Source Modeling for Long-Period Ground Motion Simulation of the 1946 Nankai Earthquake, Japan

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SUMMARY

Long-period ground motions over 2 seconds due to the 1946 Nankai earthquake are simulated. Minute 3-D crustal and sedimentary structure model developed for the purpose is employed for the simulation. Source model of the earthquake is reconsidered through source inversions with Green's functions calculated from the 3-D structure model.

Keywords: The 1946 Nankai earthquake, Japan, Source Inversion, 3-D Green's function

1. INTRODUCTION

Among earthquakes, repeatedly rupturing along the Nankai trough, source of the M8 class Nankai earthquake covers segments from cape Shiono-misaki to cape Ashizuri-misaki, southwest Japan. The last event was the 1946 Nankai earthquake (the Showa Nankai earthquake). Considering that average interval is 110 years, probability of occurrence of the next Nankai earthquake within next 30 years is estimated about 60% (HERP, 2011).



Figure 0. Target area for long-period ground motion modeling. Dashed lines: Nankai Trough and source area of Nankai and Tonankai earthquakes. Circled numbers are major sedimentary basins and structures: 1:Mikawa, 2:Nobi, 3:Ise, 4:Ohmi, 5:Kyoto, 6:Nara, 7:Osaka, 8:Wakayama, 9:Tokushima, 10:Kochi, 11:Yonago, 12:Oita, 13:Miyazaki, 14:Aso-Kushu volcanic area, 15:Unzen volcano.

In this study, long-period ground motions due to the earthquake are simulated assuming that the next Nankai earthquake will be similar to the 1946 Nankai earthquake relatively well recorded and studied in details. Simulation approach is similar to the simulation of the 1944 Tonankai earthquake (HERP, 2009), but employing additionally calibrated 3D velocity structure model and 3D source inversion



results. Source model of the 1946 Nankai earthquake of Murotani (2007) is revised, and 3-D velocity structure model, verified by simulation of 2 s and more ground motion waveforms, is used for simulation of the long-period ground motions. Observed seismic records of the 1946 Nankai earthquake are well reproduced that demonstrate appropriateness of both employed source model and velocity structure model. **Figure 1** shows the target area of this modeling that includes the source area of the Nankai and Tonankai earthquakes. Major basins are numbered in the panel.

2. PRINCIPLES OF THE SOURCE MODELING

Generally, in comparison with the inland crustal earthquakes, plate boundary subduction earthquakes have lager magnitude and shorter recurrence interval. For this reason, many research results were related to the repeating rupture of asperities of plate boundary earthquakes and some examples of periodic rupture of the same asperity are presented recently in Japan, especially in the Tohoku region (e.g., Nagai et al., 2001; Yamanaka and Kikuchi, 2004) before the 2011 Off the Pacific Coast of Tohoku Earthquake (Mw 9.0).

Asperity is a part of fault rupture area providing large slip during earthquake and due to this generating intensive ground motions. Recent source modeling is based on the estimation of slip distribution using waveforms inversion. Murotani et al. (2008) compiled results of waveform inversions of plate boundary earthquakes in Japan and studied scaling relations of source parameters vs. seismic moment. Their results demonstrate that the fault area and total area of asperities of plate boundary earthquakes are in general a few tens of percentage larger than similar parameters for inland crustal earthquakes (Somerville et al., 1999) assuming the same seismic moment. In contrast, ratio of total asperity area to the fault area and similar ratio of slip are the same as for crustal earthquakes.

In this study, for preparation of the Long-Period Ground Motion Hazard Map, we apply next procedure to the source modeling of the Nankai plate boundary earthquake. Assuming that asperities repeatedly rupture the same area and knowing that 1946 Nankai earthquake is the previous Nankai earthquake, we will use previous event inverted source model as the target source model for mapping or predicting the ground motions. However, observed strong-motion records of the 1946 Nankai earthquake are scarce and many of them are saturated at large amplitudes. Murotani (2007) digitized these records and used them for the source inversion, but reproduced details are not enough to explain ground motions having periods shorter than 5s. In order to map a shorter-period ground motions using the previous event source modeling. Consequently, for periods longer than 5 s the previous event source modeling. Consequently, for periods longer than 5 s the previous event source model of the 1946 Nankai earthquake can reproduce observed data, but for shorter periods we have to pay attention that the calculation is not well constrained.

