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THEORETICAL EVALUATION OF EFFECTS OF SEA ON SEISMIC GROUND MOTION

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SUMMARY

I evaluated effects of the sea on seismic ground motion theoretically through some numerical experiments for two-dimensionally simple subsurface structure models. Much about the sea effects remains to be examined, as indicated by the fact that most of ground motion simulations ignore the sea in Japan that is prone to oceanic earthquakes. To specify effects of the sea, I compared waveforms calculated for the models with and without the sea by means of the direct boundary element method. The following findings strongly suggest the necessity of considering the sea in ground motion simulations, although the sea effects on the three-dimensional wave-field still remain to be evaluated: (1) The Rayleigh waves are strongly influenced by the sea; (2) As the sea is deeper, it can influence the Rayleigh waves to longer periods; (3) Substituting sediments for sea water, which may be frequent in ground motion simulations, can have bad influence particularly on vertical components and we would sooner replace sea water by vacuum than substitute sediments for sea water.

INTRODUCTION

Japan is prone to oceanic earthquakes with large magnitudes. In September 2003, a large interplate event (Mw=8.0; Japan Meteorological Agency [1]) named the 2003 Tokachi-oki earthquake occurred in the subduction zone southeast off Hokkaido, Japan. Figure 1 indicated that the sea several hundred meters deep exists over the source region (Yagi [2]) of this earthquake. Along the trenches in the Pacific Ocean near Japan, several big earthquakes (Mw>7) are anticipated in the near future (The Central Disaster Management Council, Japan [3]; The Headquarters for Earthquake Research Promotion, Japan [4, 5]) and Figure 2 shows that the hypothetical source regions of these earthquakes are located under the sea several hundred meters deep. Concerns are not limited to the deep sea but extended to the shallow sea several ten meters deep, because it is located not only over the landward margins of the abovementioned source regions but also around the cities with large population such as Tokyo and Osaka. Though such sea may influence seismic ground motion, it is usual to ignore the sea in numerical simulations of ground motion for earthquake damage assessment. This study is motivated by a question whether ignoring the sea is valid in ground motion simulations.

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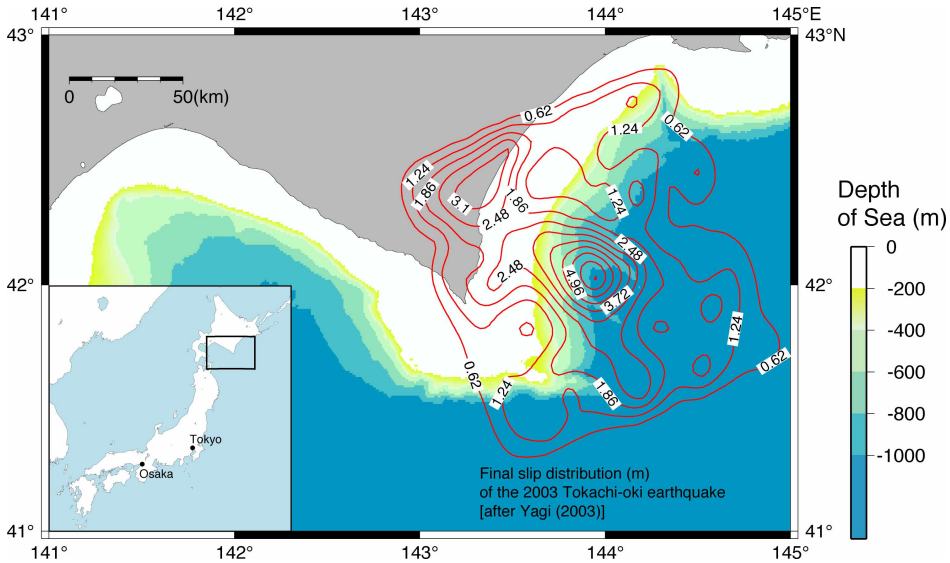

Figure 1. The source region of the 2003 Tokachi-oki earthquake and the sea depth.

