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Effect of Inclined Boundary and Embedded Foundation on Wave Propagation

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ABSTRACT: The objective of this study is to investigate the effects of the three-dimensional configuration of a soil-structure system. Analysis was conducted by a three-dimensional finite element method and the combination of a 2.5-dimensional thin layer element method and 2.5-dimensional finite element method in conjunction with a substructure technique. One of the main advantages of the method is that the far field ground involves irregularities, which is rarely seen in the previous literatures. In this paper, three-dimensional finite element analysis was conducted with the help of 2.5-dimensional analysis. The result showed that the wave field becomes very complex on the ground which has an inclined boundary and/or an embedded foundation.

1 INTRODUCTION

Since the 1995 Kobe earthquake and the 2007 Noto Hanto earthquake, it has been pointed out that the ground motion is considerably influenced by an irregular ground and can be strongly correlated with earthquake damage (e.g., Kawase 1996; Shimizu & Maeda 2010). A number of studies have been reported so far, facilitating our understanding of the effects of the irregular ground on seismic motions (e.g., Sánchez-Sesma 1988; Hisada & Yamamoto 1996; Kawase 2008). As is well known, the study on soil-structure interaction (SSI) has a long history and there exist a large number of articles published so far (e.g., Wolf 1985; Kausel 2010). However, there are only a few studies considering both SSI and irregular ground in three-dimension. The objective of this study is to investigate the effect of three-dimensional configuration of a soil-structure system from the viewpoint of elastic wave propagation.

2 METHODOLOGY

Analysis was carried out basically by a three-dimensional finite element method. This method has an advantage over other finite element methods in that it can handle a far-field ground which involves a topographic irregularity, namely a two-dimensional ground with an inclined boundary layer, as shown in Figure 1. This means that a parallel layer assumption for the far-field ground is not adopted, which is rarely seen in the previous literatures. A variety of substructure approaches have been proposed that deal with wave propagation in an elastic medium. The method used in the study follows the procedure described below (Nakai et al. 1985; Nakai & Nakagawa 2012):

(1) Subdivide the entire ground subject to investigation into two parts; a near field that involves three-dimensional irregularities - in this case, massless rigid foundation is placed, and a far field that is basically a two-dimensional ground with an inclined boundary.

(2) Obtain an impedance matrix $[K_c^*]$ of the far field at the boundary with the near field.

(3) Compute a displacement vector $\{u_c\}$ and traction vector $\{p_c\}$ at a hypothetical boundary with the near field; in this case, the far field does not have a foundation and is subject to an incident wave.

(4) Compute a driving force vector $\{f_c^*\}$ at the boundary by the following expression:

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

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

The substructure analysis described above requires a three-dimensional analysis of a two-dimensional ground with an inclined boundary subject to an obliquely incident wave. Here, oblique incidence means the vibration direction is not parallel nor perpendicular to the longitudinal direction of the inclined boundary. This type of analysis is called a 2.5-dimensional analysis (e.g., Khair et al. 1989; Nagano & Motosaka 1995). Since irregularity has been already assumed in this analysis, another sub-structuring is considered, i.e., 2.5-dimensional thin layer elements and 2.5-dimensional finite elements are combined to obtain the response of a two-dimensional irregular ground due to incident surface and body waves (Nakagawa & Nakai 2010; Nakai & Nakagawa 2012). In the 2.5-dimensional analysis of shear wave incidence, the dashpot was attached to the bottom boundary by considering imaginary frequency $i\omega$.

The substructure analysis of the target, i.e., a two-dimensional ground with an embedded foundation, 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:

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

where, $\{u_{2.5}\}$ 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 have been obtained. k_s is the wave number of an incident wave. ϕ and ψ are the azimuth and incident angles of an incident shear wave, respectively.

