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LARGE SCALE SIMULATION OF GROUND MOTIONS FOR HETEROGENEOUS SOURCE MODELS BY FDM RECIPROCITY METHOD

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Abstract

For this study we used hierarchical heterogeneous source modeling procedure of Sekiguchi et al., 2008. This modelling approach is a result of compilation of many source observations (inversions) of strong earthquakes and allow easily generate possible variations of slip distributions. As a result, we can apply probabilistic approach to study generated ground motions. Namely, we can estimate effect of many heterogeneous source models that reproduce observed (inverted) slip patterns, and choose models that have average, average plus standard deviation, or certain probability of non-exceedance levels of strong ground motions (e.g. response spectra in period range of a target structure). Many models have to be calculated in this case. E.g., in order to estimate average plus standard deviation level we may need to calculate 30 models, and we will need 2-3 times more models, when need to choose specific source model that reproduce this level. We applied above methodology to study long-period ground motions in the Osaka sedimentary basin, Japan, from a hypothetical M9 earthquake in Nankai Trough, which has high probability of occurence within next 30 years. For computing long-period motions, we used detailed 3-D crust and basin velocity structure model JIVSM, developed for Japan. Simulation space is around 820km in EW direction, 550km in NS direction and 70km in depth, and shortest period to simulate is 3sec. It takes 3 days to calculate 300sec record by FDM. Because time consuming 3D-FDM method is used, in order to calculate many source models we employed reciprocity method.

For this simulations, we constructed multiscale heterogeneous source models based on the characterized source model of the Central Disaster Management Council of Japan (CDMC, 2012) and simulated long-period ground motions in period range 3-20 sec using FDM. Natural periods of many high-rise buildings and other construction structures, e.g. numerous suspension bridges around Osaka bay, fall into this period range. 300 source models are generated randomly from initial characterized source model. Source parameters, which have randomly generated heterogeneities, are: slip, rupture velocity *Vr* and location of SMGAs. Moreover, in order to account for variations of directivity effect, we generated ground motions for three cases of rupture start: in center of model and in west and east sides of model. In the deepest landward part of Osaka basin (site Konohana, depth of sediments 1500m) the ground motions at larger NS component are estimated to have peak velocities of 40–80 cm/s, prolonged durations exceeding 300 s, and long predominant periods of 5–10 s, and velocity response spectra for this periods of 190 cm/s in average, or 290 cm/s for average plus standard deviation. Effects of rupture heterogeneity (slip and *Vr*), SMGA location and rupture starting point are approximately equal: about 30% of average amplitudes of ground motions. Variations of amplitudes among all 300 models are around 50%.

Keywords: long-period strong ground motions; 3D finite-difference method, megathrust earthquake; reciprocity method

1. Introduction

Heterogeneous source models reflect heterogeneity of ruptures related to the heterogeneity of crustal medium. Hierarchical heterogeneous rupture is considered to be necessary to reproduce observed omega-square source spectra (e.g. [1, 2]). Several researchers applied this kind of source modelling to the strong ground motion simulations (e.g. [3, 4, 5]).

For some critical and/or dangerous structures, like nuclear power plants, suspension bridges or skyscrapers, it may be necessary to know largest possible input ground motion. Heterogeneous source modelling allow us to generate numerous distributions of slip and other target parameters, and select group of them that result in largest ground motion. In this way we can find a case that results in large amplitudes, which can happen considering random nature of earthquake, but cannot be predicted neither determenistically, considering complexity of rupture propagation, path and site effects, nor from past observations, due to limited observation time.

Prediction of strong ground motions is based on the source-path-site approach. In case of long-period ground motions, finite-difference (FD) simulation of path and site effects in 3-D velocity structure model is an accurate method. Since the work [6] characterized source modeling become standard for strong-motion prediction, because it use results of many seismic source inversions and accurate for reproducing of seismic waves. In characterized model, source area is divided into background area, having small slip, and in a few strong–motion generation areas (SMGA or asperity), having large slip. This approach introduces 1st level of heterogeneity into source modelling. However, smooth rupture of SMGA generally results in underestimation of ground motions. In [5, 7] there is made next step and introduce multiscale hierarchical heterogeneous source model, which accounts for all levels of heterogeneity of slip using fractal slip distribution with spectrum k^{-a}, where k is wavenumber, and $a \sim 2.0$. They also introduce heterogeneities into rupture velocity based on the work [8].

Large earthquakes in Nankai Trough, Japan, have stable period of 100-140 years. For this reason next Nankai and Tonankai earthquakes in Nankai Trough are expected in the next 30 years with a high probability around 60%. It is possible that both sources can be ruptured simultaneously and linked with Tokai and Hyuga-nada segments of Nankai Trough, resulting in *M*9 megathrust earthquake [9]. Such a giant earthquakes produce long-period strong ground motions, 3-10sec, that are amplified and elongated in sedimentary basins of Japan, hosting large mega-cities. Many large scale structures like high-rise buildings and suspension bridges, which are sensitive to long-period ground motions, are located in these cities. Osaka city in Osaka basin is one of them.