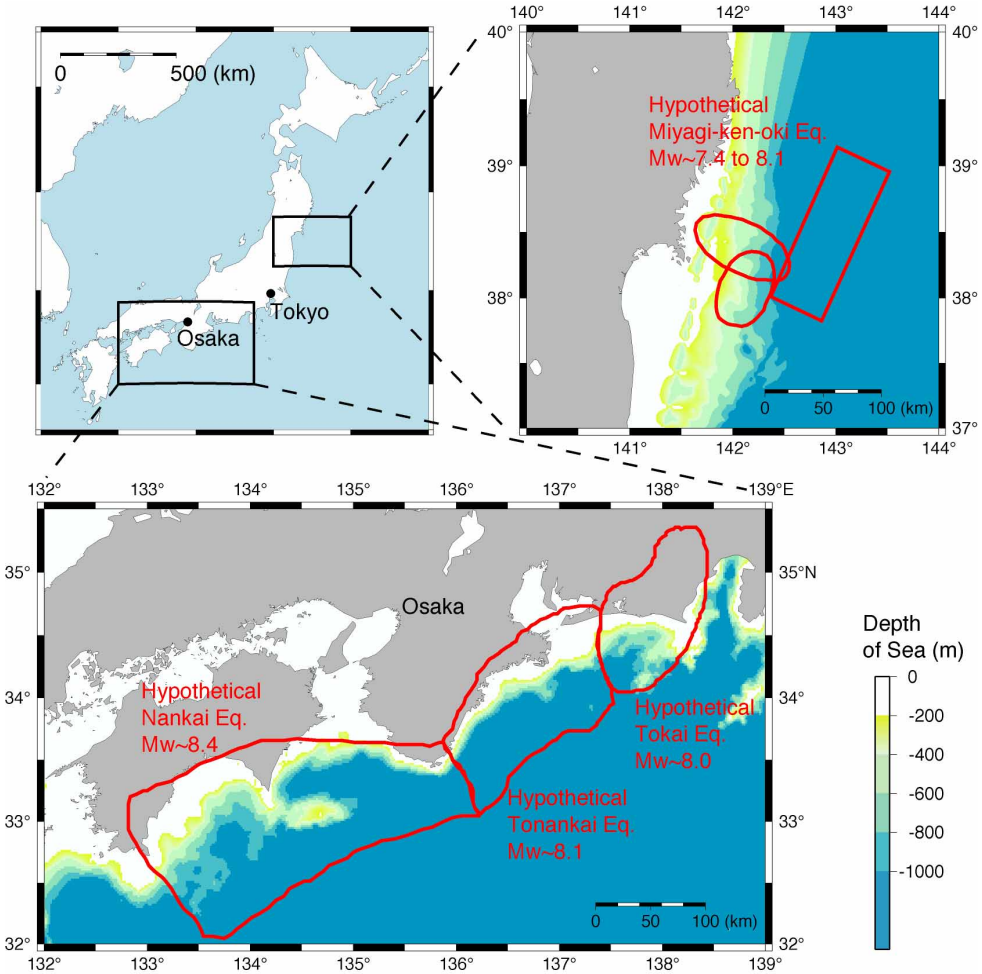

Figure 2. The hypothetical source regions of potential big earthquakes off Japan and the sea depth.

The reason why the sea is seldom or never considered in ground motion simulations is that little of effects of the sea on seismic ground motion is known. This might be against a background of a preconceived idea that the sea water probably causes numerical instabilities in calculating by the finite difference method that is popularly used in ground motion simulations. Nagano [6] simulated seismic wave propagation in subsurface structure models with the water overlying the ground by their technique based on the hyperelement method and pointed out that the water can influence seismic ground motion. In their examinations, however, the Ricker wavelets with a center frequency of 0.175 Hz were used as input motion and their findings are so limited to low-frequency ground motion that much about the sea effects remains to be examined. This would be due to low performance of computers at that time rather than their calculation technique. Effects of the sea were also found in observed recordings. Nakanishi [7] introduced an example of the Rayleigh waves with a period of around 16 s guided by the sea-trench topography where the sea depth is over 4 km.

This paper aims at evaluating effects of the sea on seismic ground motion theoretically through some numerical experiments. To specify effects of the sea, I compared waveforms calculated for models with and without the sea. The depth of the sea examined here ranges from several ten to several hundred meters. Examined in this study are two-dimensionally simple subsurface structure models. The models are composed of a sea part and a land part. Both parts are horizontally stratified layers overlying the elastic half-space and as regards the sea part the medium of the uppermost layer is water, which is regarded as the ideal fluid here. For such models, I solved point source impulse responses of the two-dimensional P-SV wave field in the frequency domain by using the direct boundary element method (BEM) and velocity waveforms are calculated by convolution with Ricker wavelets. The BEM here relies on Green’s functions for horizontally layered media. This enables to calculate Rayleigh waves alone as well as the total waves. In other words, effects of the sea can be evaluated separately on Rayleigh waves and other waves. Because of the shallow sea included in the examinations, the impulse responses were calculated up to a high frequency of 16 Hz.