3. JOINT INVERSION OF SEISMIC WAVE FORMS AND GEODETIC DATA

HERP (2001) already made evaluation of the source regions of the Nankai trough earthquakes. In recent years, the problem of reevaluation raised due to new results on the depth of the plate boundary (e.g., Sato et al., 2005). For hazard map in this study, we modeled source of the 1946 Nankai earthquake using the source spreading above Philippine Sea upper plate interface estimated with seismic exploration results of a dense network of profiles. The occurrence potential of the next M8.4 Nankai earthquake is high: approximately 60% within the next 30 years beginning from 2011 (HERP, 2011). Murotani (2007) made source inversion of the previous 1946 Nankai earthquake using joint inversion of near field strong motion, teleseismic and geodetic leveling data. Murotani (2007) used 1-D velocity structure model tuned separately for each strong ground motion site.

Here we improve this model using Green's functions from 3D velocity structure model and use it for the long-period ground motion simulation. The 3D velocity structure model is derived as follows. For mountain areas outside of sedimentary basins, uppermost crustal layer is added above the seismic

basement layer, and the thickness is calibrated in such a way to adjust simulated amplitudes to the observed amplitudes (Petukhin et al., 2012). It is confirmed that with the used uppermost crustal layer we can reproduce some independent observation data, for example results of refraction experiments, gravity anomaly observations and receiver function inversions. Basin structure model is also improved by the R/V spectral ratio modeling at strong motion sites in addition to the included well studied large basins like Osaka basins, and the newly developed Kochi basin model. Underground structure model is verified by the waveform simulations of many small-to-middle size earthquakes occurred and observed in the target area.

It is assumed that rupture of the 1946 Nankai earthquake started from south off the Kii peninsula and mainly propagated toward western direction. We re-inverted source model using source settings of Murotani (2007) (**Figure 2**) and minutely elaborated 3D crustal structure model of Petukhin et al. (2012) and basin structure model of Iwata et al. (2008) and Koketsu et al. (2008). Results of the inversion, as shown in **Figure 3**, indicate that slip on asperity is slightly larger than slip in model of Murotani (2007), but its location approximately the same. Moment magnitude Mw 8.4 is estimated. Average stress drop is 1.18 MPa, which is smaller than 3.0 MPa value assumed for the hypothecated Tokai earthquake, but similar to 1.23 MPa value used in the Tonankai earthquake long-period ground motion simulation (HERP, 2009), and stress drop values in another Nankai earthquake source models (e.g., Satake, 1993). In analysis of Murotani (2007) fault surface is divided into 20km square subfaults; depth, strike and dip angles are elongated to the subducting plate interface. Point source models of subfaults are located 1 km above the upper interface of the Philippine Sea plate.



Figure 2. Assumed fault model by Murotani(2007). The local strike and dip angles, and subfault depths fit upper surface of the Philippine Sea plate model (solid contours).



Figure 3. Inverted source model (base model): distribution of slip (contour), stars – aftershocks of the 1946 Nankai earthquake (MJMA >3) within one month.

Although spectral content of observed records of the 1946 Nankai earthquake have periods 2 seconds and more, amplitudes of many records are clipped and observation density in that time was limited.

For this reasons slip model shown in **Figure 3** is the previous event base source model valid for periods 5 seconds and more. In order to simulate 2 seconds and more ground motions, we modified source model using the approach of Miyake et al. (2001): a short pulse is added to the peak of source time function of each subfault. In this case, pulse amplitudes are tuned in such a way to extend reproduction limit of observed amplitudes of the 1946 Nankai earthquake from 5 to 2 sec. (**Figure 4**). The figures show performance of the source and ground structure model that represent observed ground motions. However, because in the 2 to 5 seconds period range observation data was insufficient, it is necessary to understand that constructed source model is just one of the possible models that can explain existing limited data.



Figure 4. Comparison of displacement amplitude spectra for Kyoto (KYT) and Miyazaki (MYZ) sites: observed (green), base source model (orange) and final source model with the short period pulses (red).

4. RESULTS OF LONG-PERIOD GROUND MOTION SIMULATION

Based on the results of simulation we calculated distributions (maps) of peak ground velocity (PGV), relative velocity response spectra and duration. Figure 5a shows distribution of PGV amplitudes of horizontal components, which are the direct result of simulation. Figure 5b shows examples of velocity responses for period 5seconds. At this period, especially large response amplitudes are expected in the Osaka and Nobi basins that are relatively close to the source and have deep sedimentary layers. At period 3 seconds, large response amplitudes are expected in Miyazaki basin also. With increasing of target periods to 7 or 10 seconds, large amplitudes are expected in lower Yoshino river basin in Tokushima prefecture. In addition to the large amplitude in the Osaka, Nobi and Yoshino river basins above, long duration ground motions are expected also in the Nara basin and Biwa Lake surroundings (Figure 5c). For the location of basins, see Figure 1 above.



Figure 5a. Distribution of the simulated peak ground velocities of horizontal components. Contour lines indicate slip distribution of the source model and star symbol shows rupture starting point.



Figure 5b. Distribution of the 5 seconds relative velocity response with 5% damping.