Precalculation of Green's functions for heterogeneous sources in complex 3-D velocity structure model is practically impossible. However, we can take advantage that in most earthquake engineering applications there is only one target site, and use reciprocity theorem (e.g. [10]). This theorem states that locations and orientations of source and site can be swapped and the same elastic response will be observed. Using reciprocity theorem, we are able greatly reduce the amount of computation and conduct a detailed study in a limited time.

In this work we apply the above approach to Konohana (OSKH02) site in Osaka basin. This site is located in the deepest landward part of the basin; depth of sediments is 1500m. Moreover, bay area where Konohana site is located, have many large scale structures sensitive to long-period ground motions: long highway bridges and high-rise buildings. One of them, high-rise Sakishima Building was damaged during the 2011 Tohoku earthquake, even though it is located 800 km far from the source.

Employed source models are multiscale heterogeneous source models constructed from the characterized source model of CDMC, 2012. Velocity structure is 3D Japan Integrated Velocity Structure Model (JIVSM, [11]). In order to simulate long-period ground motions from many sources at one site, we used FDM reciprocity method [12, 13] and adopted it for the case of extended source.

2. Source model

Multiscale heterogeneous source modelling procedure is described in detail in [7]. In this study we start source modeling by constructing initial source model by characterized source model from [9], see Fig.1. This source model is result of the seismic intensity modelling and fitting to observed data for several historical *M*8 class earthquakes: 1707 Hoei, 1854 Ansei Tokai, 1854 Ansei Nankai, 1944 Showa Tonankai, and 1946 Showa Nankai. Then, source models for the individual earthquakes are combined to a source of the largest possible *M*9 earthquake in Nakai Trough. Resulting model consists of 12 SMGA areas and background area, which cover plate interface between 10 and 40km depth. Tsunami generation area near the trench is excluded in this model.

Model from [9] consists of 1077 subsources that cover source area on a 10 km mesh. For this study we relocated subsources to the upper boundary of Philippine Sea subduction plate in the JIVSM model used in this study. Strike and dip angles are also adjusted to the plate shape. Fig.1 show slip distribution and indicates location of SMGAs numbered as follows: N1~N4 are SMGAs in Nankai segment, T1~T4 are SMGAs in Tonankai segment, H1 and H2 are SMGAs in Hyuga-nada segment, and S1 and S2 are SMGAs in Suruga segment. A grid at 440 m interval is generated over the source area taking into account target shortest period range of the modeling, which is 3 sec. Slip and rise time values are the same as in initial model. Rupture time is calculated assuming multi-hypo (black circles in Fig.1) rupture model and constant rupture velocity V_{r0} = 2.7 km/s.

Multi-scale heterogeneity is introduced both to the slip distribution and to the rupture velocity distribution of the initial source model by increasing or decreasing the respective values within randomly distributed, circular patches of multiscale sizes on the fault plane [7]. The magnitude of slip perturbation is chosen to be proportional to the radius of a patch, taking into account the power-law distribution in the wavenumber domain (according to [14]), while that of the rupture velocity is assumed to be random [8, 15]. These fluctuations are tunable, making reference to source inversion result statistics.

For this study, in order to demonstrate ability of reciprocity method to realize probabilistic approach of long-period motions prediction, we randomly generated next sets of source models: (1) 10 cases of random generator settings for slip and *Vr* distributions, (2) 10 cases of normal random shifts of SMGAs in fault plane, having standard deviation 10km (see Fig.2), which is approximately equal to uncertainty of SMGAs locations in the seismic intensity inversion results of [9], (3) 3 cases of rupture start: in center and in west and east parts of source (see Fig.1). 300 models were prepared in total. Fig.3 shows model example: heterogeneous distributions of slip and rupture velocity *Vr*.

3. Reciprocity method

Simulation approach, that is based on the scaled summation of pre-calculated and saved in computer memory Green's functions (GF), is an effective way to calculate ground motions for many source models. In order to calculate long-period GF we use 3D FDM method. This is accurate but time consuming method, because number of subsources usually large in source models of large earthquakes, especially in the multiscale heterogeneous source models. For example, our models consist of 570000 subsources, which should be multiplied by 2 for two rake angles used in simulation. Pre-calculation of GF become practically impossible in this case. In order to reduce simulation time we employed reciprocity method described in details in [12, 13], and adopted for GF calculations [16].

Reciprocity method calculates responses of the 3 point forces at the target site location, in X, Y and Z directions (see Fig.4). Resulted waveforms at each subsource are stored and manipulated then to make a subsource moment tensor response at the site. Only $3N_{site}$ FDM simulations are necessary in this case to calculate GFs for all subsources at all N_{site} sites. I.e. only 3 FDM simulations are necessary in this study, instead of 1140000 simulations.

In [16] we verified 3D-FDM reciprocity method on its validity for calculation of GF in Nankai Trough. To do this we simulated 3 point sources in different parts of Nankai Trough, having specific settings of seismic moment M_0, dip, strike and rake angles, and rise time T_{rise}. However, specification of dip, strike and rake angles for reciprocity simulations is not necessary on the FDM simulation stage, they should be specified in the moment tensor manipulation stage, which is faster. This is additional advantage of reciprocity method, because many dip, strike and rake combinations can be simulated just in 3 FDM runs. Fig. 3 of [16] shows waveform comparison of forward and reciprocal simulations for EW component. Considering uncertainty of 3D velocity structure itself, waveforms are practically the same.