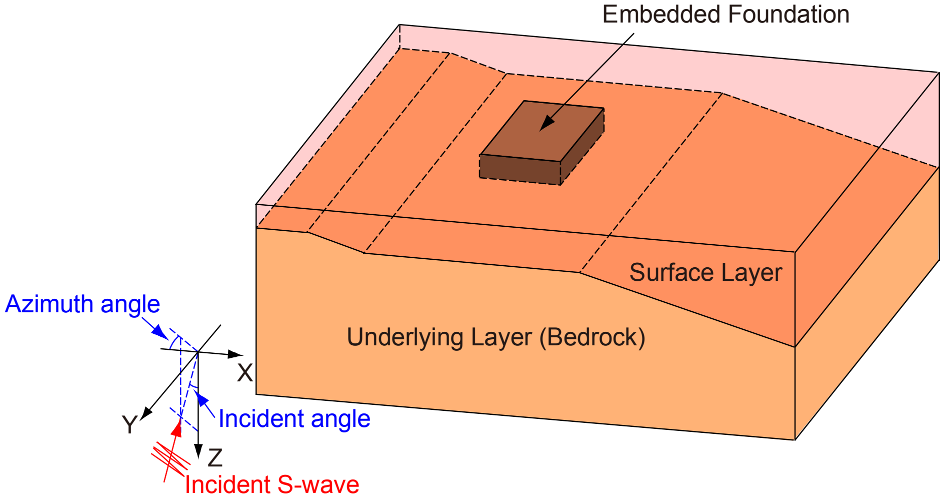

Figure 1. Schematic illustration of an irregular ground subject to investigation

3 VERIFICATION

In order to verify the calculation code of FEM analysis, the authors conducted the verification test. Figure 2 shows the comparison of the normalized three-dimensional response of a semi-circular valley embedded in a uniform half-space and subjected to obliquely incident (azimuth angle = 0º, 45º and 90º) SV-waves with different vertical angles of incidence (incident angle = 0º, 30º and 60º) between our results and previous results by de Barros & Luco (1995). As can be seen from the figure, it is confirmed that the present results by the authors (various lines) are in close agreement with the previous results (open circles).

