Numerical reproduction of Rayleigh and Love waves and assessment of their influences on subsurface ground damage

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ABSTRACT

In the hazard map published by the Cabinet Office and each municipality in Japan, seismic intensity is calculated based on only the vertical 1D elastic calculation. Because these calculations do not consider the influence of multidimensional effects such as the generation and propagation of surface waves, the extent of seismic damage may be underestimated. This study attempts to reproduce the surface waves (Rayleigh and Love waves) and assesses their influences on subsurface ground damage using multidimensional seismic response analyses that consider the effect of irregular stratigraphic composition. Owing to ground irregularity, shear strain is non-uniformly distributed, and the mean effective stress reduction ratio becomes larger than that in 1D analysis and continues to increase over a long period. These analysis results emphasize that multidimensional effects are not negligible and must be considered for precise and realistic damage prediction.

Keywords: ground irregularity; Rayleigh wave; Love wave; seismic response analysis; multidimensional effect

1 INTRODUCTION

In December 2015, the Cabinet Office, Government of Japan, published a report on the long-period ground motion by a huge earthquake along the Nankai Trough. Long-period ground motion refers to seismic motion for a slightly long period of about 2–10 s, and the expansion of seismic damage by resonance, such as large and long duration sway of high-rise buildings and sloshing of oil tanks, owing to this long-period ground motion is a matter of concern. Surface waves generated at the irregular boundary between hard bedrock and a soft sediment layer mainly constitute long-period ground motion. These waves are characterized by their small distance attenuation and propagation range of several hundred kilometers away from the epicenter. In the Great Hanshin earthquake (1995), house damage was concentrated in a narrow band area. This localized and extensive seismic damage is attributable to the interference and amplification of the surface and the body wave passing through the soft sediment layer at a specific position on the ground surface (called edge effect (Kawase et al., 1998)). However, extracting only surface wave information from the actual earthquake observation records is difficult. Moreover, the influence of surface waves on subsurface ground has not yet been sufficiently elucidated. In the hazard map published by the Cabinet Office and each municipality in Japan, seismic intensity is calculated based on only the vertical one-dimensional (1D) elastic calculation that considers the empirical N value and shear wave velocity V_s. Because these calculations do not consider the influence of multidimensional effects such as the generation and propagation of surface waves, the extent of seismic damage may be underestimated. This study attempts to reproduce the surface waves (Rayleigh and Love waves) and assesses their influences on subsurface ground damage using the two-dimensional (2D) and three-dimensional (3D) seismic response analyses that consider the effect of irregular stratigraphic composition. The analysis code employed herein is soil–water coupled finite deformation analysis ***GEOASIA*** (Noda et al., 2008), which incorporates an elasto-plastic constitutive model, namely the SYS Cam-clay model (Asaoka et al., 2002), that allows the description of the behavior of soils ranging from sand through intermediate soils to clay within the same theoretical framework.

2 REPRODUCTION OF SURFACE WAVES

Figure 1 shows the surface wave reproduction analysis model. A foundation model with depth and width of 50 and 55,000 m, respectively, was prepared, and the base inclination was established from the position that was 2,220 m from the left side. The model in this study shows an inclination angle of 5° as an example. To compare and verify the analysis and theoretical results of surface wave reproduction, one-phase linear elastic infinitesimal deformation analysis was performed. Here, the effect of gravity was not considered. The input ground motion shown in Fig.

2 is the KiK-net strong motion record of the Kumamoto earthquake (2016) at the Mashiki station, hereinafter Kumamoto earthquake.

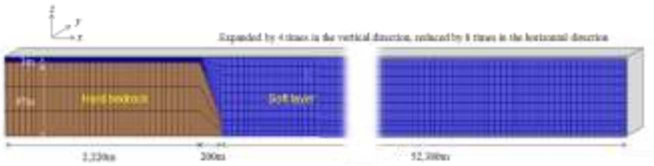

Fig. 1. Surface wave reproduction analysis model.

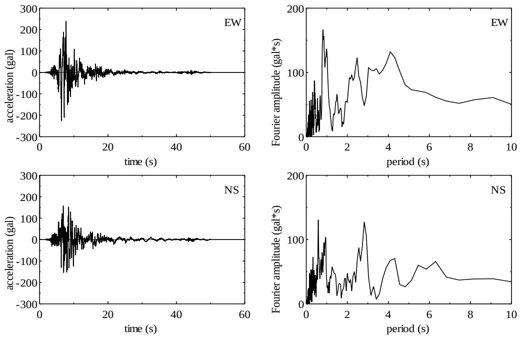

Fig. 2. Input seismic motions (Kumamoto earthquake).