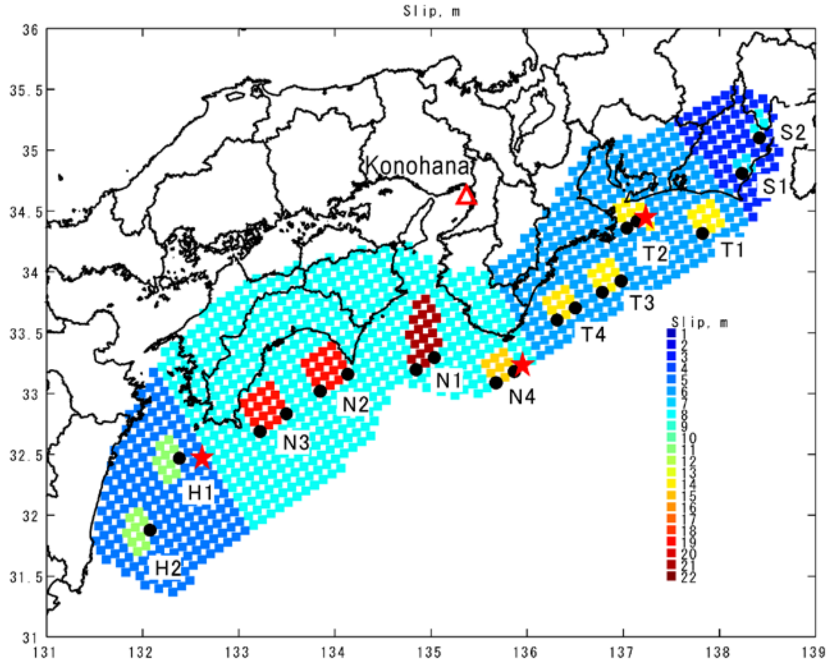

Fig. 1 – Slip distribution in characterized source model from [9] for M9 Nankai Trough earthquake. Lettered numbers indicate SMGAs for Hyuga-nada, Nankai, Tonankai and Suruga segments. Multi-hypo rupture model is used. Red star marks indicate rupture starting points (west, center and east), black circles – multi-hypo rupture starts inside each SMGA. Two multi-hypo rupture start points in some SMGAs (westward and eastward) indicate rupture starts for west and east ruptures respectively.

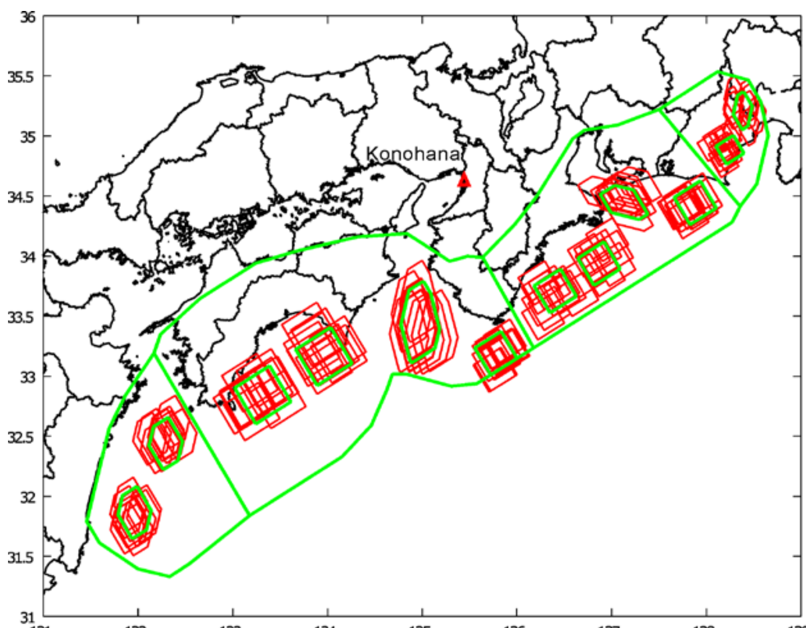

Fig. 2 – Randomized locations of SMGAs (red); SMGAs of characterized source model from [9] are also shown for reference (green).

