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Surface Wave Propagation Analysis of a Ground with Three-Dimensional Irregularities

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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.

KEY WORDS: Irregular ground, Surface wave, Microtremor, Finite element analysis, 3-D analysis, 2.5-D analysis

1 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. 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 [1]-[3]. It is also possible to obtain soil profiles from microtremor array measurement results by applying inversion techniques based on the surface wave propagation theory [4]-[7]. These approaches, however, are based on a parallel layer assumption. The surface wave propagation theory based on a 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, Figure 1 shows the landform classification of Chiba, the eastern part of Tokyo metropolitan area. As can be seen in the figure, this area consists of three major categories of landform, i.e. terrace, lowland and reclaimed ground [8]. It is also noted that one of the characteristic features of the landform is the existence of a whole lot of 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 [9], [10]. Most of them, however, deal with body waves and only a few have looked at surface waves [11], [12]. In addition, a completely flat ground surface assumption for the far field is made in almost all three-dimensional studies [13], [14].

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 Figure 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 [12] in conjunction with a substructure technique [15].

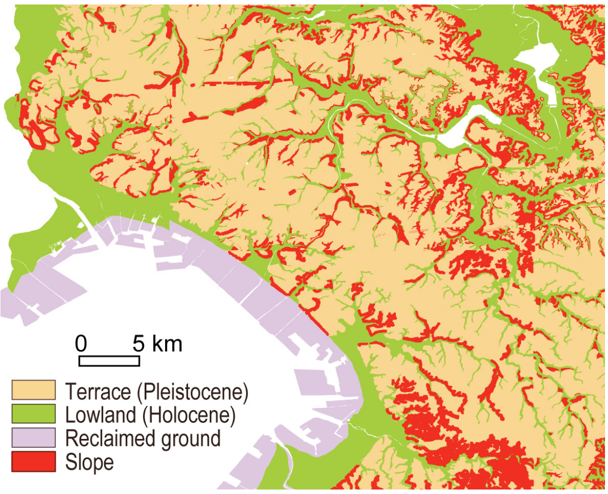


Figure 1. Landform classification of Chiba area, Japan

2 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. In order for this, 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 Figure 2. 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 ground is basically a two-dimensional slope ground.
- The ground has a small canyon that penetrates perpendicularly into the terrace.
- The soil is either uniform or two layered.
- The ground is subject to a number of incident surface waves of various modes coming from a variety of directions.

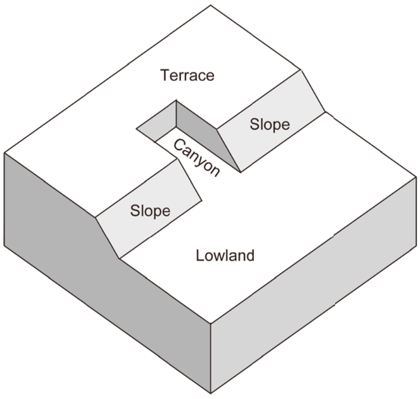


Figure 2. A slope ground with a tiny canyon

3 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.

3.1 *Substructure Method*

There exist a variety of substructure approaches that deal with a wave propagation problem. The method used in this study follows the following procedures [15]:

(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:

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

(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.

3.2 *Response of a Far Field: 2.5-Dimensional Analysis*

In 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 [16], [17]. 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. Figure 3 illustrates the method of analysis.

