JOINT CONFERENCE PROCEEDINGS
9th International Conference on Urban Earthquake Engineering/ 4th Asia Conference on Earthquake Engineering
March 6-8, 2012, Tokyo Institute of Technology, Tokyo, Japan

WAVE PROPAGATION ANALYSIS OF A GROUND WITH THREE-DIMENSIONAL IRREGULARITIES

Shoichi Nakai[1)], **and Hiroto Nakagawa**[2)]

1) Professor, Department of Urban Environment Systems, Chiba University, Japan
2) Research Engineer, Department of Earthquake Disaster Prevention, Oyo Corporation, Japan
nakai@faculty.chiba-u.jp, *nakagawa-hiroto@oyonet.oyo.co.jp*

Abstract: It is well known that the surface soil condition influences the seismic intensity of the ground and hence impact structural damage to the buildings during earthquakes. Wave propagation becomes complex when the ground has irregularities, such as slopes and canyons. This wave propagation in an irregular ground has been studied by a number of researchers. Most of them, however, made an assumption that the ground is two-dimensional or has a far-field with a horizontally flat ground surface. The objective of this study is to investigate the effect of three-dimensional irregularities on the propagation of surface waves. The analysis target is a two-dimensional slope ground with a small canyon, that penetrates perpendicularly into the upper part of the ground, subject to incident waves. It was found from the study that the wave field becomes very complex when there exists a small canyon, 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.

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 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., Cho et al., 2006). All the approaches proposed so far, however, are based on a parallel layer assumption.

A difficulty arises when the ground has an irregularity, which is often the case in an actual situation. For example, the eastern part of Tokyo metropolitan area, Japan, 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 its 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. Most of them, however, deal with body waves and only a few have looked at surface waves. 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., 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 subject to an obliquely incident surface wave is considered, as schematically illustrated in Figure 1. The analysis method used in the study is a combination of

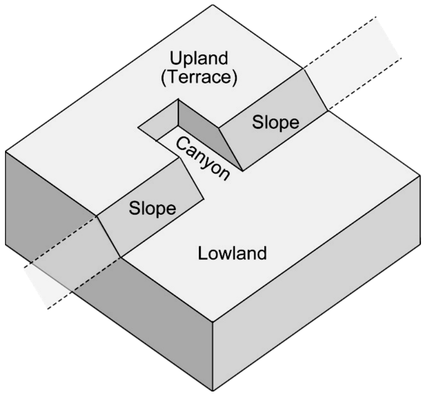


Figure 1 A Slope Ground with a Tiny Canyon

three-dimensional and two-and-a-half- (2.5-) dimensional finite element methods (Nakagawa et al., 2010) in conjunction with a substructure technique. This study is a direct extension to the previous work (Nakai et al., 2009).

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. As an attempt to address 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 1, 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 (Arai et al., 2000; Nakagawa et al., 2010). 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.

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. These points include a far field ground with topographic irregularities and surface wave propagation in such a ground.

3.1 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 that 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

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 (Nagano et al., 1985). Since irregularity (slope) is involved in this analysis itself, another substructuring 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 2 illustrates the method of analysis.

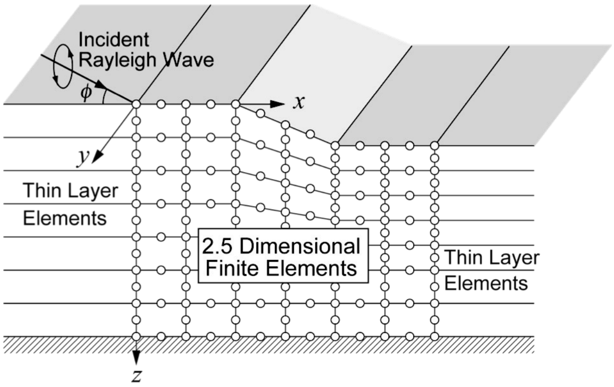


Figure 2 2.5-Dimensional Analysis

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 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:

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

in which, {$u_{2.5}$} is a displacement vector 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. Figure 3 illustrates the three-dimensional analysis.