Figure 5c. Distribution of the duration that PGV does not fall below 1cm/s.

Figure 6 shows velocity response spectra at three sites in Osaka Plain. The sites locate in different conditions. The western site Osaka Maishima is in Osaka bay area and the eastern site HigashiOsaka City Office is in a small basin. Both sites locate on thick sedimentary deposit. On the other hand the centre site Osaka Prefectural Office is on an underground ridge with thinner sediments. The ground motion at the centre site is smaller than those of the other sites. Long period ground motions around the period of 7 seconds are dominant at thick sediment sites; however they are not remarkable at the centre site. Since long period ground motion is strongly affected by the underground structure, predominant period and amplitude change quickly even within a small area.

Examples of 2 to 20 seconds three component waveforms are shown in **Figure 7**. The left traces are simulated waves at the Osaka Maishima site; western site in **Figure 6**, and the right panel is for the Osaka prefectural office site; center site in **Figure 6**. Very long duration of large ground shaking is estimated at the site on thick sediments. Similar large amplitude and long duration waves are simulated at the sites in the red color areas in **Figures 5a-5c**.



Figure 6. Velocity response spectra at three sites in Osaka Plain. Red contours show bedrock depth distribution and numbers indicate depths in kilometre.



Figure 7. Example of velocity waveforms for the Osaka Maishima site (left) and Osaka prefectural office site (right).

Kamae and Irikura (1994) simulated broadband ground motion of the 1946 Nankai earthquake at JMA observation sites by the empirical Green's function method and verified the results with the observed JMA intensities. Our simulated long-period ground motions cover the results of Kamae and Irikura

(1994) for pseudo velocity response spectra longer than 2 seconds at OSA and WOS sites in Osaka Plain (**Figure 8**), both in amplitude level and predominant periods. This suggests that our results are able to reproduce the long-period shake map due to the 1946 Nankai earthquake.



Figure 8. Comparison between simulated response spectra (red) and results of the empirical green's function simulation after Kamae and Irikura (1994) for JMA OSA and WOS sites in Osaka Plain.

5. DISCUSSION AND CONCLUSIONS

In contrast to the previously simulated Long-Period Ground Motion Hazard Map (HERP, 2009), which was made for periods 3.5 seconds and more, considering engineering needs to extend simulations to shorter periods, in this study long-period ground motion simulations were made for periods 2 seconds and more. For this, considerable improvements of the source modeling and underground velocity structure modeling were realized.

Previous studies use simplified 1D velocity structure models under observation sites for the source waveform inversion. We realized waveform inversion using 3D realistic underground structure model. Errors between observed and synthesized waveforms are drastically decreased. Although spectral content of observed records of the 1946 Nankai earthquake have periods 2 seconds and more, amplitudes of many records are clipped and observation density in that time was limited. For this reasons source inversion is realized for periods 5 seconds and more. Then, final source model of the Nankai (Showa type) earthquake is constructed through adding of the 2 seconds and more short-period content to the source inversion result and adjusting its spectral amplitude to the amplitude of observed records. In comparison to the 3.5 seconds simulations of the Tonankai earthquake (HERP, 2009), in this study, for simulation in a larger target area and in the extended to 2 seconds short-period, short-wavelength range, volume of calculations increased 20 times. We had to apply special measures to realize larger scale calculations.

As a result, it become possible to get well verified Long-Period Ground Motion Hazard Map for western Japan as the result of simulation of the Nankai (Showa type) earthquake. Moreover, due to simulation in 2 seconds and more extended period range, it become possible to calculate response amplitude map for period 3seconds. It allows a wider engineering application of the hazard map. However, because in many small basins that did not yet studied and modeled, it is hard to say that accuracy of basin response is well verified. For this reason it is necessary to continue observation, analysis and modeling for such basins.

As for the source model, estimated by the source inversion previous event base source model was valid for period range 5seconds and more. Shorter period content is modeled referring to the characterized source modeling approach. Consequently, it is necessary to recognize that at this moment source model does not cover completely 2 seconds and more ground motions due to the Nankai earthquake (Showa type) as a previous event source model. For improvement of accuracy of the shorter period source modeling, a wide field for studies is left, for example, by analysis of new records of the 2011 Off the Pacific Coast of Tohoku Earthquake (Mw 9.0).

Finally we have to mention that Showa type of the Nankai earthquake is a small scale example of earthquakes occurred in the target region in the past. In case of simultaneous occurrence of this earthquake with Tokai and Tonankai earthquakes (like the Hoei earthquake occurred in 1707), somewhat larger long-period ground motions are expected. In the next step, referring to the 2011 Off the Pacific Coast of Tohoku Earthquake as an example, it is highly required to investigate long-period ground motions assuming a larger simultaneous type earthquake.

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