METHOD

Figure 3 shows a typical subsurface structure model for which seismic ground motion was calculated in this study. The models are two-dimensional and composed of two parts of horizontally stratified layers: the sea part in the left side and the land part in the right side. In the sea part, the medium of the uppermost layer is water, which is regarded as the ideal fluid here. For this kind of models, point source impulse responses of the two-dimensional P-SV wave field were solved in the frequency domain by using the direct boundary element method (BEM) and the impulse responses were convolved with Ricker wavelets with various center periods to obtain velocity waveforms of ground motion. In formulating the BEM here, wave fields in the sea part and the land part are represented by boundary integral equations with Green's functions for the respective horizontally stratified layers. With this formulation, the discrete boundary elements have only to be deployed along the mathematical vertical boundary running between the sea and the land parts, which is depicted in the broken line in Figure 3. At first in the BEM, unknown velocities and tractions are solved for these discrete boundary elements, taking into accounts boundary conditions, and then frequency responses at arbitrary observation points are calculated by using the solutions along the vertical boundary and Green's functions between the vertical boundary and the observation points. If the second step adopts Green's functions calculated by summing up normal modes of Rayleigh waves, Rayleigh waves alone can be obtained at the observation points. If the Rayleigh waves are subtracted from the total waves calculated by adopting Green's functions of the total waves in the second step, other waves than the Rayleigh waves can be obtained at the observation points. This means that effects of the sea can be evaluated separately on Rayleigh waves and other waves. The abovementioned manner of formulating the BEM was originally proposed by Hisada [8] and Fujiwara [9] for the purpose of calculating surface

waves excited secondarily in sedimentary basins. I first adapted this method for the application to subsurface structure models even with the sea water.

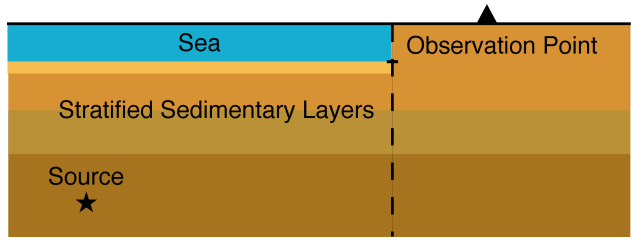

Figure 3. A typical subsurface structure model used in this study.

Because of the shallow sea included in the examinations of this study, the impulse responses were calculated up to a high frequency of 16 Hz. This required small boundary elements and they slow the convergence of wave-number integrands for calculating Green's functions in horizontally stratified layers. The convergence of the wave-number integrands is controlled by static zero-frequency components that involve singularities. I calculated the static zero-frequency components separately and then add them to dynamic components to accelerate the wave-number integration.

RESULTS AND DISCUSSIONS

Sea with firm basement rock

At first I calculated velocity waveforms for three subsurface structure models depicted in Figure 4 and compared them to specify effects of the sea on seismic ground motion. Figure 4(a) shows the sea model in which the sea 800 m deep occupying part of firm basement rock with an S-wave velocity of 3 km/s. Figure 4(b) is simply the half-space model and Figure 4(c) is the cliff model in which the sea water is omitted to take into account the sea floor topography. In these models, a point source is located 50 km off the coast and at a depth of 5 km and the impulse responses due to a horizontal or vertical single force are calculated at an observation point on the ground surface about 10 km inland from the coast.

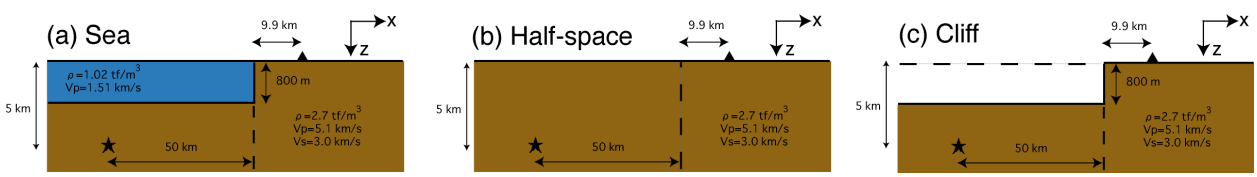

Figure 4. Firm-rock-based models with and without sea.