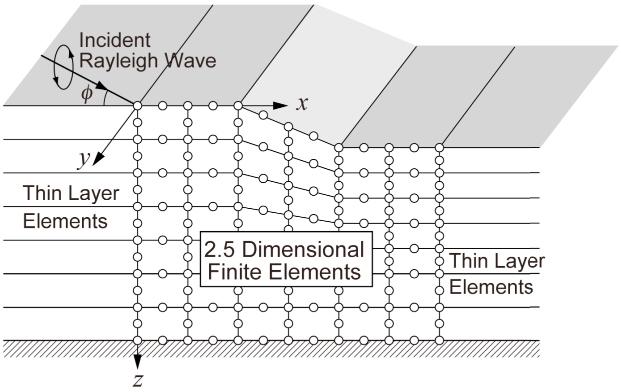


Figure 3. 2.5-dimensional analysis

3.3 *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 in 3.1. 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 can be computed from 2.5-dimensional analysis described in 3.2 by the following expression:

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

in which, {$u_{2.5}$} is a displacement vector of reference which is equal to the displacement field of the 2.5-dimensional analysis described in 3.2, k_s is the wave number of an incident surface wave of s-th mode, and ϕ is the angle of incidence.

The traction vector {p_c} of the equivalent far field can be computed by differentiating the displacement field and by applying the constitutive relationship. Finally, the driving force vector { f_c^*} can be given by Eq. (1)

Figure 4 illustrates the three-dimensional analysis.

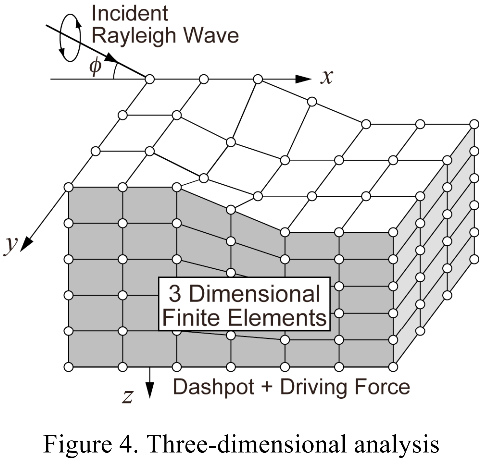


Figure 4. Three-dimensional analysis

4 SURFACE WAVE PROPAGATION IN A THREE-DIMENSIONAL IRREGULAR GROUND

4.1 *Slope Ground Composed of Uniform Soil*

In order to verify the analysis method, a slope ground with uniform soil subject to an incident Rayleigh wave of fundamental mode has been analyzed. Figure 5 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 and thin layered element analysis.