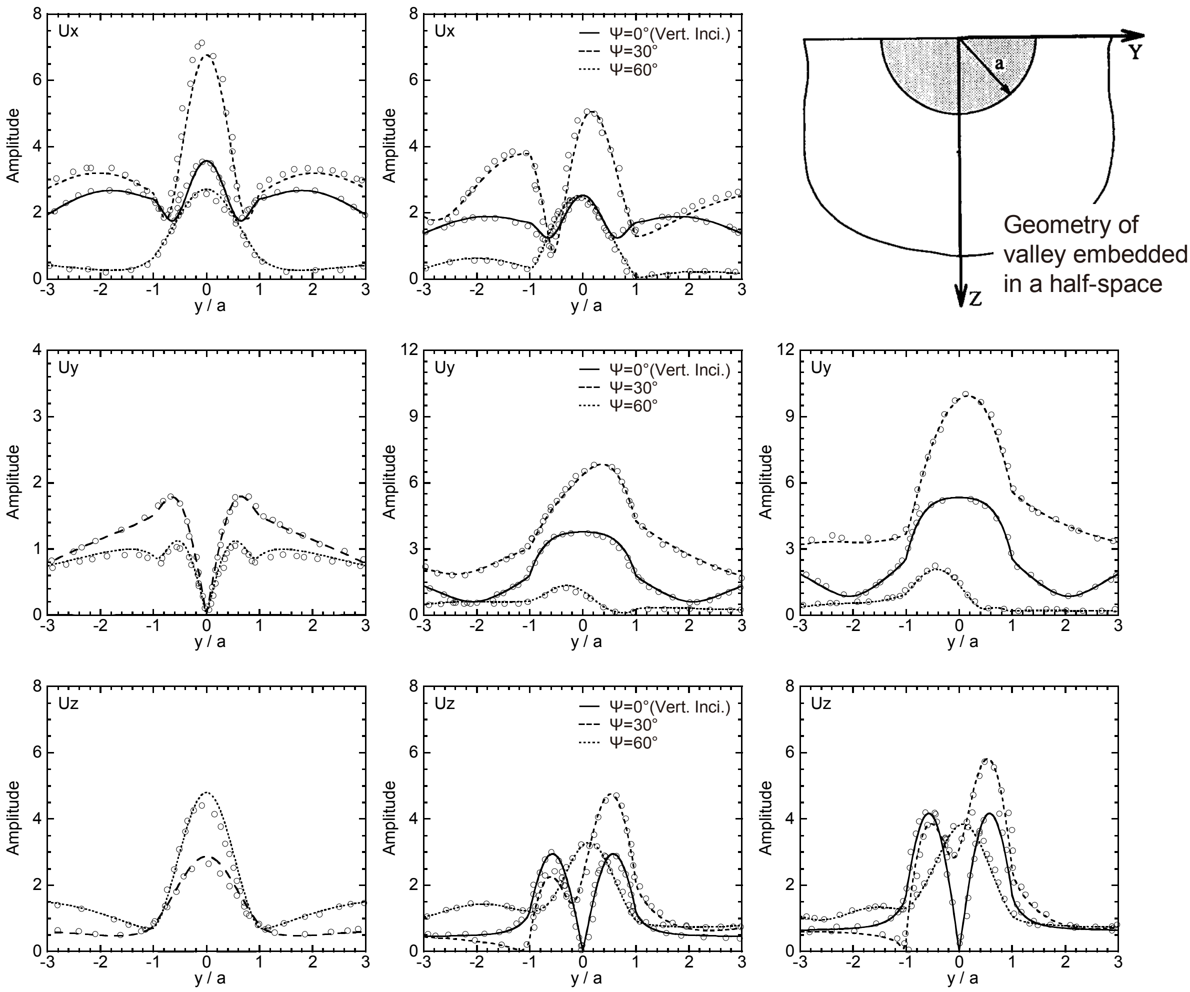

Figure 2. Comparison of the normalized 3-D response of a semi-circular valley embedded in a uniform half-space and subjected to obliquely incident (azimuth angle = (left) 0º, (center) 45º and (right) 90º) SV-waves with different vertical angles of incidence (incident angle = 0º, solid lines; 30º, long segmented lines; 60º, dotted lines) between our results and previous results by de Barros & Luco (1995). It is confirmed that the present results by the authors (various lines) are in close agreement with the previous results (open circles). Note that the coordination system is different between both the studies.

4 FEM ANALYSIS

4.1 Target site (Iwaki City Hall)

In this study, the target site is Iwaki City Hall located in Fukushima Prefecture, Japan. When the 2011 off the Pacific Coast of Tohoku Earthquake attacked, the building of Iwaki City Hall suffered some damage on concrete walls and finishing materials. According to data obtained by drilling works, such as standard penetration test (SPT) and PS-logging, it has been revealed that the depths to engineering bedrock were varied, making the site complicated. Figure 3 shows distribution of depths to the engineering bedrock in Iwaki City Hall, SPT N values, and an S-wave velocity profile by PS-logging (Nakagawa et al. 2015). From the bottom of figure 3, it is found that the S-wave velocity of a subsurface layer (alluvial soil) is about 100-150 meters per second. At the top of figure 3, a contour map was drawn based on the SPT N values. Firstly, the depths to the top of engineering bedrock, i.e., SPT N values more than 50, were obtained from all drilling data (white circles). Then, interpolation, 'Surface' of Generic Mapping Tool (GMT, Wessel & Smith 1998) was applied. The tension factor was set to 0.25 in the calculation. As can be seen from the figure, the depths to the engineering bedrock are varied complicatedly, becoming deeper toward the west and the south directions.