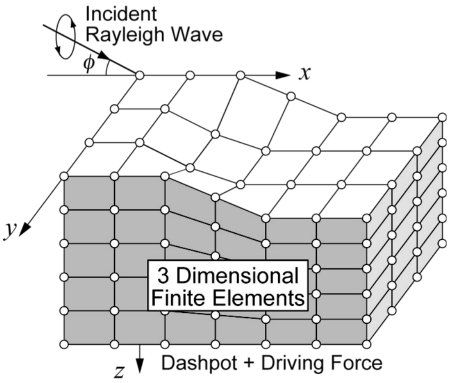


Figure 3 Three-Dimensional Analysis

4. SURFACE WAVE PROPAGATION IN A THREE-DIMENSIONAL IRREGULAR 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. According to the results, the three-dimensional analysis can give a solution that matches the 2.5-dimensional one (Nakai et al., 2011) except for a minor fluctuation due to an imperfect [K_c], i.e. dashpots.

4.1 Analysis Model

In this study, a slope ground with two-layered ground is investigated, in which there exists a small canyon that penetrates perpendicularly into the slope, as shown in Figure 4 (a) and 4 (b). Considered in the study are the two configurations of the canyon: the width of 20 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 Figure 4. 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 Figure 4 (a).

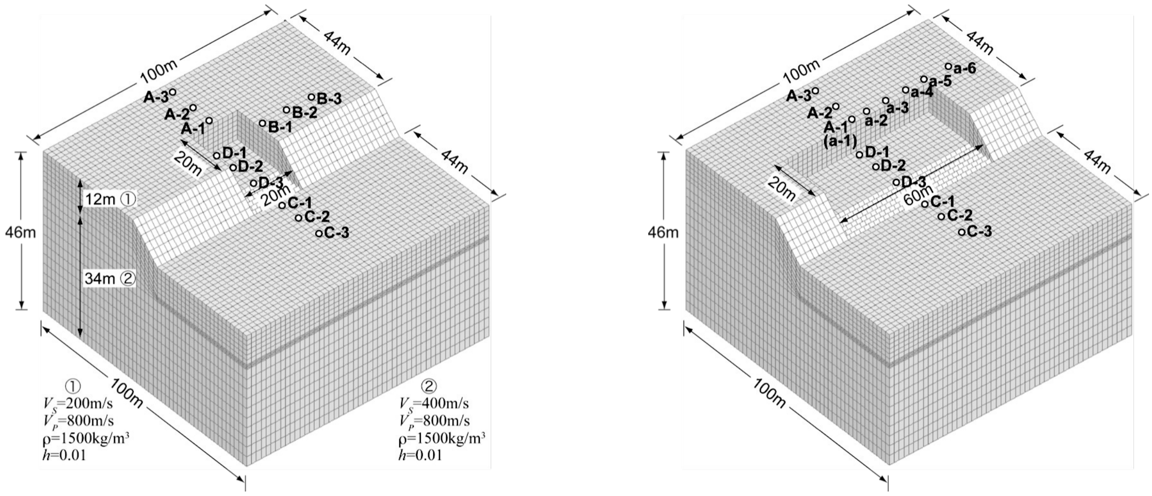
4.2 Analysis Model

Figure 5 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) and 45º 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.

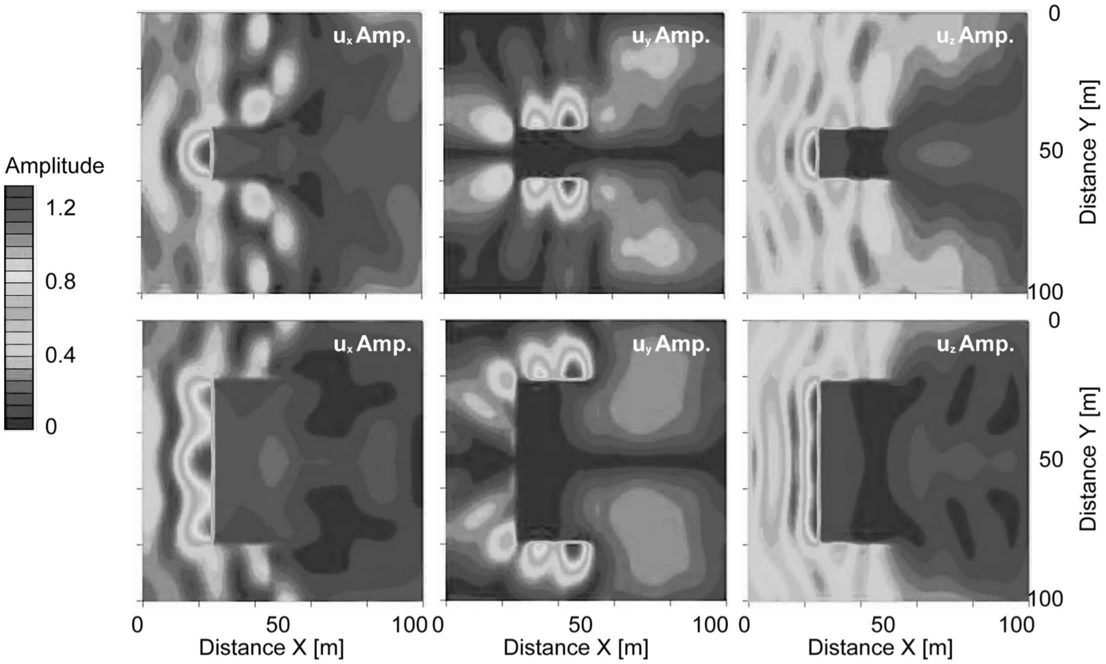
If we take a closer look at the results as well as other results not shown in this paper, it is possible to add that:

- 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

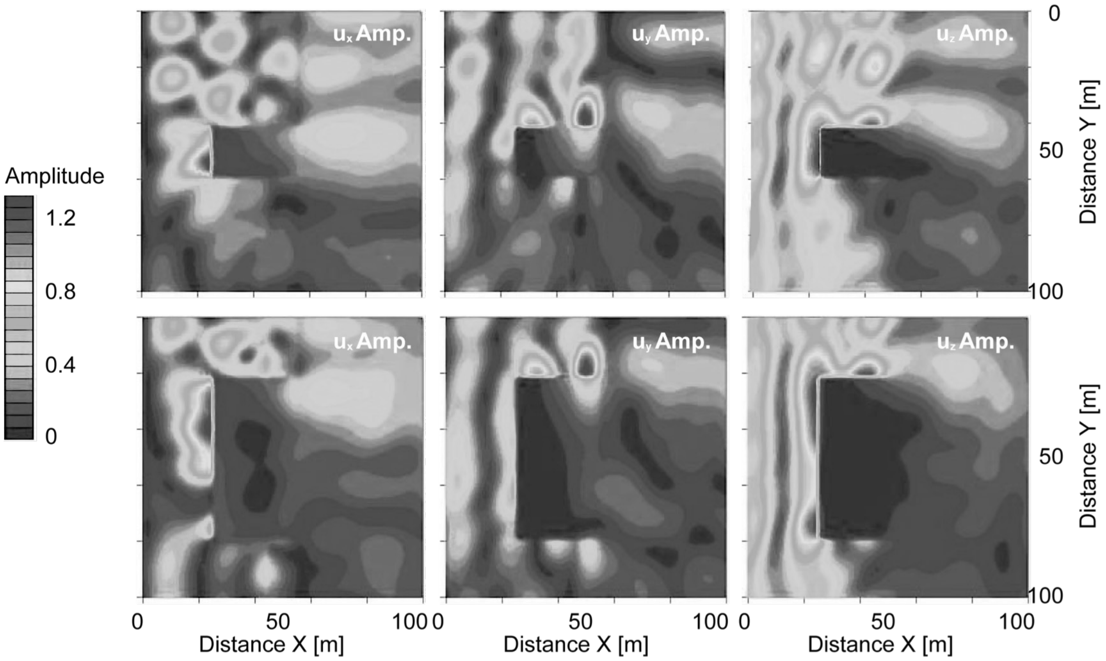


(a) Slope Ground with a Canyon of 20 Meter Width (b) Slope Ground with a Canyon of 60 Meter Width

Figure 4 Finite Element Models



(a) Incident Angle of 0º



(b) Incident Angle of 45º

Figure 5 Wave Field of a Two-Layered Slope Ground with a Canyon due to an Incident Rayleigh Wave of 8 Hz

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.

4.3 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.