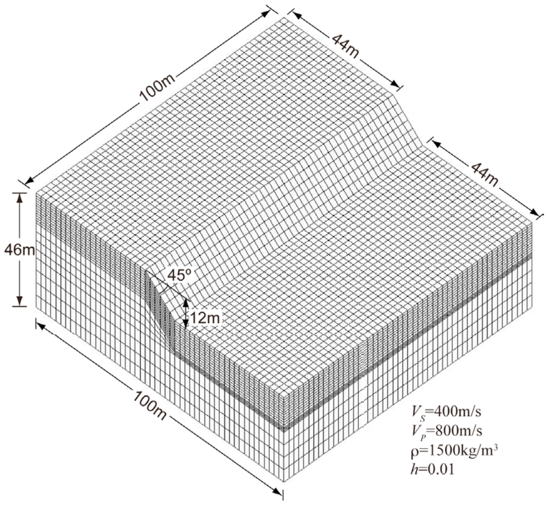
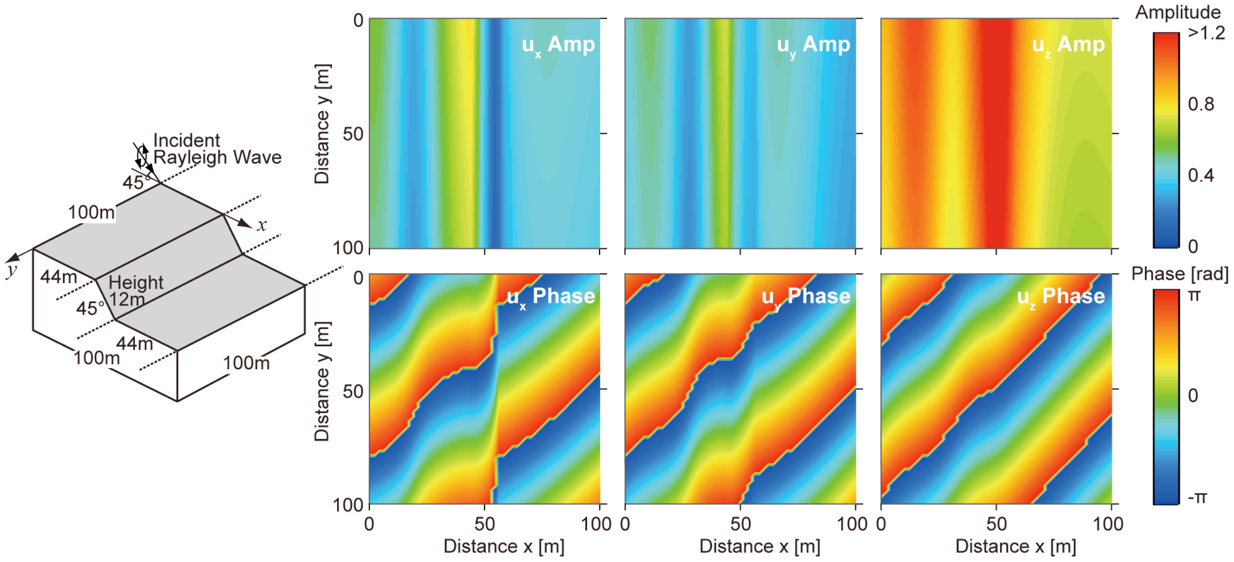
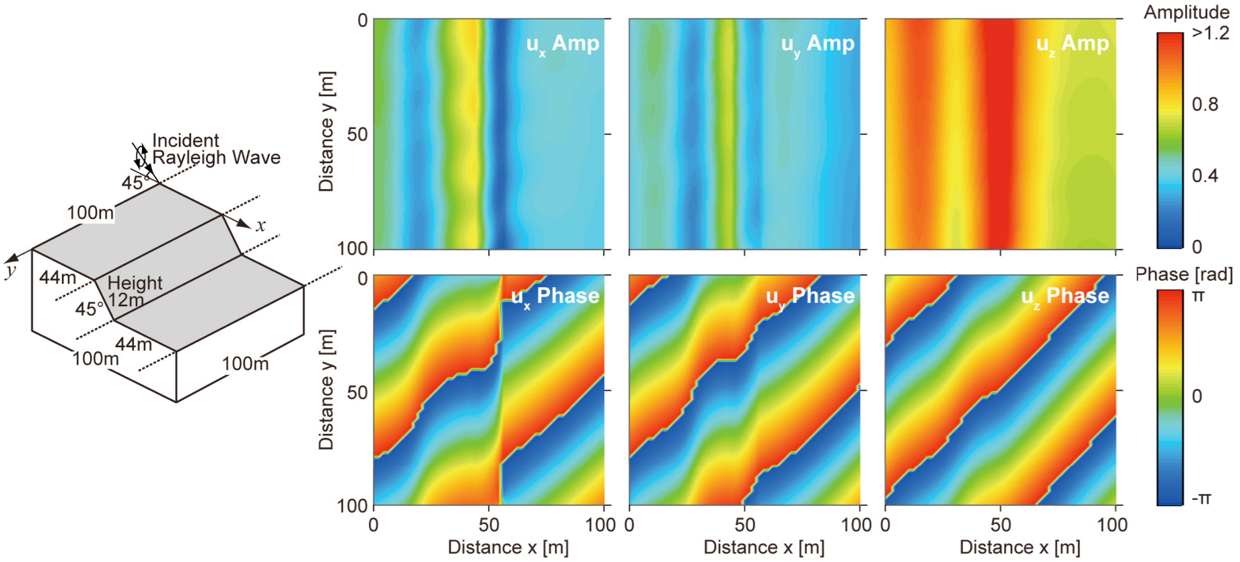