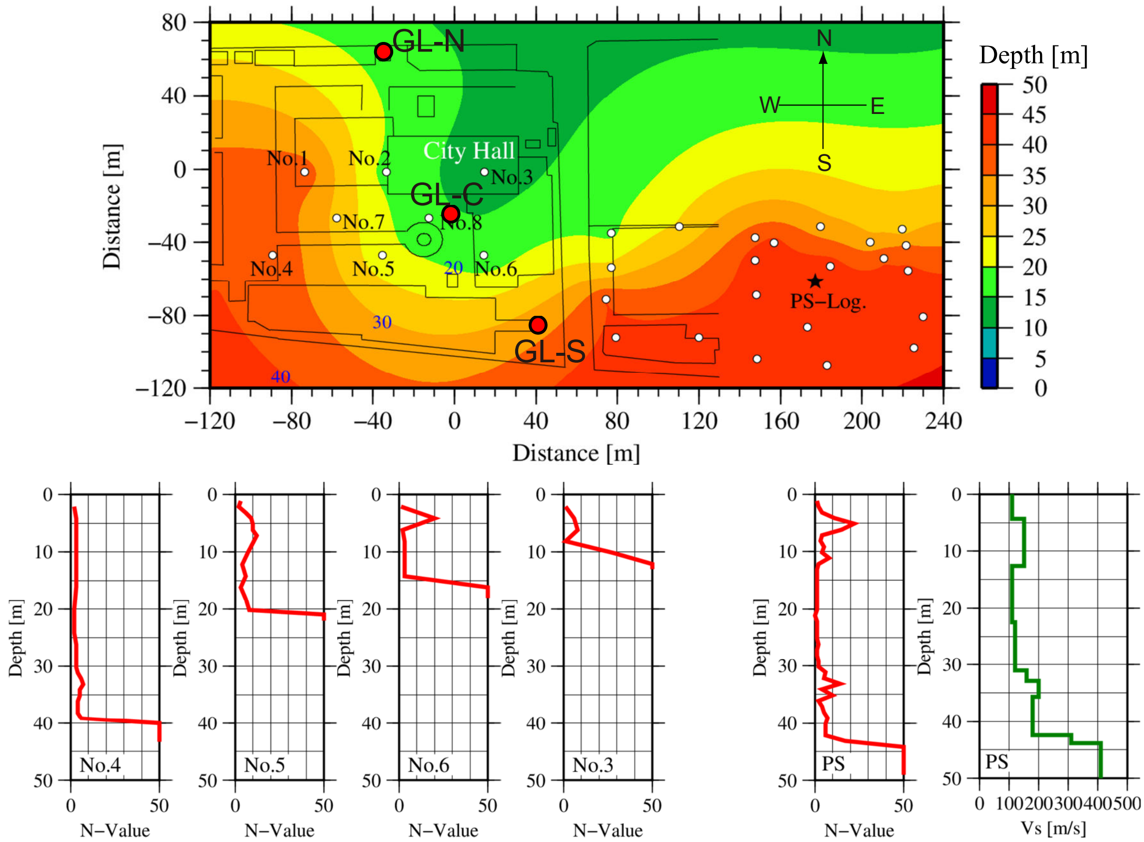

Figure 3. (Top) Distribution of depths to the engineering bedrock in Iwaki City Hall, (bottom) SPT N values, and (right bottom) an S-wave velocity profile by PS-logging (Nakagawa et al. 2015).

4.2 **Observation data**

From June 2011 to August 2011, two seismometers were installed temporarily at the stations GL-N and GL-S (see figure 3) to obtain data on earthquake ground motion, i.e., aftershock of the 2011 off the Pacific Coast of Tohoku Earthquake, in addition to the station GL-C operated by the Fukushima Prefectural Government, Japan (Kashima et al. 2011). Earthquake data observed in this site is listed in Table 1. Seven earthquake ground motions were observed. Kashima et al. (2011) have revealed that predominant frequencies at the stations GL-S and GL-N are 1 Hz, 4-5Hz, respectively. Figure 4 shows the spectral ratio divided by Fourier spectrum observed at the station GL-N. Figure 4 suggests that:

- According to data obtained at the stations GL-S / GL-N:

  - In the vicinity of frequency of 1 Hz, a significant peak is observed due to the soil profile beneath the GL-S station. There is a difference in peak frequency between NS and EW components.