Figure 5 shows the velocity waveforms obtained by convolving the impulse responses due to a horizontal single force with Ricker wavelets with center periods of 3 and 1.5 s. Each panel displays the velocity waveforms from the sea model (upper trace), the half-space model (middle trace) and the cliff model (lower trace) with Rayleigh waves (red traces) calculated separately by the abovementioned BEM, with amplitudes normalized by the peak absolute values of the horizontal components for the half-space models. The Rayleigh waves for the sea models are significantly different from those for the half-space models. The sea models also produce different Rayleigh waves from the cliff models, while the cliff models produce similar Rayleigh waves to the half-space models. Accordingly the difference in the Rayleigh waves between the sea models and the half-space models is considered to be due to the sea water.

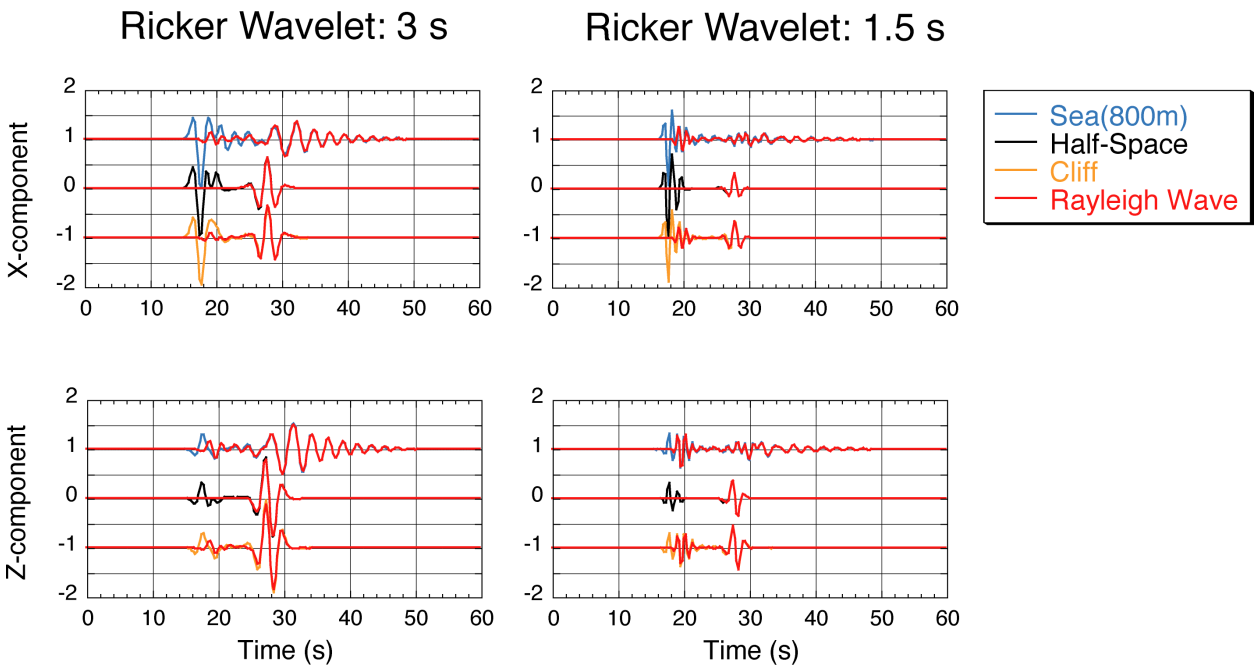

Figure 5. Velocity waveforms calculated for the models with and without sea in Figure 4.

The Rayleigh waves from the sea models seem to be dispersive. Figure 6(a) convinces us of its truth, in which dispersion curves of group velocities of Rayleigh waves are shown for the fundamental mode (black line) for the half-space model (Figure 6(b)) and the normal modes (red, blue and green lines) for horizontally layered media in which the sea water 800 m deep overlying the same firm rock as consists of the half-space model (Figure 6(c)). For the half-space composed of uniform media, Rayleigh waves are not dispersive as known well, while they become dispersive if the water overlies the half-space.

