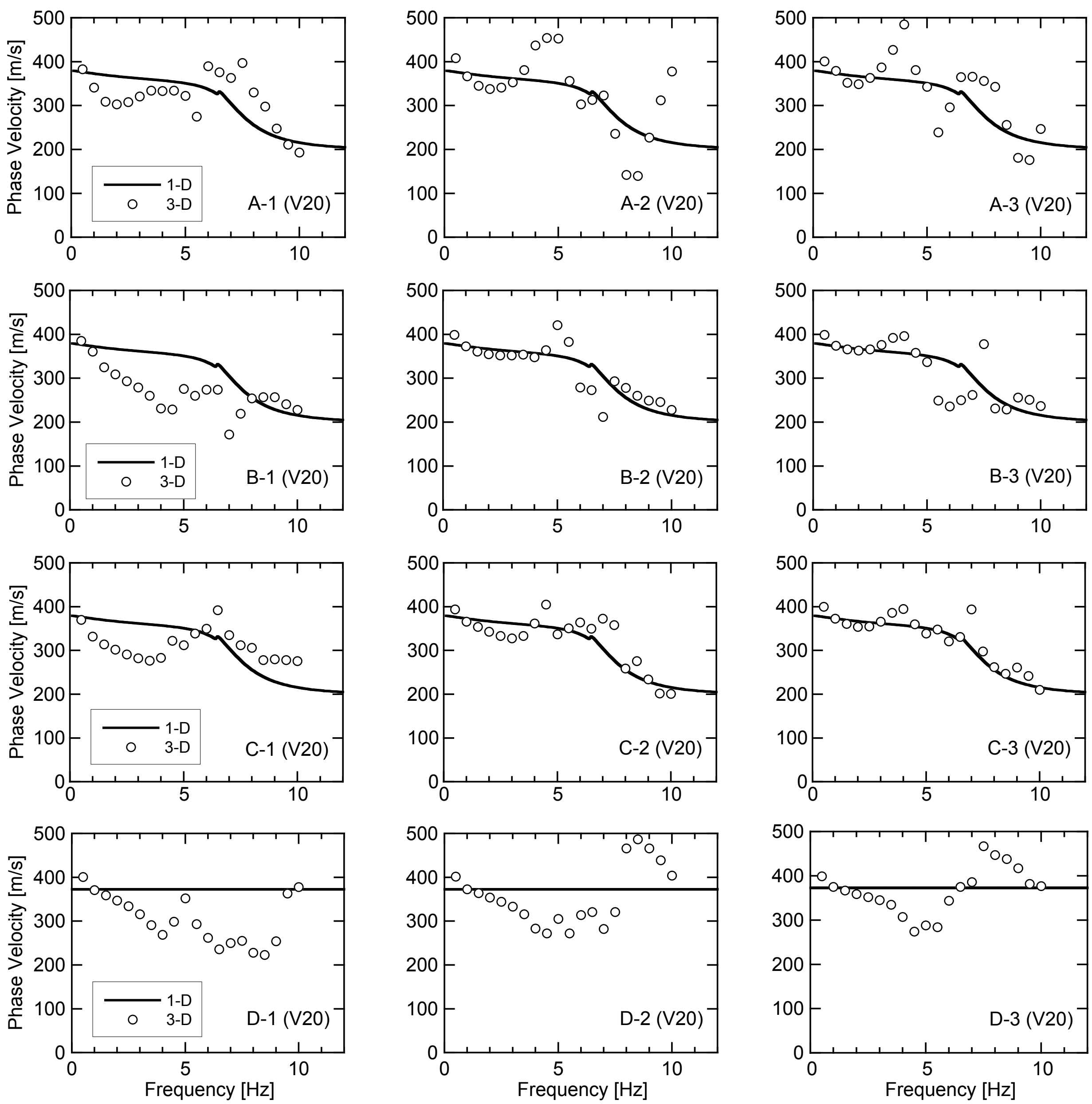
(b) Slope ground with a canyon of 40 meter width



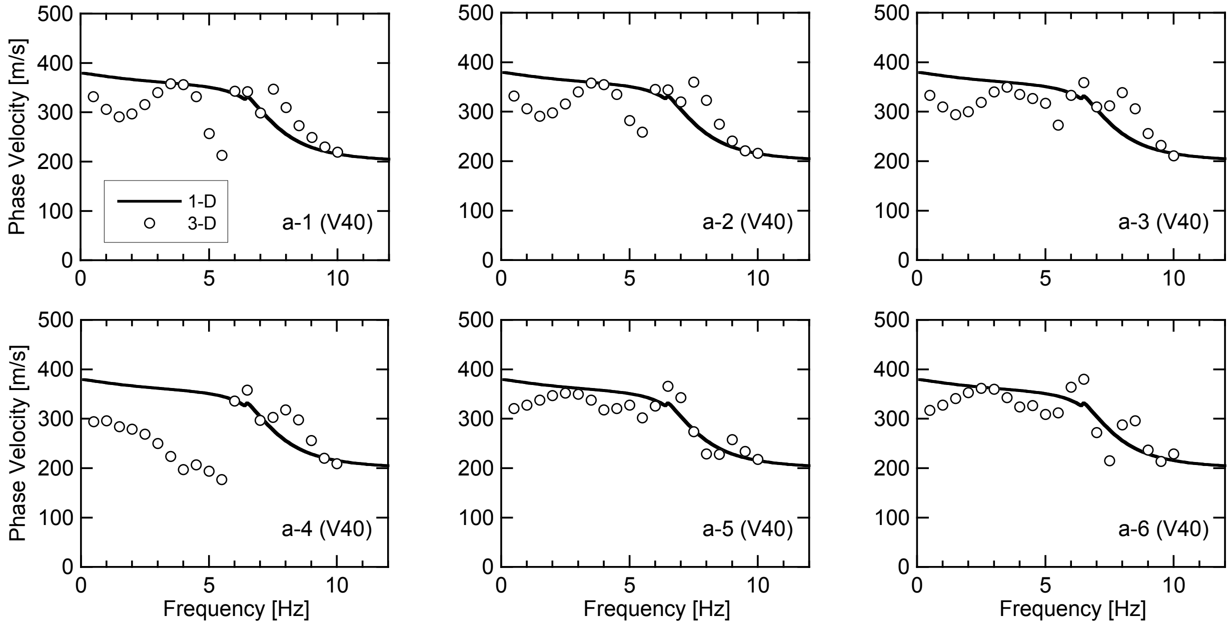
(c) Slope ground with a canyon of 40 meter width