- According to data obtained at the stations GL-S / GL-N and GL-C / GL-N:

  - In the frequency range of 3-4 Hz, there is a difference in peak value between NS and EW components (NS < EW).
  - In the frequency range of 4-6 Hz, spectral ratios of both NS and EW components are relatively small, due to the soil profile beneath the GL-N station.
  - In the frequency range of 6-10 Hz, there is a difference in value for spectral ratio between NS and EW components (NS > EW).

- According to data obtained at the stations GL-C / GL-N:

  - In the frequency range of 0-2 Hz, there is no significant peak.

Table 1. Observed earthquake data. These are determined by Japan Meteorological Agency. h and $\varDelta$ are focal depth and epicentral distance, respectively.

No.	Date & Time	Epicenter	Lon.(N)	Lat. (E)	h (km)	M_{jma}	$\varDelta$ (km)	ϕ (deg.)
Eq.1	2011/07/08 03:35	Off Fukushima Pref.	141.13	37.097	55.5	5.6	22	76
Eq.2	2011/07/10 09:57	Off Sanriku	143.507	38.032	34	7.3	255	64
Eq.3	2011/07/11 09:09	Hama-dori, Fukushima Pref.	140.835	37.093	8.2	4.4	7	-41
Eq.4	2011/07/25 03:51	Off Fukushima Pref.	141.627	37.709	45.8	6.3	98	42
Eq.5	2011/07/31 03:53	Off Fukushima Pref.	141.221	36.903	57.3	6.5	34	119
Eq.6	2011/08/05 20:16	Hama-dori, Fukushima Pref.	140.848	37.121	7.2	4.7	9	-23
Eq.7	2011/08/12 03:22	Off Fukushima Pref.	141.161	36.969	52.3	6.1	26	110

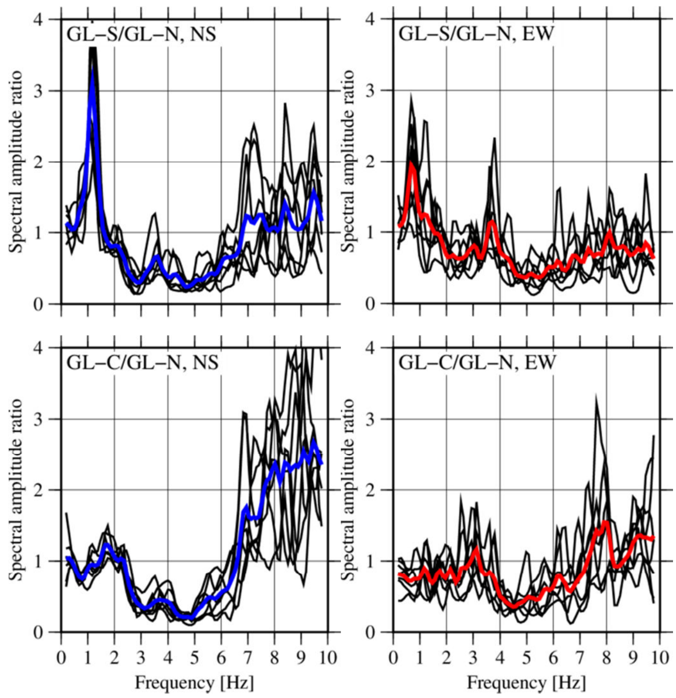

Figure 4. Fourier spectral ratio. The black lines indicate the individual results of observed ground motion. The averaged values are shown in blue and red lines for NS- and EW-directions, respectively. Each Fourier spectrum is smoothed by the Parzen window with a width of 0.4 Hz.

4.3 **FEM model**

As mentioned above, the main objective of this study is to examine the characteristics of wave propagation in an irregular ground in terms of three-dimension to evaluate their influence on the ground motion. As an attempt to address this issue, a simplified two-dimensional inclined boundary layer ground model was constructed along the NS direction as shown in Figure 5. The size of the FEM model is 200 meters by 200 meters with the depth of 72 meters. Number of degrees of freedom is 948,693. The model was constructed based on the PS-logging data and the distribution of the N values obtained by the SPT as shown in Figure 3. As can be seen from figure 5, while five soil layers were considered throughout the model, the depths to the engineering bedrock (Vs=410m/s) are varied. The size of the massless rigid foundation is 30 meters by 60 meters with the embedment of 9 meters. The incident wave considered in this study is a SV-wave only. The incident angles of 0º, 10º, and 20º are considered. The azimuth angle of the incident wave is set to 45º. The observation data in this site (see Table 1& Figure 4) shows there is no significant difference from the viewpoint of vibration direction.