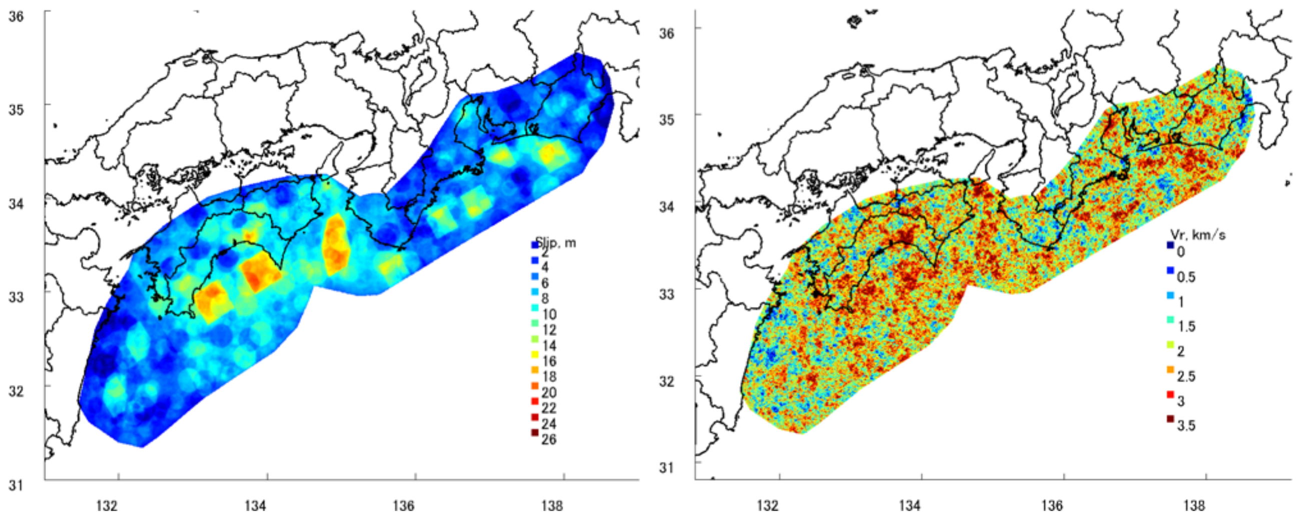

Fig. 3 – Examples of slip distribution in heterogeneous model (left) and rupture velocity *Vr* heterogeneities (right)

In this study, for simulation of ground motions from extended source, we used next GF summation procedure.

<u>Step 1.</u> Calculate and store to memory GFs $G(t)$ for 570000 subsources, using reciprocity method above. We assume dummy value of seismic moment M_{0_d} = 10^{20} Nm; strike, dip and rake angles the same as in heterogeneous models; source time function is modified (low-pass filtered) from [17] and dummy value of rise time is T_{rise_d} = 5.0sec. This source time function corresponds to the function from dynamic simulation of the 2011 Tohoku earthquake (M = 9) in [18] that employs SMGA model from [19].

<u>Step 2.</u> At the FDM step of reciprocity method we can calculate GFs only for one value T_{rise_d}. In order to calculate GFs for target values T_{rise}, which are variable over the source, we calculated Fourier spectrum of GF for T_{rise_d} and then converted it to Fourier spectrum for target T_{rise} using Eq. (1):

$$G_i(f) = G_d(f) \cdot \frac{S(f \mid T_{rise\_i})}{S(f \mid T_{rise\_d})}, \tag{1}$$

where $G_i(f)$ is spectrum of GF at i^{th} subsource, $G_d(f)$ – spectrum for dummy T_{rise_d}, $S(f| \, T_{rise\_d})$ and $S(f| \, T_{rise\_i})$ are spectra of source time function from [17] for dummy and target (i^{th} subsource) values of rise time respectively. Then we made reverse Fourier transform to calculate GF for i^{th} subsource, $G_i(t)$.

<u>Step 3.</u> Make summation of pre-calculated GFs:

$$V(t) = \sum_{i=1}^{N} G_i(t - t_{r\_i}) \cdot \frac{M_{0\_i}}{M_{0\_d}}, \tag{2}$$

where $V(t)$ is simulated velocity record, t_{r_i} and M_{0_i} – rupture time and seismic moment for i^{th} subsource, N = 570000 – number of subsources. We assume $G_i(t)$ / 0 for $t < 0$.

Fig. 7 below shows comparison of results of forward and reciprocal simulation for source model in Fig. 3. Horizontal waveforms and response spectra are practically the same. However, reciprocal result for vertical component is slightly underestimated. Special treatment may need for accurate FDM simulation of waveform in case of the point source near the ground surface.

We should notice that time consuming 1st and 2nd steps can be done in advance and results stored into memory. Multiscale heterogeneous sources in this study differ by M_{0_i} and t_{r_i} distributions. Calculations in Step 3 are fast and waveforms for many source models can be easily calculated on a desktop computer.

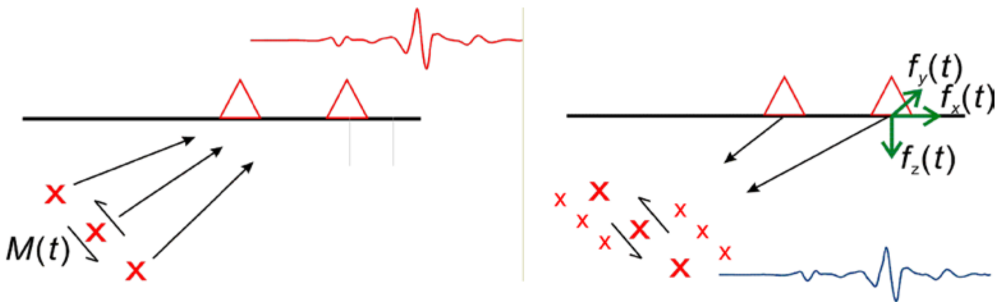

Fig. 4 – Sketch of waveform calculation in forward (left) and reciprocal (right) approaches

4. Velocity structure

For 3-D velocity structure we used well calibrated and waveform tested JIVSM model [11, 20]. Moreover, this model combines both sedimentary (basin) and crustal structure models and is ready to use for long-period simulations. This model consists of 23 layers and employs Osaka basin model from [21] and the Philippine Sea subduction plate interfaces and Accretion wedge model from [22]. Fig.5 shows *Vs* cross-section of the JIVSM model through the source area and target Osaka basin. Soft sediments of Japan Sea, Osaka basin and Accretion wedge are indicated in blue. Two layers of the Oceanic crust are dipping in right side of lower plot from right to left.