2.1 Reproduction of Rayleigh waves

The analysis was performed under the 2D plane strain condition. Therefore, for the reproduction of Rayleigh waves, the Kumamoto EW wave was regarded as a 2E wave and input equally in the horizontal direction (*x* direction) with respect to all the bottom nodes. Semi-infinite elastic foundation was assumed by setting a viscous boundary equivalent to the sedimentary layer corresponding to V_s = 60 m/s at all the bottom nodes of the foundation. During the earthquake, simple shear boundary was set at both sides of the foundation.

Figures 3 and 4 show the velocity vector around the inclined bedrock and away from the bedrock, respectively. On the left side of the inclined bedrock, although only horizontal motion is input, vertical motion is generated. With time, both the horizontal and vertical components of the waves excited at the inclined bedrock propagate to the right side of the foundation. The waves propagating far away reproduce the following characteristics of the Rayleigh waves obtained theoretically by assuming a semi-infinite elastic ground: (1) the wave is a single cycle sinusoidal wave, (2) the displacement is large at the ground surface and decreases with the increase in depth, and (3) the wave trajectory is counter clockwise on the ground surface but changes to clockwise as the depth increases The details of the characteristics are omitted here owing to space constraints.

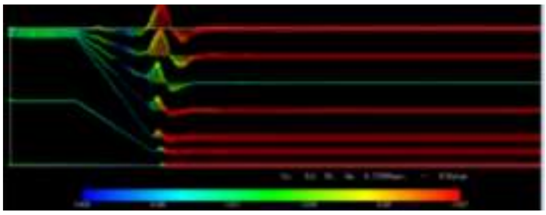

Fig. 3. Velocity vector around the inclined bedrock in the case of Rayleigh wave.

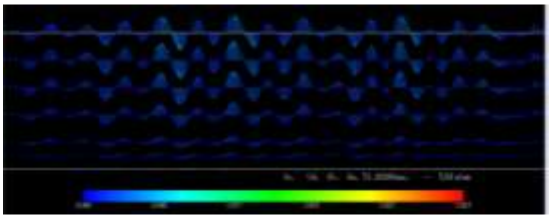

Fig. 4. Velocity vector away from the inclined bedrock in the case of Rayleigh wave.

2.2 Reproduction of Love waves

The analysis was performed under the 3D condition. For the reproduction of Love waves, the Kumamoto NS wave was regarded as a 2E wave and input equally in the paper depth direction (*y* direction) with respect to all the bottom nodes. The ground was assumed to be a two-layer elastic ground. A viscous boundary equivalent to Vs = 2,000 m/s was set at all the bottom nodes of the foundation, whereas a periodic boundary was set at the front and back of the foundation. During the earthquake, simple shear boundary was set at both sides of the foundation.

Figures 5 and 6 show the velocity vector around the inclined bedrock and away from the bedrock, respectively. During an earthquake, waves only having components parallel to the ground surface (*y* direction) from the inclined bedrock are excited and propagate to the right side of the ground. The waves propagating far away reproduce the following characteristics of Love waves: (1) the waves show dispersibility with propagation, and (2) the waves are not excited in the single-layer elastic ground. The details of the characteristics are omitted here.

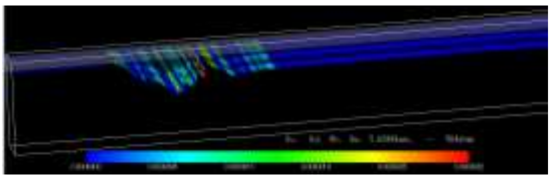

Fig. 5. Velocity vector around the inclined bedrock in the case of Love wave.

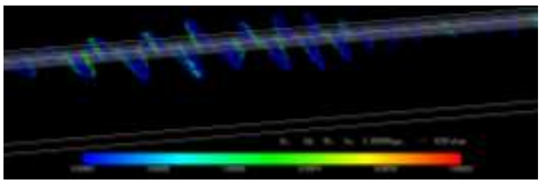

Fig. 6. Velocity vector away from the inclined bedrock in the case of Love wave.