Figure 5. Finite element mesh layout of a slope ground



(a) 2.5-dimensional analysis



(b) Three-dimensional analysis

Figure 6. Wave field due to an incident Rayleigh wave of fundamental mode of 8 Hz

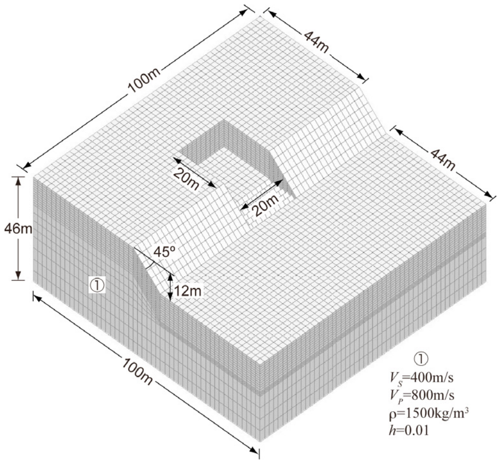
Figure 6 compares three-dimensional and 2.5-dimensional results of displacement distribution at the ground surface in the case of Rayleigh wave incidence of fundamental mode of 8Hz with the incidence angle of 45º. The wave is coming from the upland part of the ground. Although two analyses must coincide 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).

4.2 Slope Ground with a Tiny Canyon Composed of Uniform Soil

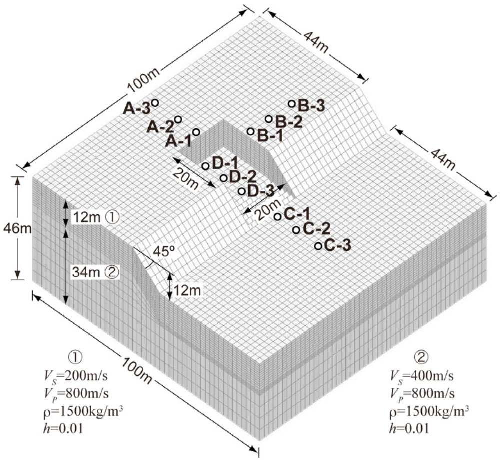
A similar slope ground with uniform soil subject to an incident Rayleigh wave of fundamental mode was considered next. The difference from the previous case is that there exists a small canyon-like hollow that penetrates perpendicularly into the slope, as shown in Figure 7(a). The configuration of the canyon has the depth of 12 meters, the width of 20 meters and the length of 20 meters. The ground surface inside the canyon is on the same level as the ground surface of the lowland. The rest of the analysis conditions, including the soil properties, are the same as those shown in Figure 5.

Figure 8 shows the displacement wave field for the frequency of 8 Hz and the incidence angle of 45º. From the comparison with Figure 6 which corresponds to the case without a canyon, it can be pointed out that:

- Due to the existence of a canyon, the displacement field changes by a great deal and becomes very complex.



(a) A slope ground with a canyon (uniform soil)



(b) A slope ground with a canyon (two-layered soil)

