Regional to teleseismic strong ground motions from a 610 km deep 24 May 2013 Sea of Okhotsk earthquake

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A very large deep earthquake (Mw8.3, 610 km depth) occurred in the Sea of Okhotsk near Kamchatka on 24 May 2013 producing a large shocks across the Japanese Islands. The maximum shaking intensity reached 3 on the JMA scale at Sarufutsu, Hokkaido and Akita, and the felt area spread to Kagoshima, 3000 km from the hypocenter. According to USGS, the shake was also reported in Northern India, California, and Dubai 6000 km away; also CNN reported that people in Moscow were evacuated from the buildings. Kuge (2015) analyzed teleseismic records and claimed that shaking at large distance is consistent with the radiation pattern of P wave, similar to the 1994 Bolivia Mw8.3 earthquake (Anderson et al., 2015). In this study we aim to understand the cause of large ground motion at regional to teleseismic distances from this very deep event using dense F-net, Hi-net, and IRIS DMC observations, complemented by 3D FDM simulation of seismic wave propagation.

Observed strong ground motion in Japanese Islands

The observed pattern of peak ground velocity (PGV) over Japan demonstrates large motions in Sea of Japan side, opposite to the large shake on the Pacific Ocean side as is usually seen in deep earthquakes. The PGV does not attenuate monotonically with distance, and a second PGV peak was seen at distance of about 2000 km.

At shorter distances (<2000 km) upward travelling waves arrive from the 610 km deep source, waves emitted downwards overlap somewhat and dominate beyond 2000 km. The large PGV is associated with successive arrivals of upgoing and downgoing S waves (near a caustic). S waves incident on the surface at the critical angle generates large sP conversions, which propagate in the crust and uppermost mantle to sustain PGV. Furthermore, a third PGV peak occurs at distances around 3000 km created by the SS wave traveling through deep mantle and reflected twice on the surface. Similar anomalous PGV attenuation is found for other deep earthquakes e.g. near Sakhalin in 2012 (Mw7.7; 600 km).

Strong motion simulation of deep earthquake

FDM simulations using ak135 model demonstrate the ways in which the S wave caustics and sP conversion create the second large PGV peak at regional distances, which moves from 1500 to 3000 km as the source depth increases from 200 to 610 km. The efficiency of sP and SS conversion and reflection is very sensitive to the thickness of the crust; SS is large and sP is weak by reflection from thick continental crust, and thin oceanic crust gives the reverse. The large SS observed over Japanese Island is due to the reflection of S wave at the thicker crust (20-30 km) in the Sea of Okhotsk, and large sP phase at Izu-Ogasawara Islands and the Northwest Pacific, corresponds well with the simulation results.

With a Pacific slab model (Yokota et al., 2017) in the 3D FDM simulation model, we find that S waves traveling through the High-V plate are refracted into the Low-V mantle, making large ground motions on the Sea of Japan side. This anti-waveguide effect differs from the stochastic waveguide effects in the plate at high-frequency (>1-2 Hz) waveguide effect, which is weak for the long-period wave of this distant earthquake with oblique transmission.

Shaking at thousands of kilometers due to long-period ground motion?

The IRIS DMC records show that the PGV has large peak at distance of about 3500 km due to the arrival of the SS wave. Then, PGV attenuate gently until the next large PGV peak around 7000 km with the arrival of the SSS phase. Shaking in the distance range 4000-6000 km from the Sea of Okhotsk earthquake comes from long-period SS and SSS waves. At Obinisk (OBN; 6050 km) near Moscow long-period S and SS produce 0.7 cm/s ground velocity at a period of 3.5 s. With amplification of long-period ground motions in sedimentary basins, the ground motion can grow to the JMA’s long-period intensity scale 1 (> 5 cm/s).

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