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Determining slip near trench in the M 9 Tohoku-oki earthquake using bathymetry differences before and after the rupture

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SUN, Tianhaozhe[1*] ; WANG, Kelin[2] ; FUJIWARA, Toshiya[3] ; KODAIRA, Shuichi[3] ; HE, Jiangheng[2]
SUN, Tianhaozhe[1*] ; WANG, Kelin[2] ; FUJIWARA, Toshiya[3] ; KODAIRA, Shuichi[3] ; HE, Jiangheng[2]

[1]School of Earth and Ocean Sciences, University Of Victoria, Victoria, BC, Canada, [2]Pacific Geoscience Centre, Geological Survey of Canada, Sidney, British Columbia, [3]Japan Agency for Marine-Earth Science and Technology, Japan
[1]School of Earth and Ocean Sciences, University Of Victoria, Victoria, BC, Canada, [2]Pacific Geoscience Centre, Geological Survey of Canada, Sidney, British Columbia, [3]Japan Agency for Marine-Earth Science and Technology, Japan

Many studies of the 2011 M 9.0 Tohoku-oki earthquake indicate very large coseismic slip that breached the trench and induced the devastating tsunami. In order to understand the behavior of the shallow fault during the earthquake, it is important to know the amount of coseismic slip near the trench and how the slip varies in the updip direction. However, a compilation of more than 40 published rupture models derived from various datasets, including seismic, tsunami, and geodetic observations, shows large uncertainties in determining the near-trench coseismic slip. While some models show that the slip peaked at the trench, other models show that it peaked at some distance from the trench and then decreased trenchward. The large uncertainties are due mainly to the lack of very-near-field observations. For example, the most near-trench seafloor GPS/Acoustic site operational at the time of the earthquake is ~50 km from the trench. However, high-resolution multi-beam bathymetry surveys conducted by JAMSTEC before and ~10 days after the 2011 earthquake recorded coseismic deformation directly at the trench. In this work, we use differential bathymetry, i.e. bathymetry differences before and after the earthquake, to determine the shallow coseismic slip in the area of the largest moment release. Using a 3D elastic finite element model with actual seafloor and fault geometry of the Japan trench subduction zone, we produce Synthetic Differential Bathymetry (SDB), and compare the SDB with observations. The SDB can well predict short-wavelength features, which correspond mainly to local seafloor slope variations. For longer-wavelength features, our tests using different slip profiles with slip increasing or decreasing to the trench show that the internal elastic deformation of the hanging wall plays an important role in generating bathymetry differences. We use two parameters, the average fault slip over the most near-trench 50 km and a constant gradient of the slip over the same distance, to describe the assigned slip distribution, and search for the slip profile that can best explain the observed differential bathymetry. Bathymetry surveys before the Tohoku earthquake were conducted in 1999 and 2004. Our modeling indicates that a fault slip averaging 65 m over the near-trench 50 km and decreasing by 5 m over the same distance can optimally predict the differential bathymetry from the 1999 and 2011 data. Because the coverage seaward of the trench in the 2004 survey was shorter, causing greater uncertainty in correcting depth bias between surveys, differential bathymetry between 2004 and 2011 is less reliable. Compared to the 1999-2011 data, a smaller average slip (45 m) with a larger trenchward decrease over the most near-trench 50 km is required to explain the 2004-2011 data. Although some uncertainties exist in determining the absolute amount of slip, moderate decrease in fault slip to the trench should be a robust feature, as required by both the 1999-2011 and 2004-2011 data. If some pre-seismic slip and/or short-term afterslip occurred near the trench, the finding of the trenchward decrease of the coseismic slip would be further strengthened. The large coseismic slip but with a small decrease toward the trench suggests that the shallow megathrust may have initially exhibited velocity-strengthening at low slip rates but then changed to dynamic weakening at higher rates. The delay of weakening in the shallow fault may have led to less net coseismic weakening than in the deeper seismogenic zone.

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