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NUMERICAL EVALUATION PRECISION OF NEAR-FAULT GROUND MOTIONS

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ABSTRACT

To estimate amplitudes and/or spatial variation of near-fault pulse-like ground motions, we need to verify precision of numerical evaluation methods carefully. This study investigates numerical precision of the near-fault ground motions calculated by the thin layer method. First, ground motions evaluation method based on the thin layer method is addressed as a numerically effective tool including the case for surface rupture of the seismic fault. Next, the observed near-field pulse-like ground motions during the 2016 Kumamoto earthquake are simulated to show the validity of the numerical method used in this study. Velocity waveforms at Mashiki-machi site are fairly reproduced in all components at both ground surface and downhole. In the forward sides of sub-faults, short period motions are predominant, especially from the sub-fault closest to the ground surface at Mashiki-machi. Finally, we estimate the numerical evaluation precision of surface rupturing near-fault ground motions adjacent to a vertical strike-slip fault, focusing on effects of rupture patterns, subsurface structure. In numerical evaluation of ground motions adjacent to seismic fault with surface rupture, evaluation points of the Green's function is crucial rather than subsurface structure. The obtained results will be applicable for ground motion prediction at the nuclear power plant sites during the surface-rupture earthquakes.

INTRODUCTION

Evaluation of ground motions adjacent to the surface-rupture of the seismic fault is of great interest to many earthquake engineers. In the 2016 Kumamoto earthquake, near-fault pulse-like ground motions with predominant period of 1 s. hit to the populated area resulting in devastating damages to many wooden houses. Although the surface-rupture of the seismic fault occurred in Japan, structural damages adjacent to fault lines were relatively small even in the 1995 Kobe earthquake, where surface-rupture appeared in northern part of Awaji Island. In addition to that, pulse-like ground motions during the 2016 Kumamoto earthquake showed strong directivity in fault parallel direction. This has been not the case in the previous inland earthquake in Japan.

The near-fault ground motions can be evaluated by using the numerical method, e g., the wavenumber integral method, the thin layer method, the finite difference method, etc. To estimate amplitudes and/or spatial variation of near-fault pulse-like ground motions, we need to check precision of numerical evaluation methods carefully. These numerical methods are elaborately validated in the "Benchmark Test Project for Ground Motion Evaluation Method" (Hisada et al., 2012), including the case for the near-fault ground motions.

This study investigates numerical precision of the near-fault ground motions calculated by the thin layer method. First, ground motions evaluation method based on the thin layer method is addressed as a numerically effective tool including the case for surface rupture of the seismic fault. Next, the observed near-field pulse-like ground motions during the 2016 Kumamoto earthquake are simulated to show the validity of the thin layer method. Strong ground motions in Mashiki-machi are theoretically synthesized using the rupture process model by Hikima (2016) based on waveform inversion analyses. Then, amplification mechanism is elucidated for rupturing in deep and shallow part of seismic fault. Finally, we estimate the numerical evaluation precision of surface rupturing near-fault ground motions adjacent to a vertical strike-slip fault, focusing on effects of rupture patterns, subsurface structure. The obtained results will be applicable for ground motion prediction at the nuclear power plant sites close to surface-rupturing faults.

GROUND MOTION EVALUATION METHOD USING THIN LAYER METHOD

The thin layer method (hereafter, TLM) has been numerically effective tool to evaluate Green's function in stratified soil (e.g. Tajimi, 1981, Kausel, 1982). Originally, the method is developed as an application tool to the soil-structure interaction problem including evaluation of the dynamic impedance functions.