For this study we made further improvements of velocity structure and embedded new Osaka basin structure [23], see Fig.6, into JIVSM model. In contrast to model [21], which is simply compiled from many data into 3-layer spline model, in [23] spline model is tuned using linear waveform inversion. As a starting model they employed Osaka basin model [24], which is extended version of the model [21] and use the same principles. Target periods for waveform inversion are 3-10sec, which perfectly fits the needs of this study. For testing of new velocity structure model we simulated surface/basement spectral ratios and compared them with observed spectral ratios for surface and 1500m depth bottom-of-borehole seismometers at Konohana site during the 2011 Tohoku earthquake. The fit of spectral ratios is good.

5. Simulation and results

3-D simulations here were carried out by the conventional staggered grid fourth-order FDM scheme with a non-uniform grid size [25, 26]. This approach allow easy introduce seismic source and carefully consider the effects of sedimentary layers. The shortest target period in the simulations was 3.2 s. Smallest shear-wave velocity value in JIVSM model (shear-wave velocity of the uppermost soft sedimentary layer in Osaka basin having around 500m depth), that define grid size vs. target period combination, is 350 m/s. Finite difference grid size in horizontal directions was 220 m (5 grids for the shortest wavelength). In depth direction, non-uniform grid size was used. For the sedimentary layers shallower than 4200 m (deepest level of soft oceanic sediments in target area) grid span was designed to be 150 m. For seismic basement and hard oceanic sediments, grid span was 300 m (shallower than 9200 m and deeper than 4200 m). The rest of the model had grid span 600 m. The depth of calculation volume was 70000 m. For the calculations we used 24000 time steps at 0.0125s time interval.

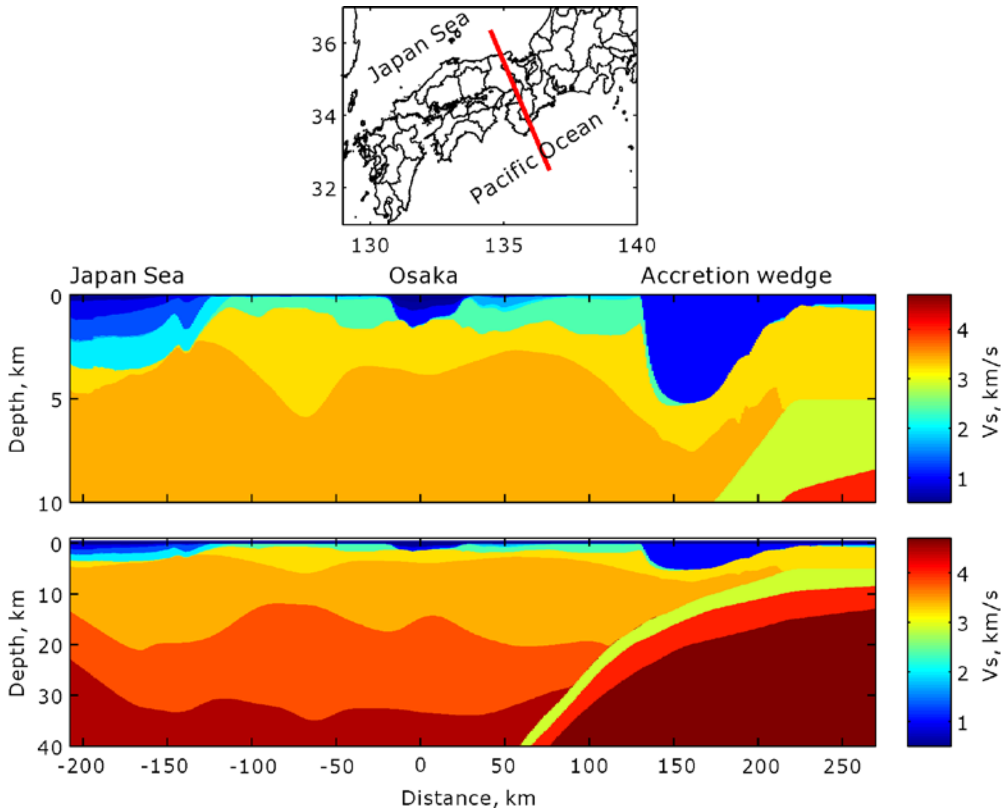

Fig. 5 – Cross-section of the crustal structure model through Osaka basin. Red line on the upper plot indicates location of cross-section. Middle plot show details of sedimentary layers and lower plot show the whole structure.