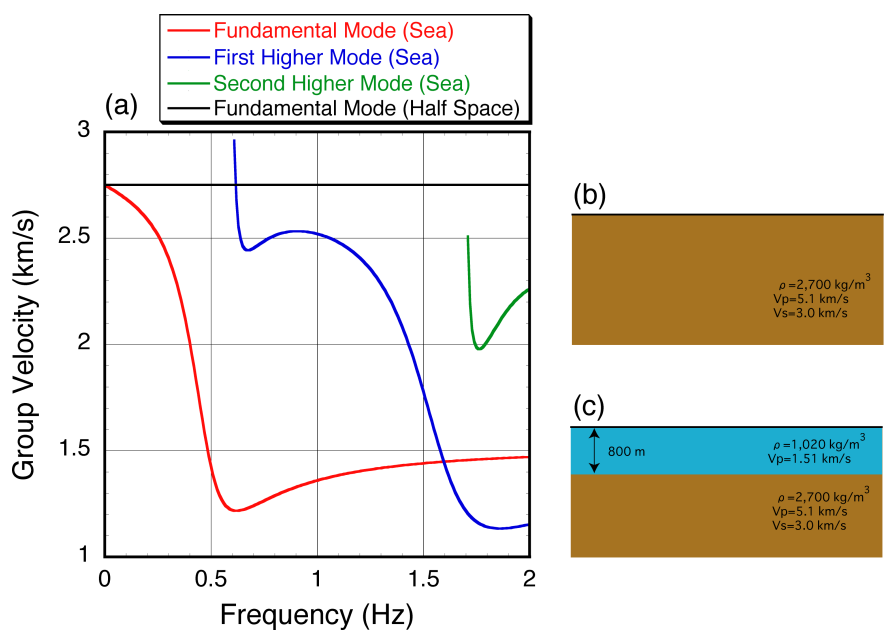

Figure 6. Dispersion curves of group velocities of Rayleigh waves.

Sea depth vs. sea-influencing period range

Because the effects of the sea water found above appears in the dispersive characteristics of the Rayleigh waves, period ranges for which the sea water can influence would depend on sea depths. I here examine the effects of the sea with various depths and specify the relation between the sea depths and the sea-influencing period ranges. Examined are the same models as in Figure 4(a), but the sea depths and the cliff heights range from 25 to 800 m. Figure 7 shows the vertical components of velocity waveforms obtained by convolving the impulse responses due to a vertical single force with Ricker wavelets with center periods ranging from 6 to 0.1875 s. Each panel displays the waveforms in the same way as in Figure 5, where the cliff heights are the same as the respective sea depths. If the Rayleigh waves for the sea model are different from those for both the half-space model and the cliff model and if the cliff model produces similar Rayleigh waves to the half-space model, the sea water effects on the Rayleigh waves can be recognized. In this case in which the S-wave velocity is assumed to be 3 km/s for the basement rock, the significant sea effects are found in the lower-right area enclosed by the bold line in Figure 7: around a period of 0.1875 s for the sea 50 m deep, a period range from 0.1875 to 0.375 s for the sea 100 m deep, from 0.1875 to 0.75 s for 200 m, from 0.1875 to 1.5 s for 400 m, from 0.1875 to 3 s for 800 m. For the sea 25 m deep, no significant sea effects were found in the period range examined in this study. To be brief, as the sea is deeper, it can influence Rayleigh waves to longer periods. Although this is natural or somewhat trivial, it is important to specify quantitatively the period range for which the sea water can influence. However the sea-influencing period range will depend on the medium property surrounding the sea and the above findings cannot necessarily regarded as universal. A parameter study of examining various typical models with the sea is needed to present tables that indicate the sea-influencing period ranges.