Figure 7. Three-dimensional analysis model

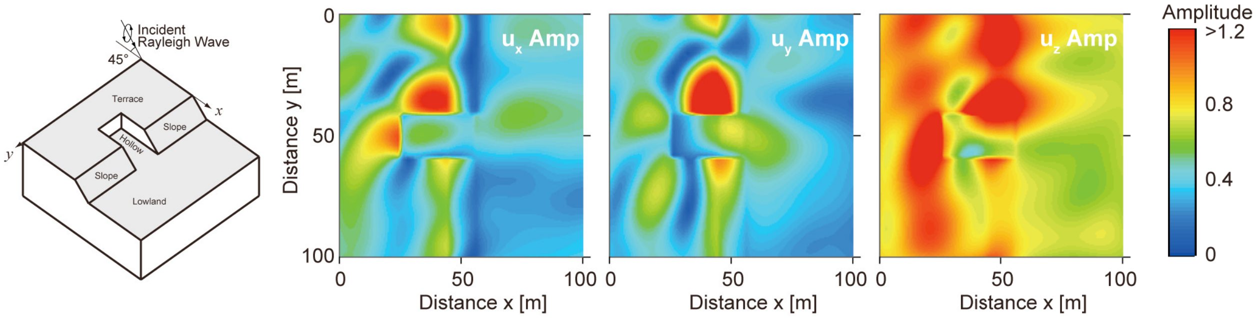


Figure 8. Displacement amplitude due to an obliquely incident Rayleigh wave (uniform soil)

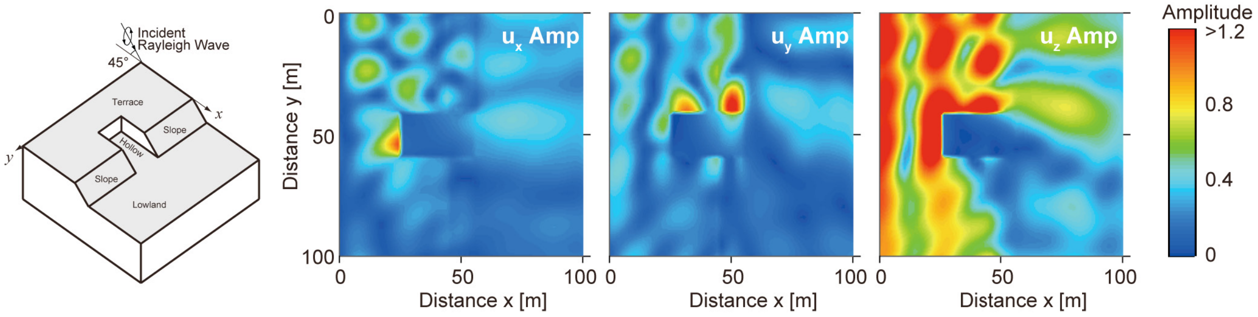


Figure 9. Displacement amplitude due to an obliquely incident Rayleigh wave (two-layered soil)

- 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 on the ground surface inside the canyon is fairly small.

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

4.3 Slope Ground with a Tiny Canyon Composed of Two-Layered Soil

Finally, a two-layered ground is investigated. The analysis model is the same as before except that the shear wave velocity of the surface layer is half of that of the underlying layer as shown in Figure 7(b). 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.

Figure 9 shows the displacement wave field for the frequency of 8 Hz and the incidence angle of 45°. When compared with Figure 8 for the case of uniform soil, it is noted that, although the overall tendency is similar, the