3 INFLUENCE OF SURFACE WAVES ON THE SUBSURFACE DAMAGE OF A BASIN

In the previous section, the surface wave (Rayleigh wave and Love wave) was confirmed to be excited from the bedrock owing to ground irregularity. Therefore, we investigate the influence of surface waves on subsurface ground damage via finite deformation analysis of a two-phase elasto-plastic material. Here, we mainly focus on the mean effective stress reduction ratio (ground rigidity reduction) owing to earthquake motion. The analysis model is shown in Fig. 7. The ground was assumed to constitute soft sediment clayey soil on hard bedrock exhibiting a basin shape. For the material constants used for the analysis, refer to Nakai et al. (2015). The bottom and lateral sides were assumed to be undrained boundaries, and the ground surface was assumed to be an atmospheric pressure boundary. A viscous boundary equivalent to V_s = 2,300 m/s was set at all the bottom nodes of the ground. The following three kinds of waves were input to the ground and excited at the bedrock: (1) Kumamoto EW wave in the horizontal x direction (Rayleigh wave), (2) Kumamoto NS wave in the depth y direction (Love wave), and (3) both Kumamoto EW and NS waves in the x and y directions, respectively (both the Rayleigh and Love waves).

Position	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Soft layer thickness	0.0	3.5	6.0	8.5	13.6	18.6	24.9	28.5

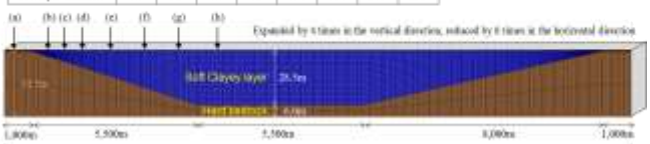

Fig. 7. Basin shape analysis model.

3.1 Influence of soft layer thickness

First, to assess the influence of the stratigraphic composition, i.e., thickness of sedimentary layer, on seismic motion, 1D seismic response analyses with different thicknesses of the soft clayey layer were conducted. The input seismic motion is the Kumamoto EW wave. The analysis target reflects the composition of the strata just below positions (a)–(h) in Fig. 7. Figure 8 shows the mean effective stress reduction ratio of the subsurface layer. This ratio increases with the increase in the sediment layer thickness ((b)-(c)-(f)-(g)-(h)). However, at positions (d) and (e), the increase in the mean effective stress reduction ratio is large relative to the sediment layer thickness. Figure 9 shows the Fourier amplitude spectrum of the velocity response at each position. With the increasing thickness of the sediment layer, the natural period of the ground increases, making the amplification with the long cycle component prominent. The figure shows that the natural period at positions (d) and (e) is about 1.0–1.3 s, which coincides with the dominant period of the input seismic motion shown in Fig. 2. The mean effective stress reduction ratio is larger at positions (d) and (e) than the other positions because of the resonance phenomenon owing to the coincidence of the natural period of the ground and the dominant period of the input seismic motion.

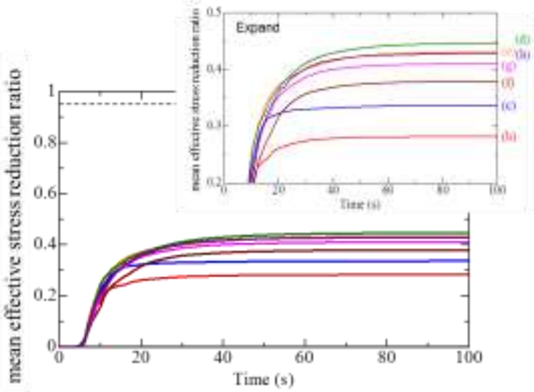

Fig. 8. Mean effective stress reduction ratio with different sediment layer thicknesses.

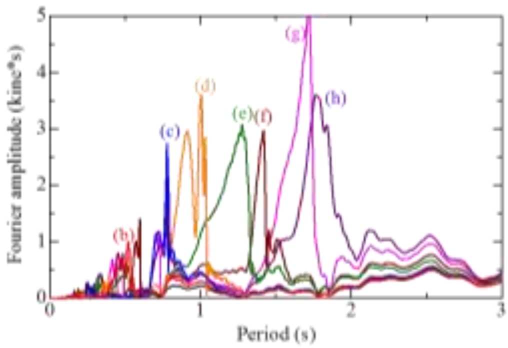

Fig. 9. Fourier amplitude with different sediment layer thicknesses.