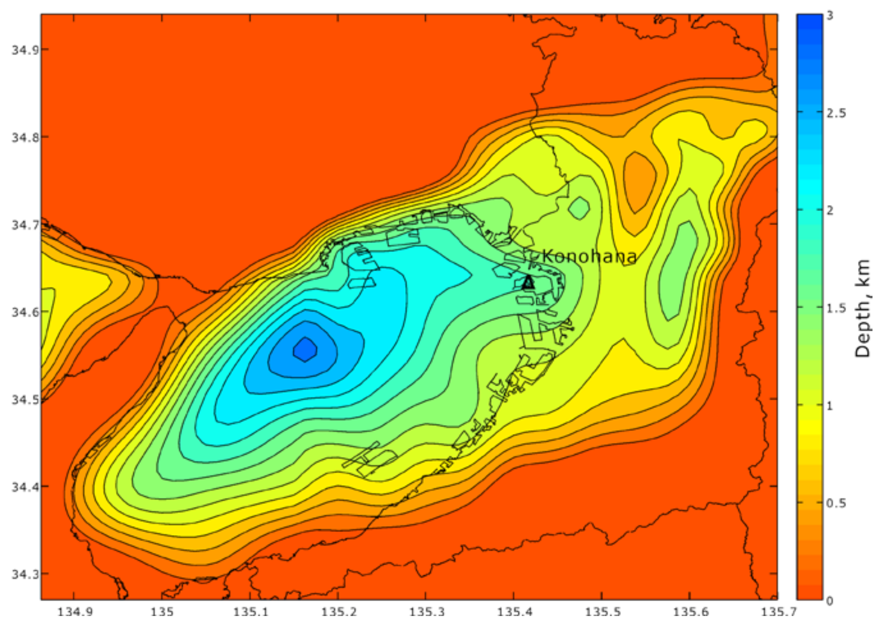

Fig. 6 – Osaka basin structure model: depth of basin rock basement (Vs = 5.5 km/s)

Heterogeneous source models produce results in a wide range of simulated peak amplitudes and response spectra. In some extreme cases amplitudes can be very large; however probability of their occurrence is very low. Probabilistic approach is an effective tool to predict ground motions in this case. First we should assume allowable conditional probability P of failure, in case of the M9 earthquake in Nankai Trough will occur. It can be relatively large for inhabited buildings and small for important structures (public buildings, government offices, power plants, etc.). Then we can estimate number of source models that are necessary to estimate ground motions for assumed value P. For accurate estimation of target level of ground motions we may need at least N_{src_min} = 5 cases that exceed this level. Than we can estimate number of necessary models N_{src} as:

$$N_{src} = N_{src\_\mathrm{min}} / P \, , \tag{3}$$

This gives us N_{src} = 10 for P = 0.5 (average value), N_{src} = 30 for P = 0.16 (average + standard deviation), or N_{src} = 100 for P = 0.05 (in case of important structure).

In this study we estimated response spectra for average and average + standard deviation level. For this we calculated velocity waveforms and Sv response spectra for 3 cases of rupture start: central, west and east rupture (see Fig.1), 10 cases of normal random shift of SMGAs in a distance having standard deviation 10 km (see Fig.2), and 10 cases of random distributions of slip and Vr. 300 cases are simulated in total. Waveform example is shown in Fig.7 and results for response spectra of all 300 cases are shown in Fig.8.

At Konohana site the ground motions are estimated to have prolonged durations exceeding 300 s, and long predominant periods of 5 sec at EW component or 5–10 sec at NS component. Velocity response spectra for these periods are 150 cm/s in average, or 240 cm/s for average plus standard deviation at EW component and 190 cm/s in average, or 290 cm/s for average plus standard deviation at NS component. Peak velocities at EW component are in a range 30–60 cm/s, at NS component are in a range 40–80 cm/s

Comparison of resuts for different points of rupture start in Fig.7 demonstrates that due to directivity effect amplitudes of response spectra can differ +/-50 cm/s. Largest amplitudes are simulated for periods 4-6 sec of the West rupture. Amplitudes of East rupture are the smallest at all periods. Comparison of average response spectra for 10 cases of random locations of SMGAs in Fig.8 demonstrates that some extreme cases of large amplitudes, around 300 cm/s, are possible. This result confirms our previous result [16] that due to anomalies in distribution of GF amplitudes, even a small shift of SMGA can result in large increase of simulated amplitudes. Although beign possible, such cases are rear and their influence should be evaluated on the probabilistic base.

6. Discussion

Source heterogeneities is result of heterogeneous medium of rupture propagation and for this reason shouldn't be limited to slip and rupture velocity, but also should include other heterogeneities of kinematic source parameters: rise time and rake angles (e.g. [27]). Strike, dip and depth of subsources are related to the fault shape and may be fixed.