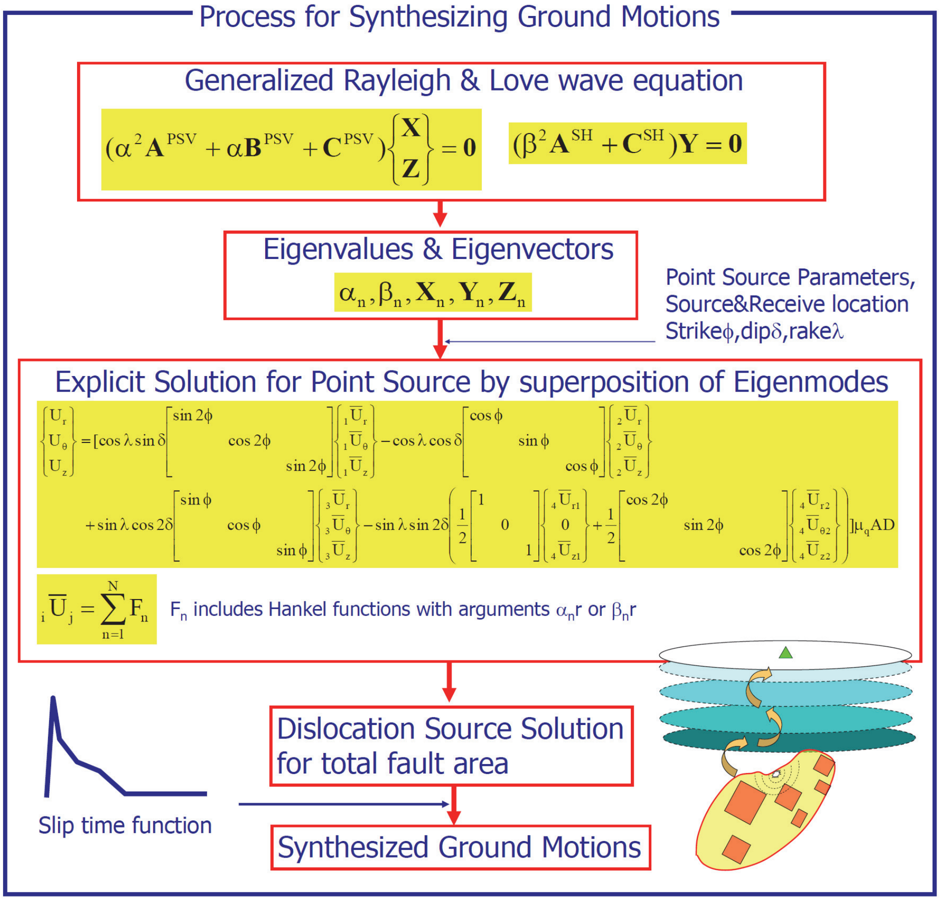


Figure 1. Process for dislocation source solution by using Thin Layer Method.

The TLM also can be applied to calculate theoretical ground motions due to dislocation rupture of a large-scale seismic fault. Process for dislocation source solution by the TLM is summarized in Figure 1. Compared with conventional integral transform methods accompanying infinite wavenumber integration, the TLM has several numerical advantages, e.g., high calculating efficiency for enormous combinations of source and receive points for a large seismic fault plane with strong complexity in rupture process, and for soil property with vertical heterogeneity, once eigenvalues and modes of Rayleigh and Love wave equations are obtained.

There remains several issues in TL calculation with regard to numerical accuracy in connection with its formulation, e.g., discretization artifacts, artificial reflection of waves impinging at the bottom, and numerical instability when distance between source and receive points (i.e., epicentral distance) is extremely small. We incorporated some numerical techniques into the TL code in Figure 2 to improve these numerical problems (Nagano & Watanabe, 2007) as follows;.

(1) Use of higher-order (quadratic) elements.
(2) Combination of buffer zone of some wavelength (Maeda & Kausel, 1991) with gradually increasing high attenuation (Cerjan et al., 1985). Latter method is preferably used in FD calculation. Combination with viscous boundaries at the bottom of TL region well works to deter artificial reflection at the bottom of the TL region as shown in Figure 2.