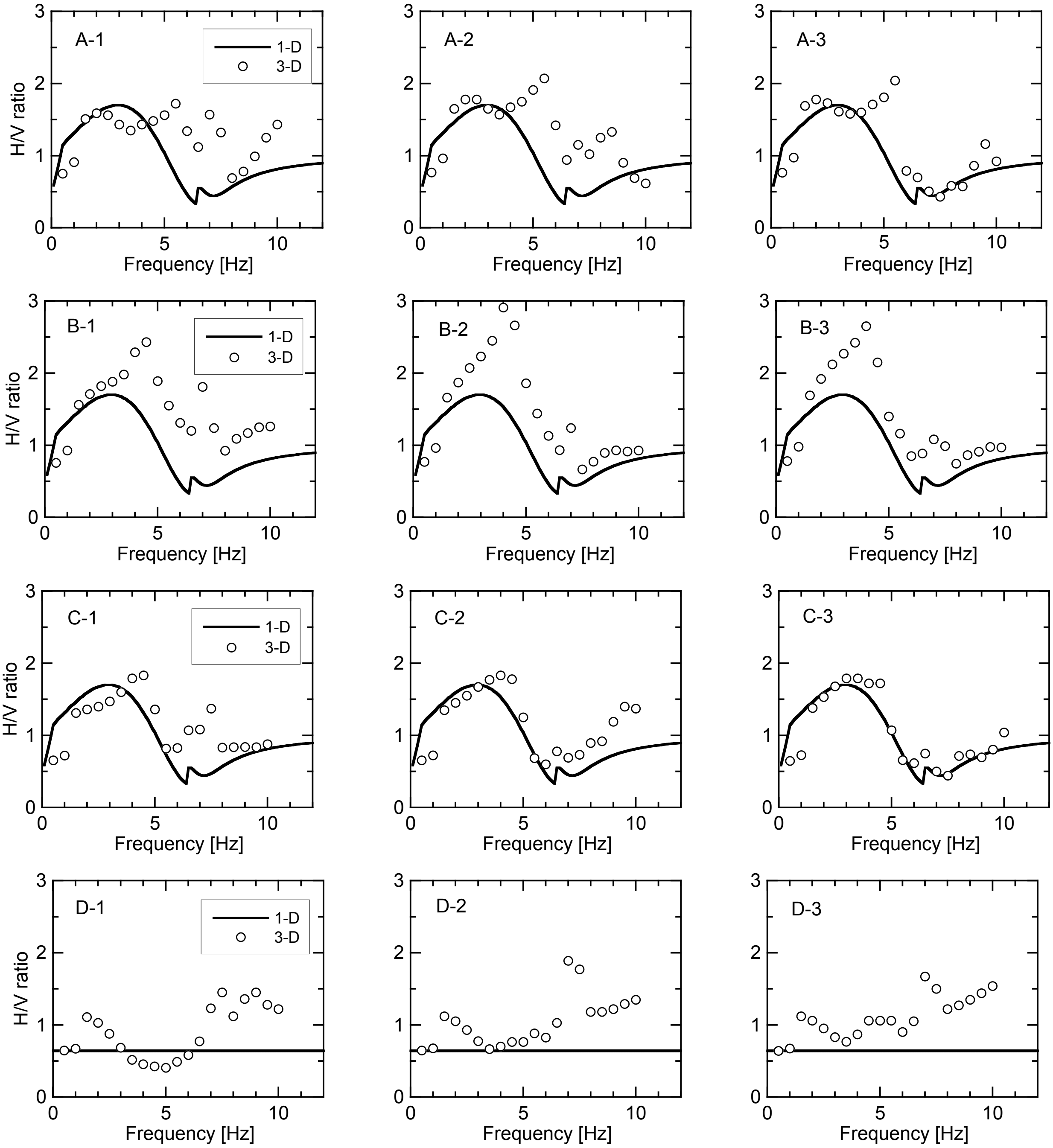


Figure 10. Comparison of H/V spectra

displacement distribution shows finer fluctuation. This may be resulted from the existence of higher modes of Rayleigh and Love waves which have larger values of phase velocity.

Figure 10 shows the horizontal to vertical Fourier spectral ratios, or H/V spectra, while Figure 11 shows the phase velocity dispersion curves at various locations near the canyon in this slope ground. Both H/V spectrum and dispersion curve were computed based on the aggregated displacement wave field at each point indicated in Figure 7(b) by summing up the displacements due to all possible surface (Rayleigh and Love) waves including higher modes with the incidence angles of −135º, −45º, 0º, 45º, 135º and 180º. Summation was done in the form of the power of displacements. The dispersion curve was computed by the centerless circular array method proposed by Cho et al. [6] by considering the surrounding four nodes of the finite element mesh as censor locations. From Figures 10 and 11, it is observed that:

- 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 micro-tremor 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.