It is important to compare effects of heterogenity of different parameters: slip, Vr, Trise or rake angle, on the estimated ground motion level in comparison with the homogeneous model. In this case we understand which of the parameters require detailed study. Here, we tried to compare ground motions of four models having: homogeneous slip and Vr, heterogeneous slip and Vr, heterogeneous slip and homogeneous Vr, homogeneous slip and heterogeneous Vr. It is found that of Vr heterogenieties is much larger than effect of slip heterogenieties. This is expected result. Spectrum of slip heterogenieties is of the order of k^{-2}, i.e. small scale heterogenieties has small amplitude and small effect on the ground motions respectively. From another side, large scale and large amplitude heterogenieties (SMGAs), that have large effect on the simulated ground motions, are already included in the characterized source model. This finding initiated detailed study of Vr [15] that confirmed initial assumption in [5] on the random distribution of Vr having k^0 spectrum of heterogenieties.

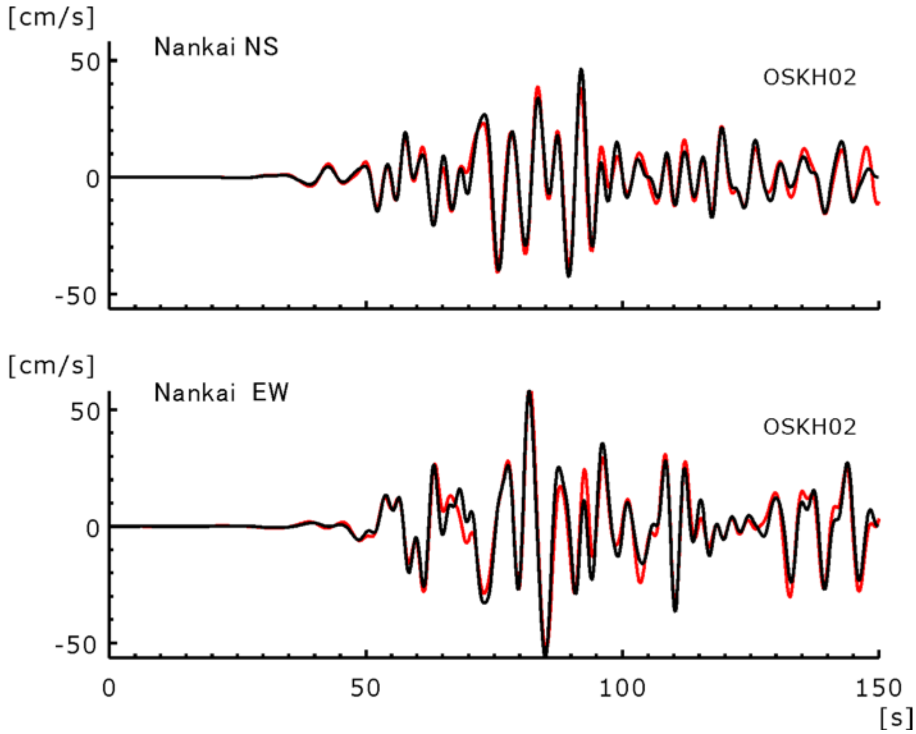

Fig. 7 – Test of reciprocal approach for site Konohana. Waveforms for two horizontal components are calculated using forward (black lines) and reciprocal (red lines) methods; source model in Fig. 3 is used

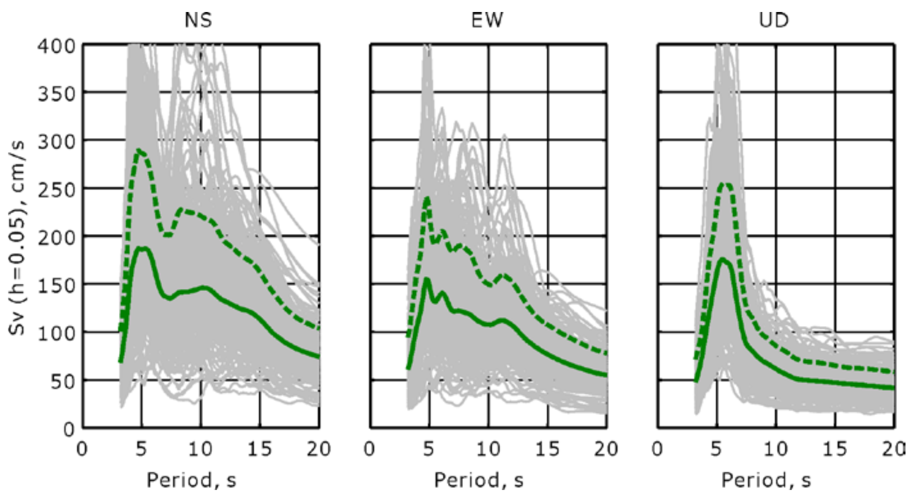

Fig. 8 – Velocity response spectra for all 300 simulated heterogeneous source models (grey lines), and their average (solid green line) and average + standard deviation (dashed green line) spectra