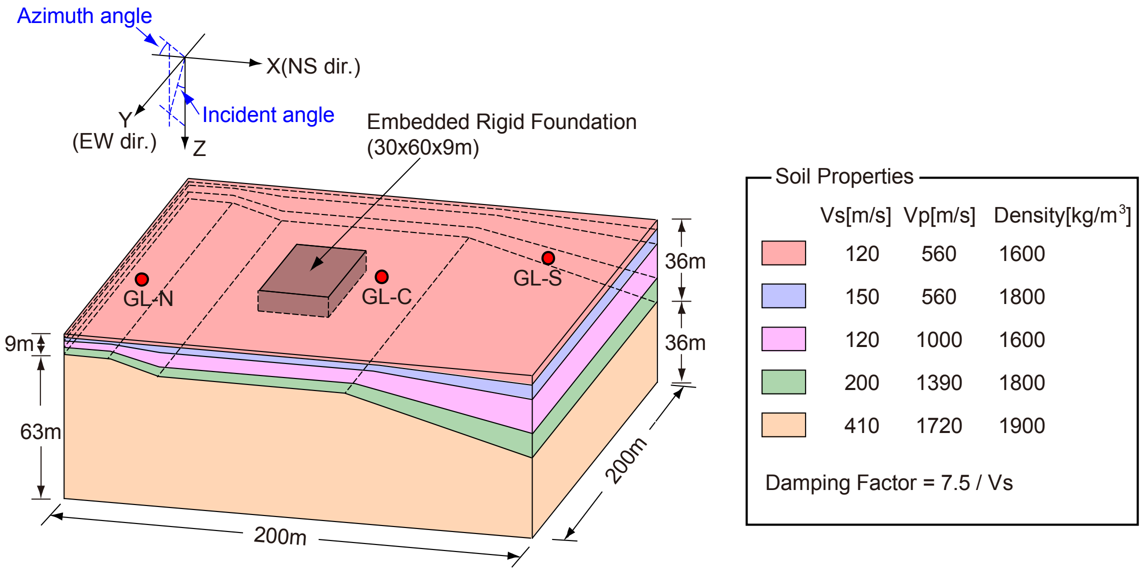

Figure 5. Schematic illustration of the FEM analysis model

4.4 **Analysis Result**

Figure 6 shows the snapshots of ground motion obtained from the 2.5-D and 3-D analyses result using a vertically incident shear wave with an azimuth angle of 45°. In this study, the analysis was conducted in the frequency domain. In order to obtain time histories at each nodal point from the analysis, the authors have utilized the interpolation technique of the transfer functions and the inverse Fourier transform (Ghiocel 2011). As can be seen from the figure, the wave field becomes very complex when the ground has a foundation. Vertical motions, in particular, are generated by the irregularities. Figures 7 and 8 show the amplitude ratios obtained from the 2.5-D and 3-D analyses. The result shows that considerable difference is observed between the results of 2.5-D analysis (inclined boundary layer ground subject to obliquely incident waves) and of 3-D analysis (ground with inclined boundary and with an embedded foundation subject to obliquely incident shear waves). It is not easy to discuss about correspondence with observed data as shown in figure 4; however, it is noteworthy that the spectral ratios obtained from 3-D analysis are coincident with observation data in the vicinity of frequency of 3-4 Hz.