Fig. 8. Comparison of H/V spectra

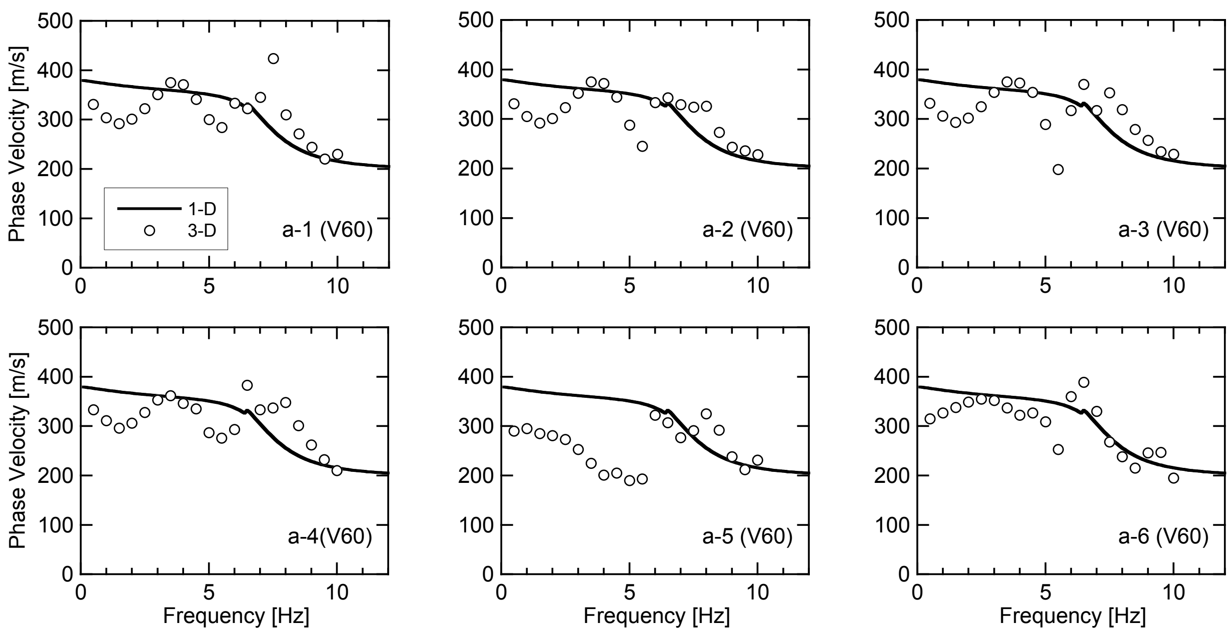
- The difference between 1-D and 3-D results is fairly large for both H/V spectra and dispersion curves, meaning that the influence of a three-dimensional irregularity on the microtremor wave field is very large.
- The difference is large especially in the frequency range near the natural frequency of the surface soil (4.17Hz).
- This may suggest that the parallel layer assumption may result in some errors when conducting an inversion analysis based on it.
- Both H/V spectra and dispersion curves in the lowland part of the ground (C-1 to C-3) are less influenced by the existence of the irregularity when compared to the upland part and the inner valley. And its influence diminishes fairly quickly as the distance from the slope becomes large.
- When looking at the upland part of the ground, it is noted that H/V spectra at the locations next to the inner most part of the valley (A-1 to A-3) have two peaks, at around 2 Hz and 6.5 Hz, which is very different from one-dimensional results.
- The phase velocity dispersion curves at these locations fluctuate very much with respect to the frequency.
- At the locations along the slope (B-1 to B-3), H/V spectra have single peaks which are slightly higher than the one-dimensional estimation.



(a) Slope ground with a canyon of 20 meter width



(b) Slope ground with a canyon of 40 meter width



(c) Slope ground with a canyon of 60 meter width

Fig. 9. Comparison of phase velocity dispersion curves

One of the reasons for the fluctuation of H/V spectra and dispersion curves is the interference of the incident wave, waves reflected from the slope and waves scattered by the small valley. This fluctuation may also be resulted from insufficient number of incident waves and insufficient capability of dashpots as impedance functions of the far field ground. This subject will be addressed in the future work.

CONCLUSIONS

In order to examine the effect of irregularity of a ground on the microtremor wave field by taking a slope ground with a tiny canyon as a target and conducting a three-dimensional finite element analysis in conjunction with a 2.5-dimensional thin layered element analysis. It was found from the study that:

- It is possible to conduct a three-dimensional analysis of a ground with basically a two-dimensional topography.
- The wave field becomes very complex when there exists a small canyon that penetrates into the upland through the slope, causing a big difference between the results in 2.5 and three dimensions.
- The microtremor wave field is also affected by the existence of a small canyon and the frequency dependency of H/V spectra and dispersion curves in the area close to the canyon show significant fluctuation because of this.

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