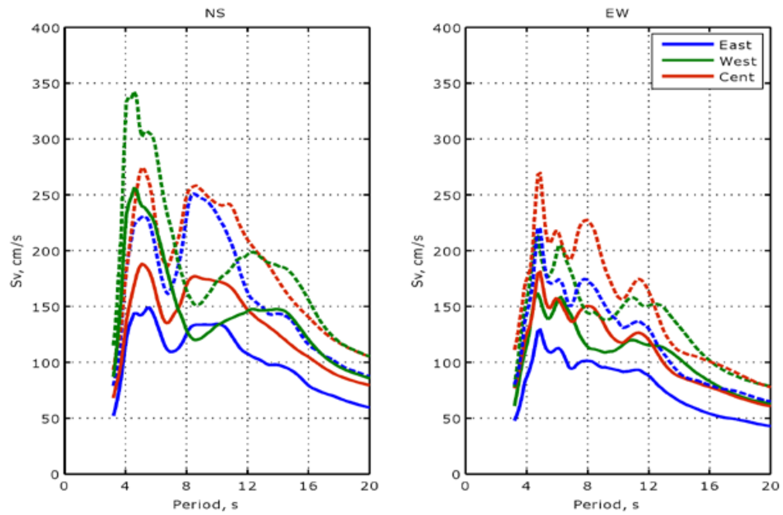

Fig. 9 – Comparison of velocity response spectra for central (red), west (green) and east (blue) ruptures. Solid lines are average, dashed lines are average + standard deviation values.

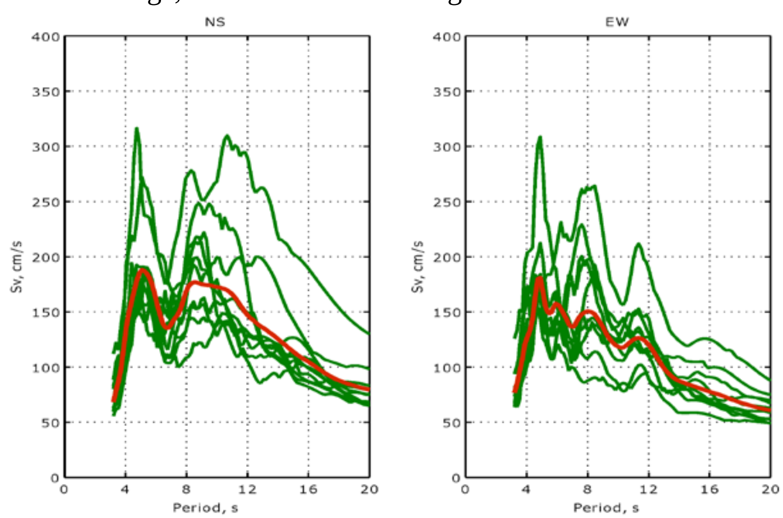

Fig. 10 – Average velocity response spectra for 10 random locations of SMGAs, central rupture (green lines). Average spectra for all cases of central rupture (red) are shown for reference.

Parameters of heterogenieties used in this study, *k*-spectra and standard deviations, are estimated from the seismic source inversion results. In this way we can expect that the simulated ground motion reproduce observed motions. However, detailed check and tuning of parameters, similarily to [27], may be necessary for practical applications. Moreover, [14, 15] used inversions of inland earthquakes to estimate parameters of heterogenieties. Additional study is necessary for subduction earthquakes.

In most cases heterogeneous models have larger amplitudes than initial characterised model. This is effect of the normalization of source spectra to the omega-square model, see example in Fig.6 of [5]. However, opposite tendency is possible, e.g. due to destruction of the directivity pulses by the heterogeneous (*Vr*) rupture propagation.

Another reason of the increased amplitudes is the correlation between *Vr* and slip values assumed in model [5], and adopted here. Although this is frequently used assumption (e.g. [27]), there are almost no direct evidences. From source inversion results [28] found evidnces of spatial coherence between slip and *Vr*. However, in most their examples coherence is shifted in space; i.e. large *Vr* values are observed not in the same place where large slip is observed, like in our case, but shifted for a few kilometers.

By Eq. (3) above we estimated number of heterogeneous models that are nesessary to simulate in order to get accurate estimate of response level at a target probability *P*. However, having only 5 models that exceed *P*-level, it may be difficult to select model that perfectly fit estimated *P*-level. Best fit model will lead to overestimation or underestimation of the target level. In order to get good fit, especially in wide period range, it may be necessary to simulate several times more models than estimated by Eq. (3). Reciprocity method is perfect to deal with such situation too.

7. Conclusions

1. We applied reciprocity method for large scale 3D-FDM simulations of long-period ground motions from the megathrust earthquake in deep sedimentary basin. We demonstrate that reciprocity method has good performance in case of probabilistic approach, which requires simulations for many randomly generated source models, is used for estimation of ground motions at a target level of probability of non-exceedance.
2. Long-period (3-10 sec) ground motions from hypothetical megathrust earthquake in Nankai Trough are simulated for deep sedimentary site Konohana in Osaka basin, Japan. For this, 300 heterogeneous source models are generated randomly from initial characterized source model. The last one is the largest case of source models that reproduce observed historical distributions of seismic intensity. Source parameters, which have randomly generated heterogeneities, are: slip, rupture velocity and location of SMGAs. Moreover, in order to account for variations of directivity effect, we generated ground motions for three cases of rupture start: in center of model and in west and east sides of model.
3. Simulation results demonstrate that effects of rupture heterogeneity (slip and *Vr*), SMGA location and rupture starting point are approximately the same, about 30% of average amplitudes of ground motions. Variations of amplitudes among all 300 models are around 50%.

8. Acknowledgements

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