Free oscillations of the 2011 Tohoku earthquake: source models and the GOPE data

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Summary

The March 11, 2011 Tohoku earthquake together with 2004 Sumatra-Andaman and 2010 Maule are the three largest earthquakes recorded during the last decade. Such extraordinary events generate clear signals with a broadband content that is rich enough for both detailed structural studies associated with the eigenfrequencies of the Earth and source studies based on body wave amplitudes (Park et al., 2005, Oiki and Stein, 2009). Because of the complexity of the source region of such events their Mw magnitude estimates are subject to substantial uncertainty.

The aim of this study is to test several published fast source solutions of the 2011 Tohoku earthquake in the low-frequency range (~1.3 Hz) using data from a superconducting gravimeter at the Geodetic Observatory Pecny (GOPE) (49° N, 14° E) in the epicentral distance of 81°.

Data from SG and BB

The superconducting gravimeter (SG) OSG-650 with the sampling frequency of 1 Hz was installed at the GOPE station in February 2009. The new instrument allows to study a number of geodynamic phenomena towards both higher frequencies (i.e., free oscillations of the Earth, long-period seismic waves) and the lower frequencies (e.g., environmental effects, long-period tides). In May 2009 the broadband seismometer (BB) OSG-1TD was installed in a new steel-case 60 m deep borehole in immediate vicinity to the gravimeter. We have used this collection of two modern instruments to calculate and compare amplitude spectra of the records from both instruments. Data from the SG were corrected for bias and pressure variations. The mean value and linear trend have been removed to eliminate the instrumental drift. The main advantage of the BB is that it directly yields vertical acceleration of the instrument, was used, and the same detrend procedure was applied.

References


Synthetic calculations

When spherical harmonic analysis is employed, the equations describing the free oscillations can be written as a system of boundary-value problems for second-order ordinary differential equations. The standard approach to solve eigenvalue problems based on formal integration of a characteristic equation. The solution of this equation can be numerically problematic, especially when close eigenfrequencies are to be separated and/or the skin effect of the eigenfunctions is significant. Our research team has been developing a novel numerical approach, where high-accuracy pseudospectral methods have demonstrated that, in general, the studied 2011 Tohoku earthquake source models

Conclusions

Employing the data from the superconducting gravimeter installed at the GOPE station, we have demonstrated that, in general, the studied 2011 Tohoku earthquake source models obtained from surface waves generate synthetic signals that are in a good agreement with the observed data. Whereas analysis of long-period normal-mode data of the 2004 Sumatra-Andaman and 2010 Maule earthquakes in the GOPE time series was averaged over the time window of 137 hours, in this study the data from both SG and BB were processed with a Hann filter and Fourier transform to 137-hour time series.

Acknowledgements

We thank M. Valko, V. Pálíř and V. Hlinka for providing us with the data, F. Gallot for his help with data processing, J. Zahrádecký for discussion and J. Vlček for a technical help. This research has been supported by the Grant Agency of the Charles University under projects Nr. 146160 and SVV-2011-263308.

Source models

Table 1: The relative agreement between the synthetic calculations and the GOPE data for the most fundamental free oscillation modes calculated by $a_1(a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_{10})$, where $a_i$ is the amplitude spectrum of the $i$-th degree of freedom and $a_0$ is the frequency of the $i$-th degree of freedom. The values in the table are the root mean square deviations of the calculated and observed amplitude spectra.

Table 1 Sol-Va copy 2: Source models

Source model | Source model PS1: Global OY Project Moment Tensor Solution Strike=203, Dip=10, Slip=80, Mw 5.31+0.15/0.10, depth 20 km | Source model PS2: USGS Central Moment Solution Strike=187, Dip=14, Slip=88, Mw 4.5+0.05/0.05, depth 10 km | Source model PS3: USGS WPhase Moment Solution Strike=199, Dip=15, Slip=100, Mw 4.5+0.05/0.05, depth 24 km | Source model PS1: 352 subsources Strike=203, Dip=10, Slip=80, Mw 5.31+0.15/0.10, depth 20 km | Source model PS2: 3525 subsources Strike=187, Dip=14, Slip=88, Mw 4.5+0.05/0.05, depth 10 km | Source model PS3: 35255 subsources Strike=199, Dip=15, Slip=100, Mw 4.5+0.05/0.05, depth 24 km

Fig. 1. Vertical acceleration amplitude spectra of the superconducting gravimeter (red line) and the broadband seismometer (blue line) after the March 11, 2011, Tohoku earthquake. The Fourier transform was applied to both the time series and the station was averaged over the time window of 137 hours.

Fig. 2. The relative agreement between normal-mode eigenfrequencies obtained by means of our finite-difference matrix-eigenvalue code calculated for the fiducial 1-D PREM model and corrected for the mode frequency.

Fig. 3. Vertical acceleration amplitude spectra after the March 11, 2011, Tohoku earthquake. Red line - superconducting gravimeter data observed at the GOPE station, green lines – synthetic calculations for the three point-source solutions PS1 and PS2 and for the 3D multisphere solution PS3. The black line and the gof factor were applied to 137-hour time series. The PS2 solution is preferred because its amplitude is closest to the observed data. The remaining two models except PS2 is higher. The reason is that its slip of 68° is rather anomalously in comparison with the other models.

Fig. 4. Vertical acceleration amplitude spectra after the March 11, 2011, Tohoku earthquake calculated for the point sources PS1, PS2 and finite-source PS1 and PS2 and compared to the observed SG signal. The synthetic R0 and M2007 models are calculated for a more realistic approach and by methods, respectively. The Hann filter and the Fourier transforms were applied to 137-hour time series.

Fig. 5. Vertical acceleration amplitude spectra after the March 11, 2011, Tohoku earthquake calculated for the point sources PS1, PS2 and finite-source PS1 and PS2 and compared to the observed SG signal. The synthetic R0 and M2007 models are calculated for a more realistic approach and by methods, respectively. The Hann filter and the Fourier transforms were applied to 137-hour time series.