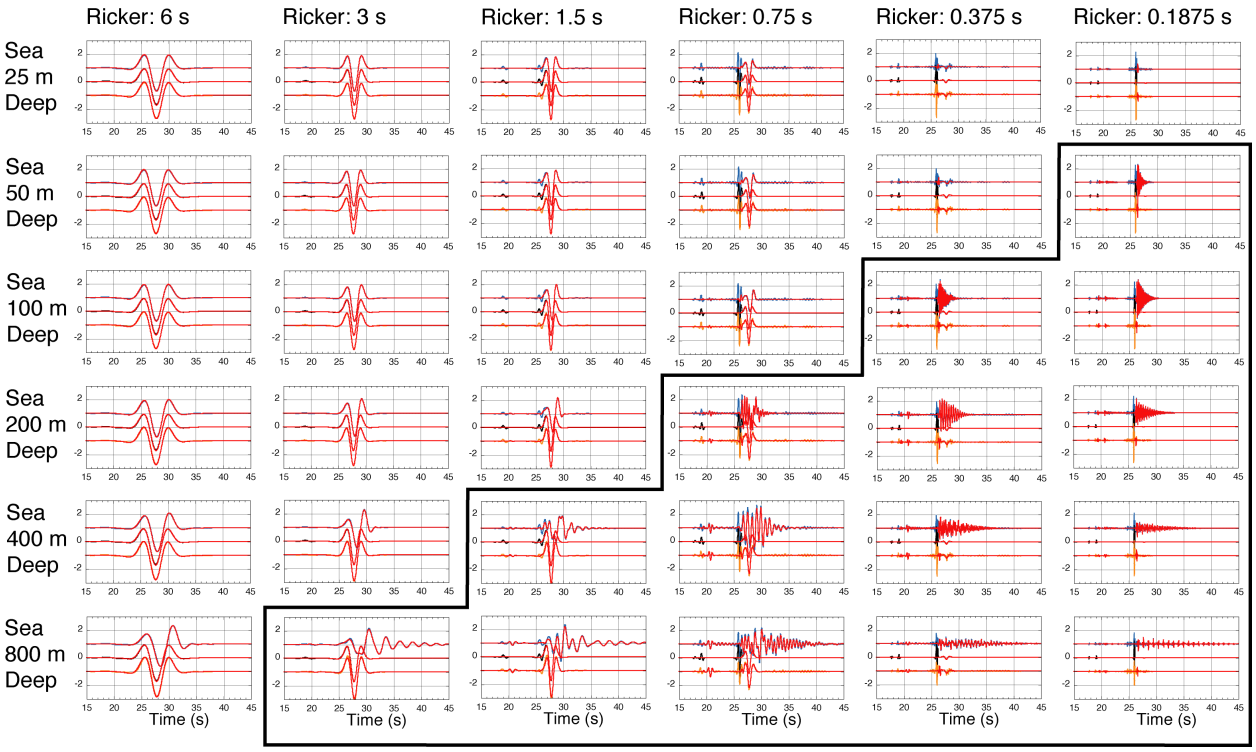

Figure 7. Sea depths vs. period ranges for which the sea water can influence in the case in which the sea occupies part of the firm-rock half-space with an S-wave velocity of 3 km/s.

Sea with sedimentary layers

In the above examinations, the reference medium was simply the half-space in which Rayleigh waves are not dispersive and so the effects of the sea water could easily recognized. These sea effects however might be so weak that they cannot appear clearly in originally dispersive Rayleigh waves in stratified layered media. I here specify the sea water effects on the dispersive Rayleigh waves by using three subsurface structure models depicted in Figure 8. Figure 8(a) shows the sea model in which the sea 400 m deep occupying part of two sedimentary layers stratified horizontally on the same firm basement rock as in Figure 4. Figure 8(b) is simply the stratification model and Figure 8(c) is the cliff model in which the sea water is omitted to take into account the sea floor topography. The configuration of a point source and an observation point is the same as in Figure 4.

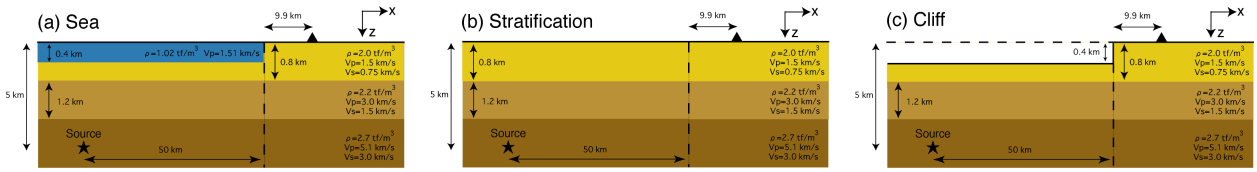

Figure 8. Sediment-based models with and without sea.