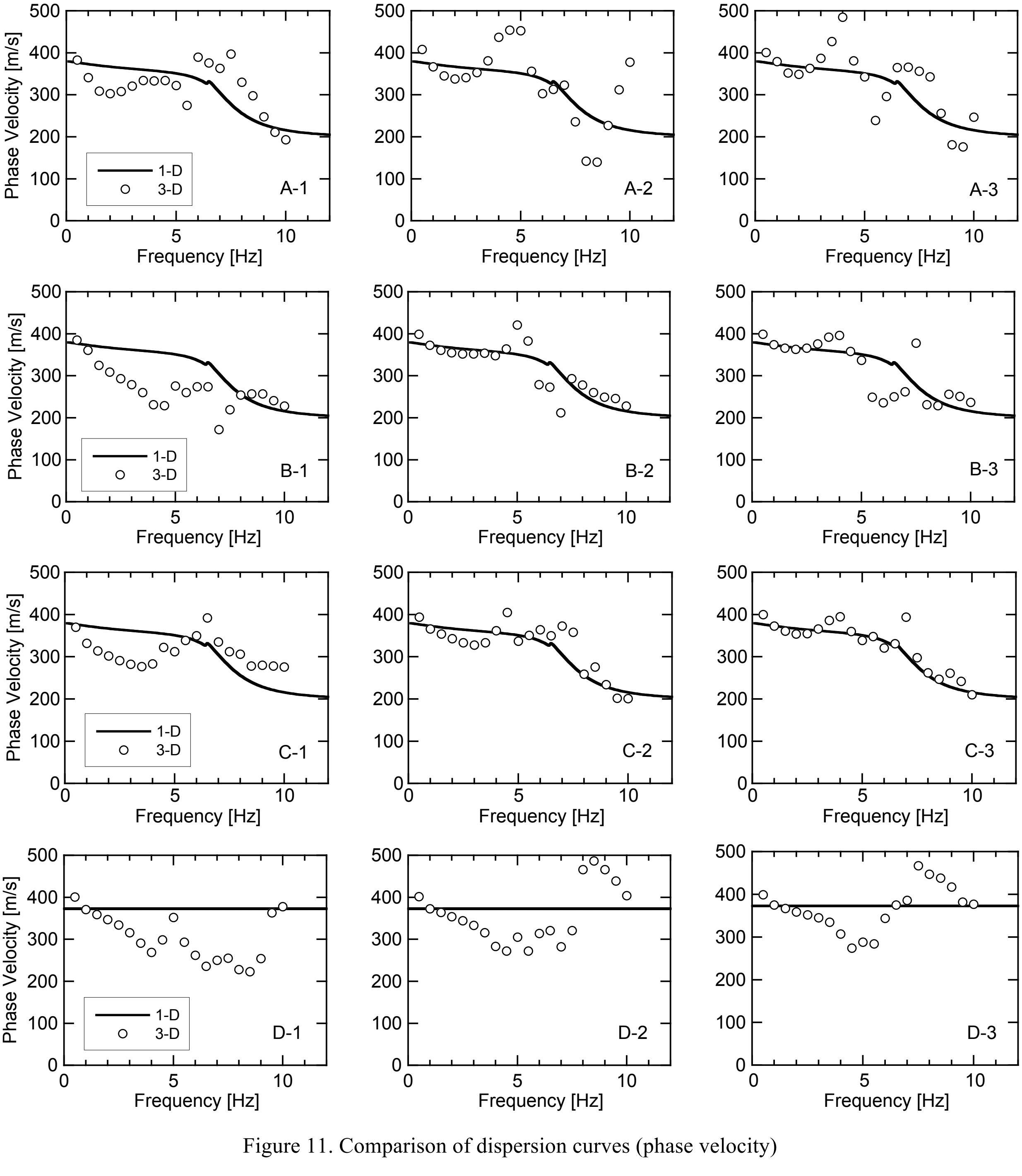


Figure 11. Comparison of dispersion curves (phase velocity)

Fluctuation of H/V spectra and dispersion curves may 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.

5 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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