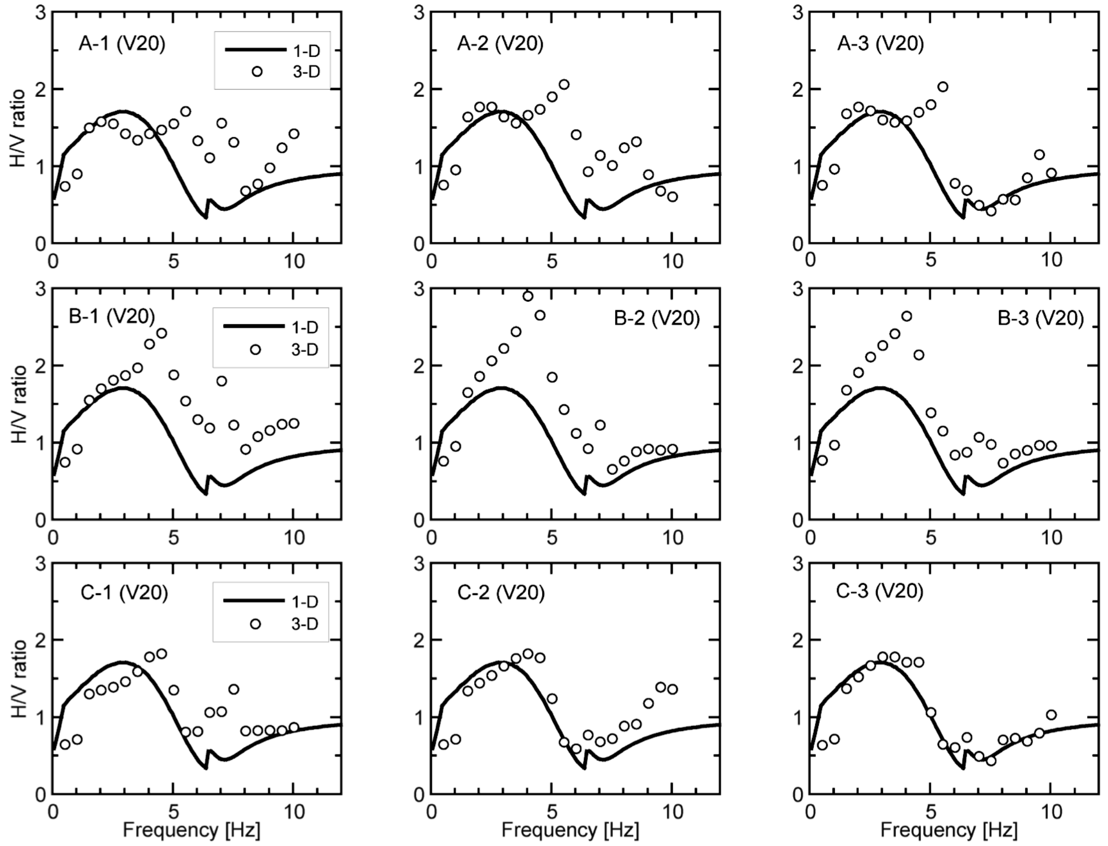


Figure 6 Comparison of H/V Spectra (Slope Ground with a Canyon of 20 Meter Width)