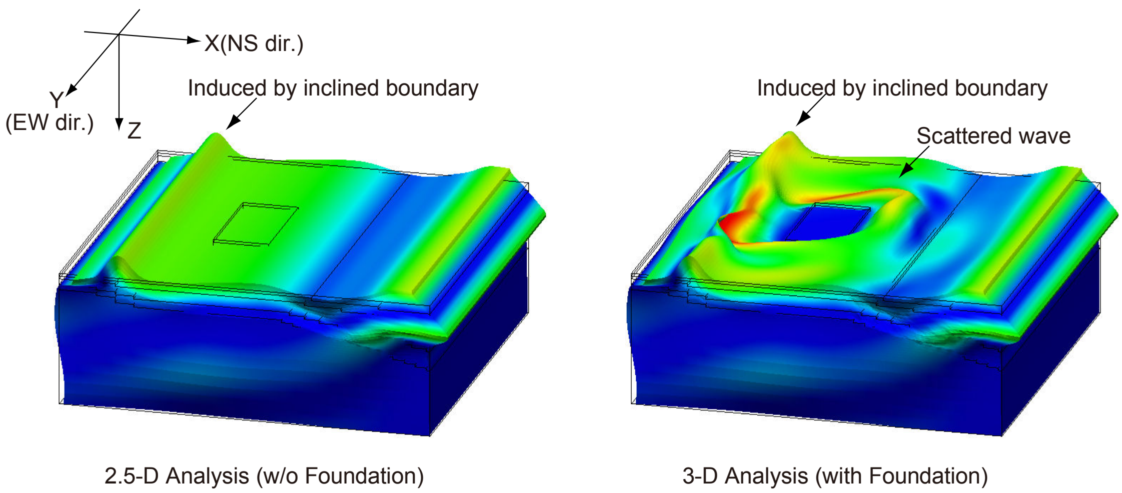

Figure 6. Snapshot of ground motion obtained from (left) 2.5-D and (right) 3-D analyses with a vertically incident shear wave. The input motion is a Ricker wavelet of frequency of 4 Hz and an azimuth angle of 45°. Cold colors express low amplitudes. Warm colors represent high amplitudes.

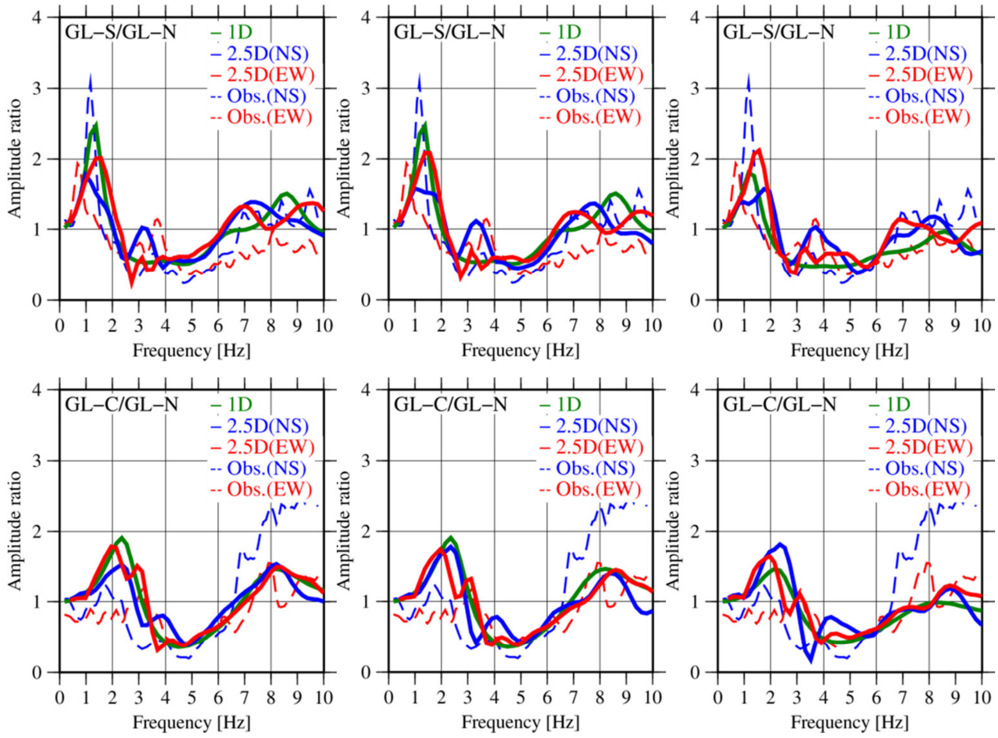

Figure 7. Comparison of the amplitude ratio between 2.5-D analysis result and observed data. The incident angles of SV-wave are (left)0º, (center)10º and (right)20º. The incident angles are considered in the 1-D analysis (green solid curve).