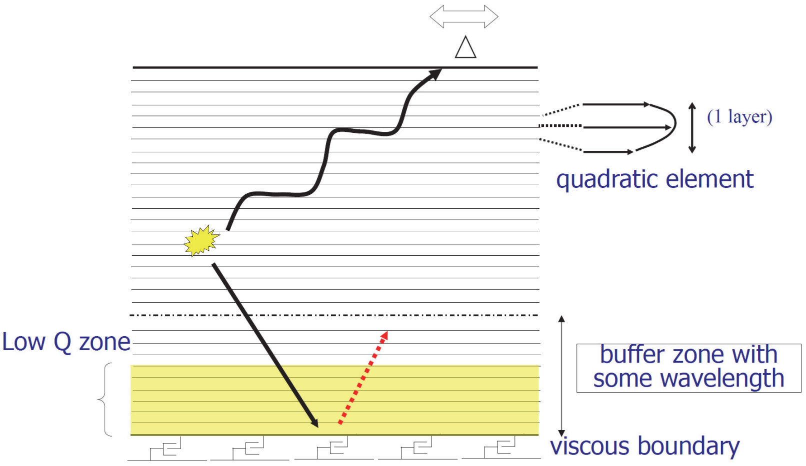


Figure 2. Modeling techniques into TL code to improve numerical problems.

(3) Spatial integration of Green's function to avoid numerical singularity due to Hankel function of 2nd order.
(4) Different Q values for S- and P-waves are incoporated by decomposing B^{PSV} matrix in Figure 1 into B^S and B^P.
(5) Use of tuning factors for consistent and lumped mass and stiffness matrices.

Theoretical ground motions by the TLM has been carefully calibrated in the "Benchmark Test Project for Ground Motion Evaluation Tools" (Hisada et al., 2012), including the case for the near-fault ground motions. Validation is made by comparing with integral transform methods based on generalized R/T matrix (Hisada, 1994). The TLM is also applied to ground motion evaluation at near-fault, surface faulting (Nagano & Watanabe, 2007).

THE 2016 KUMAMOTO EARTHQUAKE

The main shock of the 2016 Kumamoto earthquake with Mw7.0 occurred in the midnight of April 16th (hereafter referred as the main shock) and massive shaking with the JMA intensity level of 7 hit to densely populated area of Mashiki-machi leading to devastating damages to lots of wooden houses, as shown in Figures 2 and 3. Features of near-fault ground motions recorded in Mashiki-machi are summarized as follows: (1) Pulse-type motions with predominant period of 1 s. were recorded adjacent to surface rupture. (2) Amplitude level was equal to or greater than the Takatori motion during the 1995 Kobe earthquake. (3) Principal axis was close to east-northeast direction parallel to Futagawa segment. (4) Spatial variation of recorded ground motions is large in short distance within 2 km.

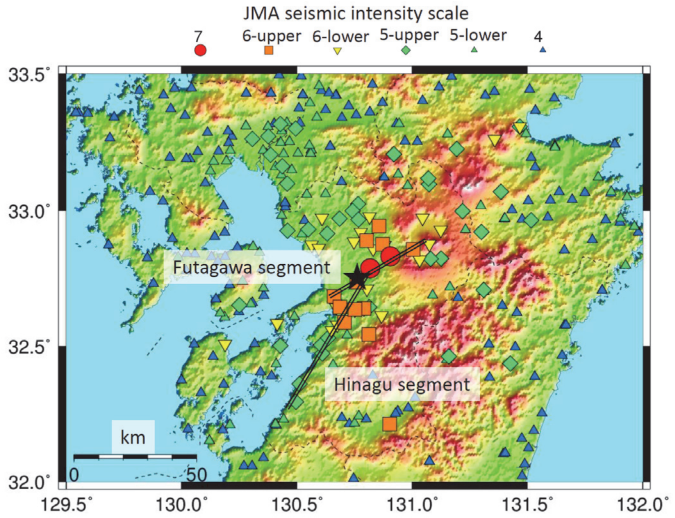
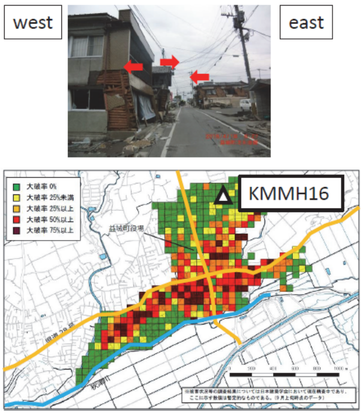
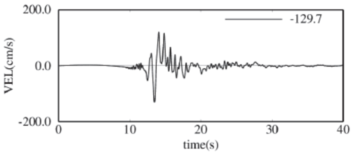


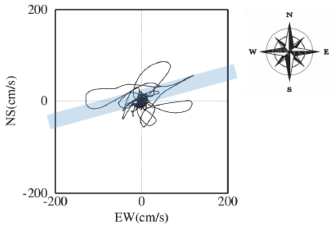
Figure 3. Spatial distribution of JMA seismic intensity scale during the main chock in Kyushu area.