3.2 Influence of surface waves excited owing to ground irregularity

To grasp the influence of surface waves on seismic motion, multidimensional seismic response analysis was conducted. Figure 10 shows the shear strain distribution at different time periods when the Kumamoto EW wave in the x direction was input. Because surface waves propagate to the central part of the basin with time, shear strain also spreads to the central part ((1)-(6)). Surface waves have small distance attenuation; therefore, they continue to propagate even after the earthquake ((5) and (6)), and consolidation occurs with the dissipation of excess pore water pressure accumulated during the earthquake ((7)). Around the inclined bedrock, the shear strain increases not only in the surface layer but also in the deeper part. This is considered as the resonance effect described in Section 3.1 and the complex interference between the surface and body waves. In this manner, considering ground irregularity, the shear strain generated in the subsurface ground is unevenly distributed owing to the interference of the body and surface waves in addition to the generation and propagation of the surface wave. The shear strain distribution is non-uniform even in the central part of the ground, where layers in the vertical direction are equal. These results cannot be explained via 1D analysis. The analysis results obtained using the Kumamoto NS wave in the *y* direction and both Kumamoto EW and NS waves in the *x* and *y* directions, respectively, were omitted here; however, non-uniform shear strain distribution generally occurs.

Figure 11 summarizes all the results, including those of 1D analysis, of the mean effective stress reduction ratio at point (e). The figure clearly shows that in 1D analysis, the mean effective stress reduction ratio is constant immediately after the earthquake; however, in multidimensional analysis, it continues to increase even after the earthquake. This is attributable to the surface waves accumulated in the basin in addition to the generated surface waves. Furthermore, the mean effective stress reduction ratio is higher in multidimensional analysis than in 1D analysis. Moreover, this multidimensional analysis, the degree of contribution of the Rayleigh wave is clearly higher than that of the Love wave.

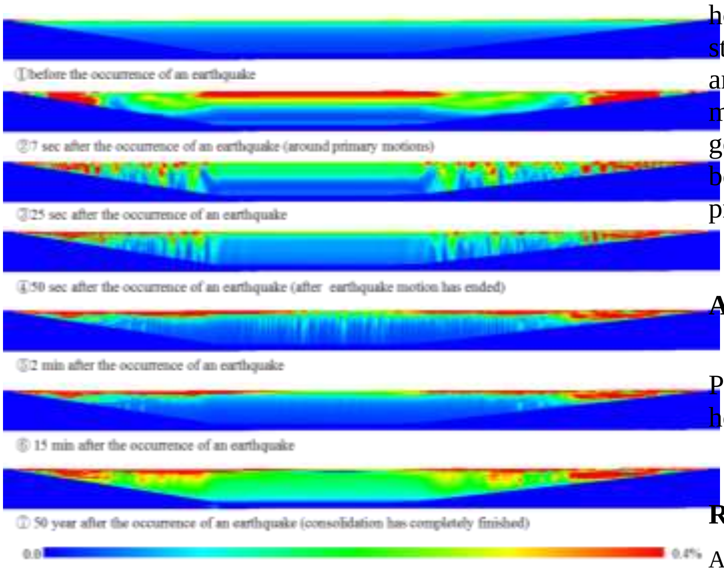

Fig. 10. Shear strain distributions with time in the case of Rayleigh wave.

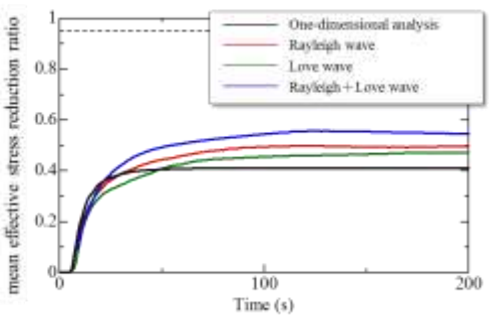

Fig. 11. Comparison of mean effective stress reduction ratio.

4 CONCLUSIONS

In this study, we conducted a series of seismic response analyses considering the irregularity of the stratum to numerically reproduce surface waves (Rayleigh and Love waves) and investigate their influence on subsurface ground. The following conclusions were obtained: (1) When seismic motion was input in the horizontal direction (x direction) with respect to the base inclination, Rayleigh wave was excited. Conversely, when seismic motion was input in the depth direction, perpendicular to the base inclination (y direction), Love wave was excited. Moreover, the reproduced surface wave was confirmed to represent the characteristics of the elastic theoretical solution. (2) Owing to ground irregularity, shear strain is non-uniformly distributed. (3) When ground irregularity is considered, the mean effective stress reduction ratio becomes larger than that in 1D analysis and continues to increase over a long period of time. (4) In this study, the contribution of the Rayleigh wave to the mean effective stress reduction ratio is greater than that of the Love wave. Many existing seismic damage prediction methods are based on vertical 1D evaluation; however, multidimensional effects due to irregular stratigraphic composition are not considered. The analysis results of this study emphasize that multidimensional effects typified by surface wave generation and propagation are not negligible and must be considered for precise and realistic damage prediction.

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