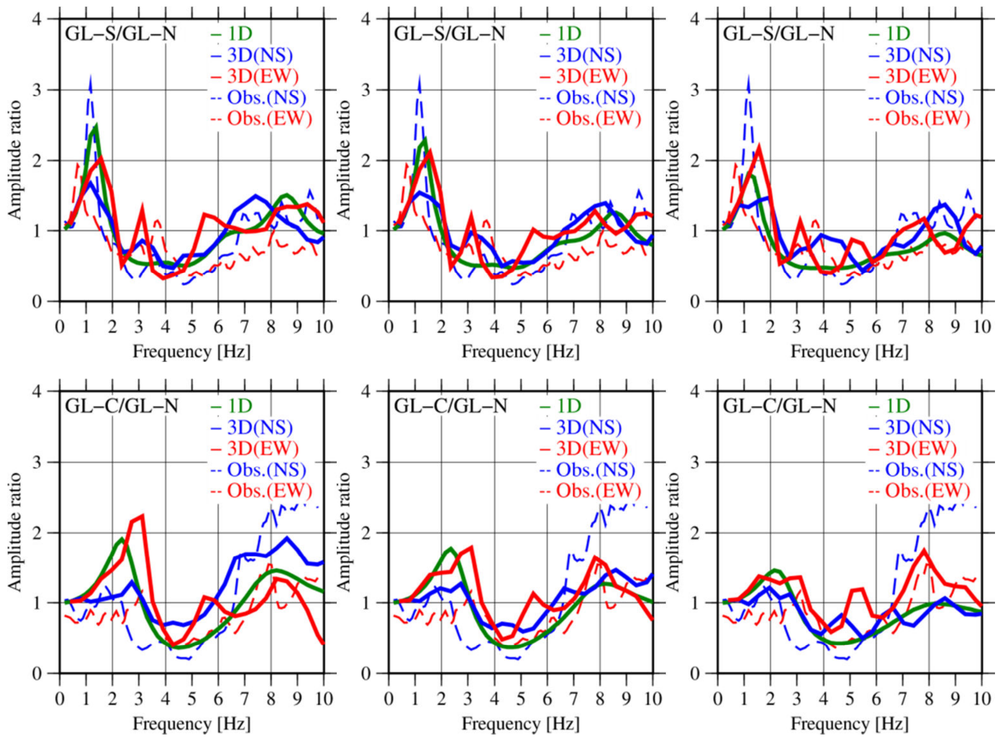

Figure 8. Comparison of the amplitude ratio between 3-D analysis result and observed data. The incident angles of SV-wave are (left) 0º, (center)10º and (right)20º. The incident angles are considered in the 1-D analysis (green solid curve).

5 CONCLUSION

In this paper, the effects of a three-dimensional configuration, i.e. a two-dimensional inclined boundary layer ground, on which a massless rigid foundation with embedment is placed, and subject to an incident wave, has been studied using a substructure-based combination of three-dimensional and 2.5-dimensional finite element methods. The followings findings were demonstrated by the study.

- The wave field becomes very complex on the ground having a foundation, causing a considerably big difference in result between 2.5-dimensional (inclined boundary layer ground subject to obliquely incident waves) and three-dimensional analyses (a ground with inclined boundary and with an embedded foundation subject to obliquely incident shear waves).
- It was also found that it is noteworthy that the spectral ratios obtained from 3-D analysis are coincident with observation data obtained in the vicinity of frequency of 3-4 Hz.

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