(a) Damage distribution in downtown Mashiki (referred from NILIM & BRI report)and Damage to wooden houses and direction of inclination



(b) Velocity seismogram at KMMH16



(c) Velocity orbit at KMMH16. Principle direction is almost parallel to Futagawa segment

Figure 4. Structural damage in downtown Mashiki and recorded motion at KMMH16.

SIMULATION ANALYSES OF NEAR-FAULT GROUND MOTIONS

Discussion has been made for why the pulse-type near-fault ground motions with large amplitude were generated, e.g., rupturing in deep and shallow part of seismic fault, site amplification in shallow and deep part of subsurface structure. Quantitative evaluation of amplification mechanism of pulse-type near-fault ground motions is important for predicting input ground motions to structures adjacent to seismic faults.

Strong ground motions during the mainshock at KiK-net Mashiki-machi (hereafter, KMMH16) are theoretically synthesized using the source process model by Hikima (2016) based on source process analyses in Figure 5.

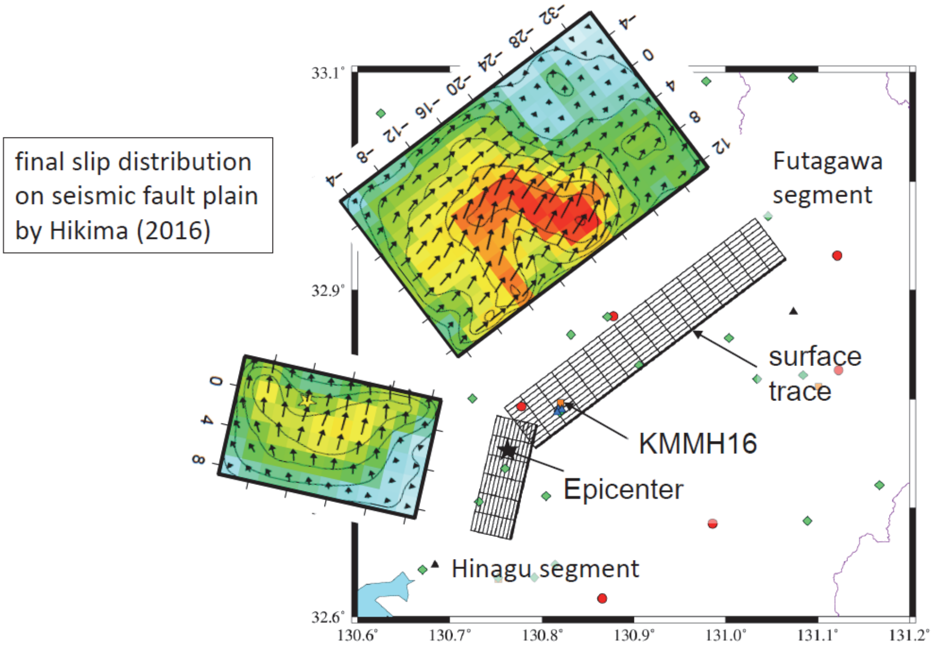
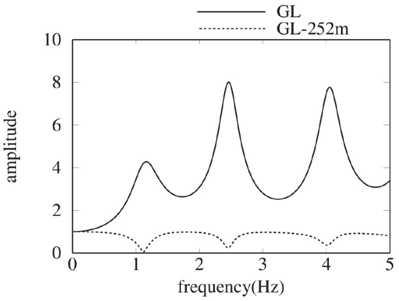


Figure 5. Seismic fault and source process model by Hikima (2016) based on wave inversion analyses

Layer No.	V_S (km/s)	V_P (km/s)	ρ (t/m^3)	thickness (km)
1	0.11	0.24	1.70	0.003
2	0.24	0.38	1.70	0.012
3	0.50	1.18	1.82	0.018
4	0.40	1.18	1.82	0.008
5	0.76	1.95	2.06	0.028
6	0.82	2.30	2.15	0.032
7	1.47	2.80	2.26	0.032
8	0.70	2.80	2.26	0.010
9	1.38	2.80	2.26	0.026
10	0.84	2.30	2.15	0.032
11	1.47	2.30	2.15	0.033
12	2.70	4.80	2.58	1.214
13	3.20	5.50	2.65	1.881
14	3.40	5.80	2.70	12.918
15	3.80	6.40	2.80	16.060
16	4.50	7.50	3.20	-