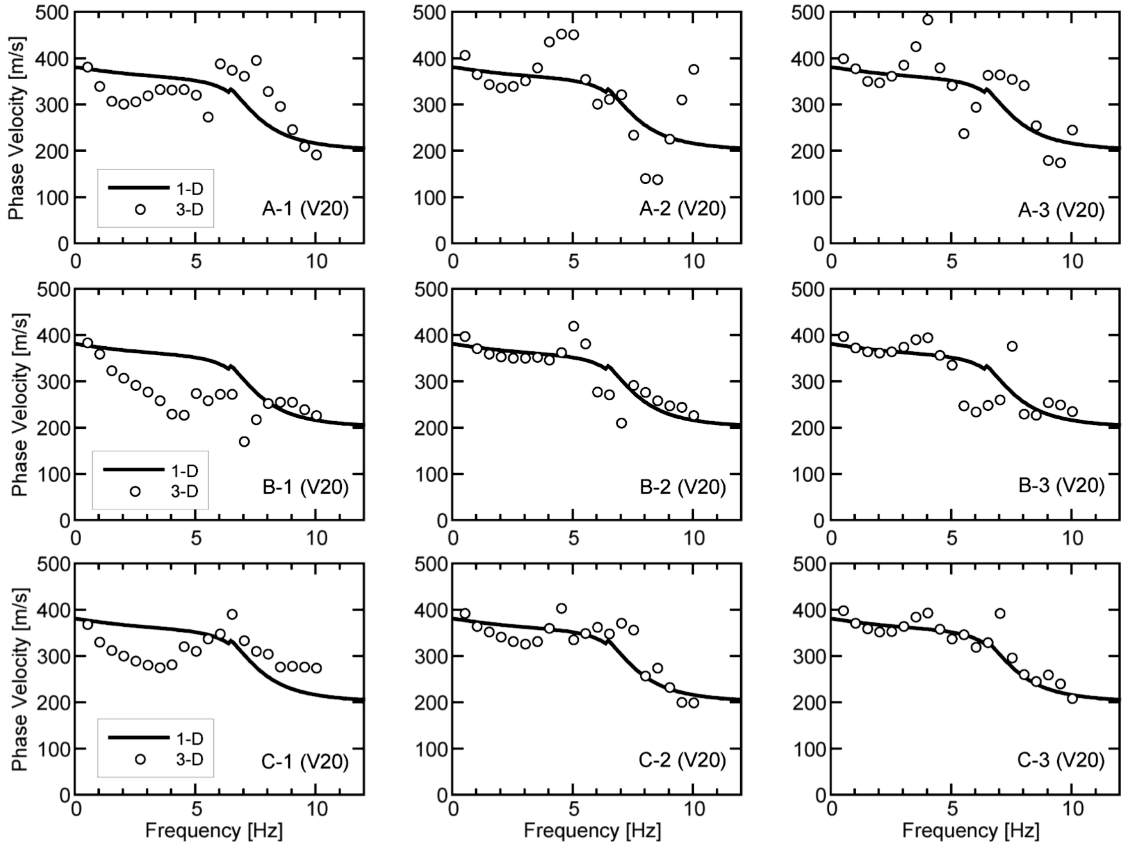


Figure 7 Comparison of Phase Velocity Dispersion Curves (Slope Ground with a Canyon of 20 Meter Width)

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, ui (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. Figure 6 shows H/V spectra, while Figure 7 shows the phase velocity dispersion curves at various locations near the canyon in this slope ground as shown in Figure 4. From these figures as well as those not shown in this paper, it is possible to say the followings.

- 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 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.

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.

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.

References:

Arai, H. and Tokimatsu, K. (2000), "Effects of Rayleigh and Love Waves on Microtremor H/V Spectra", *Proc. 12th World Conf. on Earthq. Eng.*, 2232/4/A, 8p.

Arai, H. and Tokimatsu, K. (2004), "S-Wave Velocity Profiling by Inversion of Microtremor H/V Spectrum", *Bull. Seism. Soc. Am.*, **94**(1), pp. 53-63.

Bielak, J. et al. (2003), "Domain Reduction Method for Three-Dimensional Earthquake Modeling in Localized Regions, Part I: Theory", *Bull. Seism. Soc. Am.*, **93**(2), pp.817-824.

Cho, I., Tada, T. and Shinozaki, Y. (2006), "Centerless Circular Array Method: Inferring Phase Velocities of Rayleigh Waves in Broad Wavelength Ranges using Microtremor Records", *J. Geophys. Res.*, **111**(B09315), doi:10.1029/ 2005JB004235.

Nagano, M. and Motosaka, M. (1985), "Response Analysis of 2-D Structure Subjected to Obliquely Incident Waves with Arbitrary Horizontal Angles", *J. Struct. Constr. Eng.*, AIJ, 474, pp. 67-76. (in Japanese)

Nakagawa, H. and Nakai, S. (2010), "Propagation of Surface Waves in an Irregular Ground based on the Thin Layered Element and Finite Element Method", *Proc. 5th Int. Conf. on Recent Adv. in Geotech. Earthq. Eng. and Soil Dyn.*, San Diego, Paper No. 2.17, 12 pp.

Nakai, S. et al., (1985), "On an Interface Substructure Method for Soil-Structure Interaction - Part I Classification of an Interface Substructure Method", *Summaries of Technical Papers of Annual Meeting*, AIJ, **B**, pp. 349-350. (in Japanese)

Nakai, S. and Nakagawa (2009), "Propagation of Rayleigh Waves in Irregular Ground", *Proc. 6th Int. Conf. Urban Earth. Eng.*, Titech, Tokyo, pp. 133-138.

Nakai, S. and Nakagawa (2011), "Surface Wave Propagation Analysis of a Ground with Three-Dimensional Irregularities", *Proc. 8th Int. Conf. Str. Dyn.*, Leuven, Paper ID 584, 7 pp.

Nakai, S., Ohta, T. and Bae, J. (2007), "Construction of surface soil model and its application to earthquake damage prediction", *Proc. 8th Pacific Conference on Earthquake Engineering*, Singapore, Paper No. 106, 8 pp.

Nakamura, Y. [1989], "A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface", *Q. Rep. Railway Tech. Res. Inst.* **30**(1), pp. 25-33.