Figure 9 shows the velocity waveforms obtained by convolving the impulse responses due to a horizontal single force with Ricker wavelets with center periods of 6, 3 and 1.5 s. Each panel displays the waveforms in the same way as in Figure 5, but amplitudes are normalized by the peak absolute values of the horizontal components for the stratification models. The Rayleigh waves for the sea models are different from those for both the stratification models and the cliff models. It follows that the sea water effects are so strong that they can distort originally dispersive Rayleigh waves. It can also be found that the stratification models produce different Rayleigh waves from the cliff models, which is unlike the results from the models based on the firm rock depicted in Figure 4, and the Rayleigh waves for cliff models are more similar those for the sea models than those for the stratification models. The most remarkable differences from the sea models are found in the vertical components for the stratification models. These findings suggest that substituting sediments for the sea water, which may be frequent in ground motion simulations, can have bad influence particularly on vertical components and that we would sooner replace sea water by vacuum than substitute sediments for sea water.

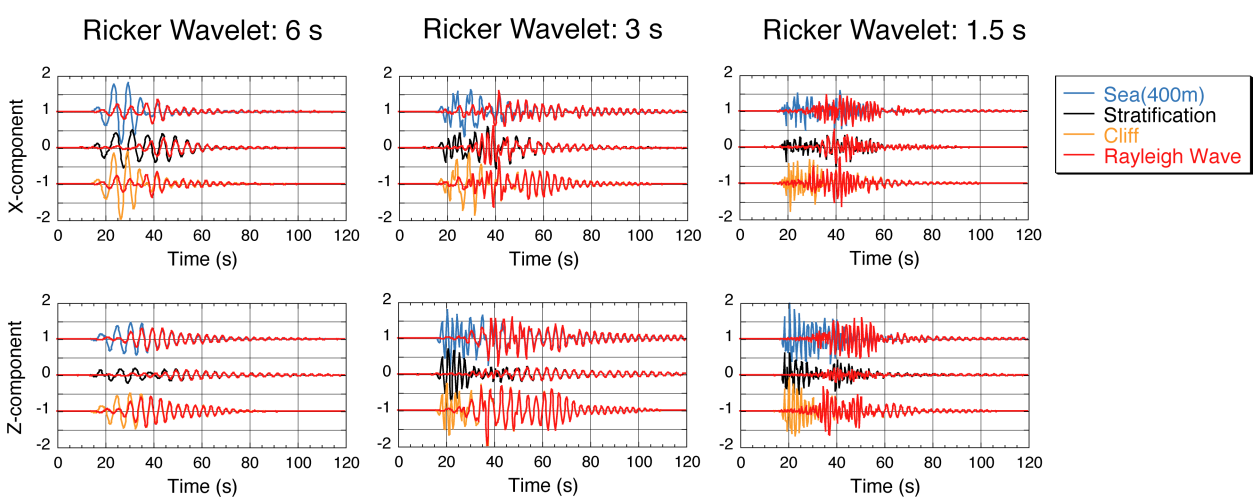

Figure 9. Velocity waveforms calculated for the models with and without sea in Figure 9.

CONCLUSIONS

I evaluated effects of the sea on seismic ground motion theoretically through some numerical experiments. To specify the effects of the sea, I compared waveforms calculated for models with and without the sea.

Examined in this study are two-dimensionally simple subsurface structure models. The models are composed of a sea part and a land part. Both parts are horizontally stratified layers overlying elastic half-space and as regards the sea part the medium of the uppermost layer is water, where various depths of the sea are assumed in a range from 25 to 800 m. By comparing the waveforms from the models with and without the sea, I found the following effects of the sea:

(1) Rayleigh waves are strongly influenced by the sea;

(2) As the sea is deeper, it can influence Rayleigh waves to longer periods; the intense effects of the sea with depths of 50, 100, 200, 400 and 800 m appear up to periods around 0.1785, 0.375, 0.75, 1.5 and 3 s, respectively, although these periods are for the simple case of the sea occupying part of bedrock with an S-wave velocity of 3 km/s and they may depend on velocity structures surrounding the sea;

(3) Substituting sediments for sea water, which may be frequent in ground motion simulation, can have bad influence particularly on vertical components and we would sooner replace sea water by vacuum than substitute sediments for sea water.

The above findings strongly suggest the necessity of considering the sea in ground motion simulation and the effects of the sea on the three-dimensional wave-field still remain to be evaluated.

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