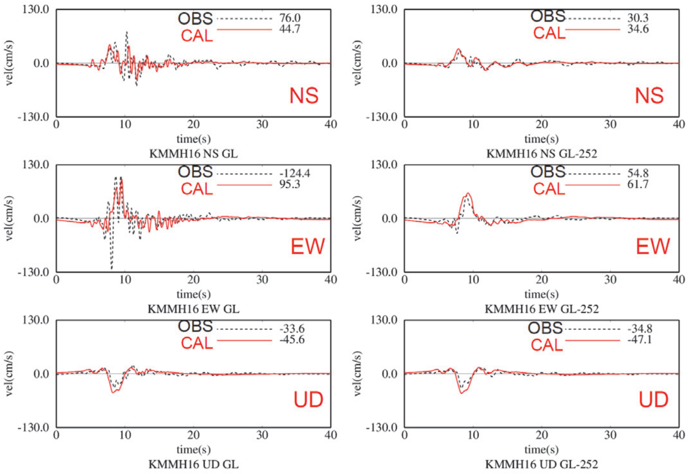


Amplification factor of subsurface structure above seismic bedrock with V_S=2.7km/s

Figure 6. Velocity structure model at KMMH16 and 1-D amplification factor of subsurface structure

Observed ground motions at the KMMH16 site during the main shock are calculated by using the TLM. Velocity structure model at KMMH16 in Figure 6 is referred from PS logging data at the KMMH16 site for the shallow part and the "preliminary nationwide velocity structure model"(The Headquarters for Earthquake Research Promotion, 2012) for the deep part.

Hikima (2016) estimated the rupture process model using the Green's function, which is evaluated only at the central points of 2km squared sub-faults, for the frequency range from 0.05 to 0.8 Hz. In this study, ground motions are calculated considering rupture propagation within 2km squared sub-faults including larger frequency range up to 2 Hz, because the ground motion with 1s is important in evaluating the pulse-type near-fault ground motions with large amplitude. To compensate amplitude of synthesized motions due to rupture propagation within sub-faults, all motions are adjusted by multiplication of factor 2, for simplicity. Figure 7 shows calculated velocity waveforms by the TLM compared with those by recorded motions at the KMMH16 site. Although the peak velocity in the EW direction on ground surface underestimates recorded motions, intensive pulse-like phase is well reproduced in all components at both ground surface and downhole. Notice that frequency component around 1 s.is rather underestimated, partly because the source process model used dot not guarantee the higher frequency component over 0.8Hz.



(a) Ground surface (b) Downhole(GL-252m)

Figure 7. Simulated velocity time histories of observed ground motions at KMMH16

EFFECTS OF SURFACE RUPTURE ON NEAR-FAULT GROUND MOTIONS

To estimate effects of surface rupture on ground motions at KMMH16 site, theoretical ground motions are calculated for source models with limited area of 10km in strike and 8km in dip direction just below the KMMH16 site as shown in Figure 8. In preliminary calculation, contribution of the Hinagu segment to ground motions at the KMMH16 site is found to be ignorable. Although the peak velocity in the EW direction is reduced by about 16%, pulse-like phase is almost consistent with those by the original source model in Figure 7. This implies that ground motions at the KMMH16 site can be reproduced only by shallow part of seismic fault of the Futagawa segment.

Figure 9 traces velocity waveforms in the EW direction at the KMMH16 site for the 20 sub-faults selected above as limited area of source model. In the forward sides of 20 sub-faults, short period motions are predominant, especially at the sub-fault just close to ground surface and the KMMH16 site. On the contrary, long period pulse-like motions are noticeable in the backward sub-faults. From these results, numerical precision of the Green's function is important in evaluating the theoretical near field ground motions.

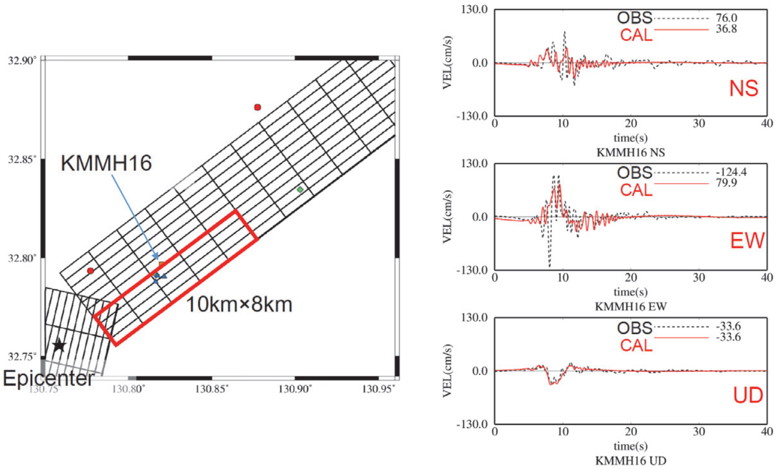


Figure 8. Limited rupture area of Futagawa segment and calculated ground motions at KMMH16

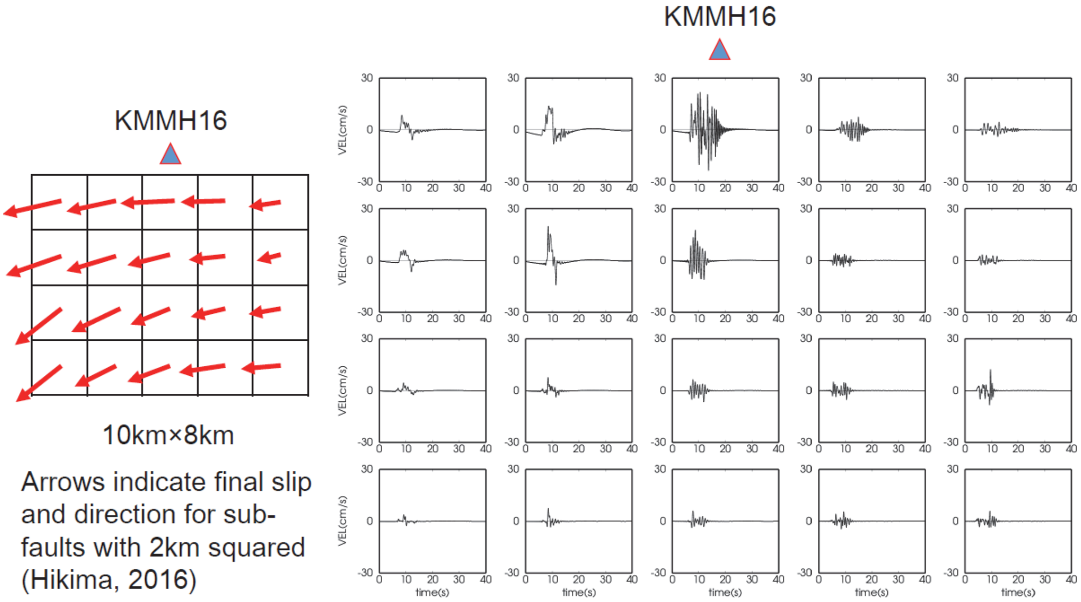
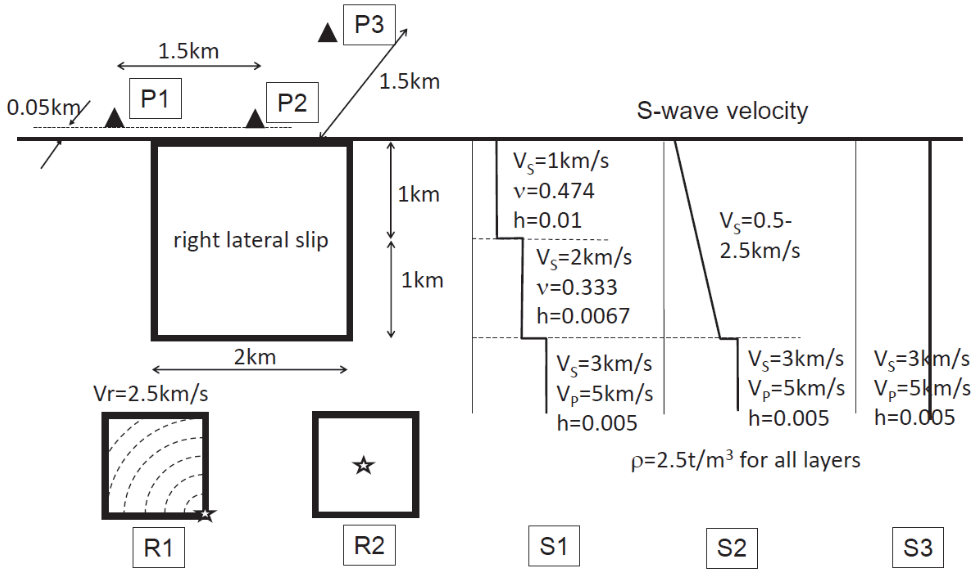


Figure 9. Contribution of 20 sub-faults to velocity waveform at KMMH16(EW)

NUMERICAL EVALUATION PRECISION OF NEAR-FAULT GROUND MOTIONS WITH SURFACE RUPTURE

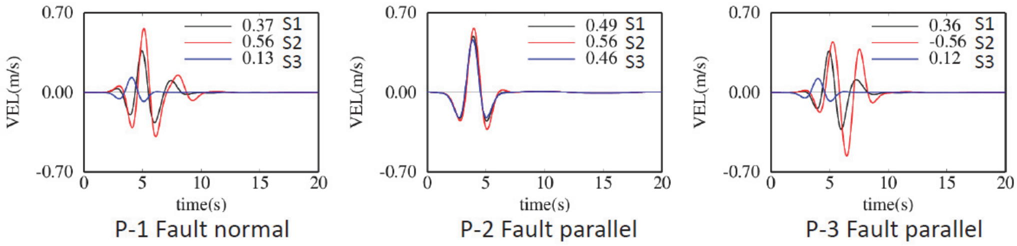
From the sensitivity analyses using the calculated ground motions at the KMMH16 site, numerical precision of the Green's function is found to be important in evaluating the near field ground motions with surface rupture. This fact is also essential in ground motion prediction for the nuclear power plants during the surface-rupture earthquake.

Ground motions are synthesized for several cases by combination of subsurface structures and source models with surface rupture. Figure 10 shows subsurface structures and source models used for sensitivity analysis on near field ground motions. For simplicity, we use 2km squared vertical fault with right lateral strike slip. We also assume two types of rupture pattern, i.e., rupture propagation case using 0.04km squared 2500 sub-faults and a point source at the centre of squared plane, and three types of velocity structures in Figure 10. Ricker wavelet with predominant period of 3 s is used for the slip velocity to avoid inadequate non-causal component due to static term.

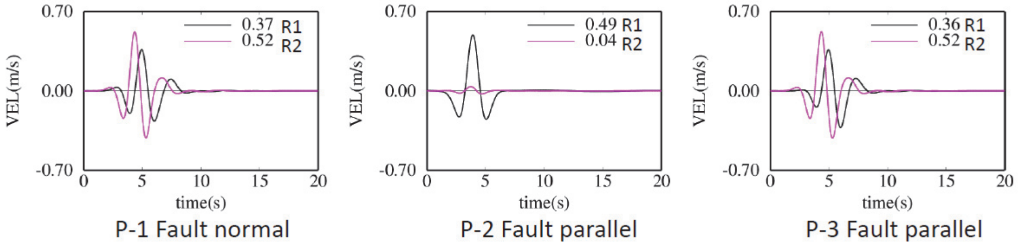


(a) rupture pattern (b) subsurface structure

Figure 10. Seismic fault and subsurface structure used for numerical evaluation precision.



(a) Effect of subsurface structure (R1)



(b) Effect of rupture propagation (S1)

Figure 11. Comparison of velocity waveforms for combination of rupture pattern and subsurface structures.

Velocity waveforms are traced in Figure 11 in fault-normal and parallel directions for combination of rupture pattern and subsurface structures. Ground motions just above centre of the seismic fault (P-1) is almost identical to the prescribed slip velocity function with half amplitude and difference for three types of subsurface structures is relatively small. Amplitudes of ground motions at P-1 and P-3 away from seismic fault depend on subsurface structures. The fault-parallel ground motion at P-1 for point source case (R2) is much smaller than that of rupture propagation case (R1). In numerical evaluation of ground motions adjacent to seismic fault with surface rupture, evaluation points of the Green's function is crucial rather than subsurface structures.

CONCLUSION

This study investigates numerical precision of the near-fault ground motions with surface rupture calculated by the thin layer method with special reference to the observed near-field pulse-like ground motions during the 2016 Kumamoto earthquake. Findings in this study are summarized as follows;

(1) Strong ground motions in downtown Mashiki are theoretically synthesized using the rupture process model based on waveform inversion analyses. Velocity waveforms at KMMH16 site are fairly reproduced in all components at both ground surface and downhole by using the thin layer method.

(2) Amplification mechanism is elucidated for rupturing in deep and shallow part of seismic fault. In the forward sides of sub-faults, short period motions are predominant, especially from the sub-fault closest to the ground surface at the KMMH16 site.

(3) Numerical evaluation precision of near-fault ground motions adjacent to a vertical strike-slip fault is investigated focusing on effects of rupture patterns, subsurface structure. Ground motions just above centre of the seismic fault is almost identical to slip velocity with half amplitude for any types of subsurface structures. In numerical evaluation of ground motions adjacent to seismic fault with surface rupture, evaluation points of the Green's function is crucial rather than subsurface structure.

ACKNOWLEGMENT

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REFERENCES

Tajimi, H. (1980). "A contribution to theoretical prediction of dynamic stiffness of surface foundations," *Proc. of 7th World Conference on Earthquake Engineering*, 5, 105-112.

Kausel, E. (1981). "An explicit solution for the Green's functions for dynamic loads in layered media," *Technical Report, Department of Civil Engineering, MIT,* R81-13.

Nagano, M. and Watanabe, T. (2007). "Improvement of calculation precision of theoretical ground motions using thin layer method and its verification," *AIJ J. of Technol. Des*, 13, 26, 451-456. (in Japanese with English abstract)

Hisada, Y. et al. (2012). "Benchmark tests for strong ground motion prediction methods using theoretical methods," *Proc. of 15th World Conference on Earthquake Engineering*.

Hikima, K. (2016). "Source process analyses for main- and fore-shocks using strong ground motions during the 2016 Kumamoto earthquake," *Proc. of 12th Annual Meeting of Japan Association for Earthquake Engineering*. P4-17. (in Japanese)

Maeda, T. and Kausel, E. (2012). "On the accuracy of some approximate antiplane half-space stiffnesses," *Bull. Seism. Soc. Am*. 81, 1340-1399.

Cerjan, C., Kosloff, D., Kosloff, R. and Reshef M. (1985). "A nonreflecting boundary conditions for discrete acoustic and elastic wave equations," *Geophysics*, 50, 705-708.

Hisada, Y, and Bielak, J. (2003). "A Theoretical Method for Computing Near-Fault Strong Motions in Layered Half-Space Considering Static Offset due to Surface Faulting, with a Physical Interpretation of Fling Step and Rupture Directivity," *Bull. Seism. Soc. Am*, 93, 1154-1168.

NILIM & BRI (2016). "Quick Report of the Field Survey on the Building Damage by the 2016 Kumamoto Earthquake," TECHNICAL NOTE of NILIM, 929, Building Research Data, 173. http://www.kenken.go.jp/japanese/contents/publications/data/173/index.html (in Japanese)

The Headquarters for Earthquake Research Promotion (2012). "Preliminary nationwide velocity structure model, "National Seismic Hazard Maps of long-period ground motions, (in Japanese)
http://www.jishin.go.jp/evaluation/seismic_hazard_map/lpshm/12_choshuki/

Wessel, P., Smith, W. H. F., Scharroo, R., Luis, J. F. and Wobbe, F. (2013). "Generic Mapping Tools: Improved version released," *EOS Trans.* AGU, 94, 409-410.