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A Ghost Tsunami without Warning

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ABSTRACT
In December 2018, a tsunami took 437 lives and injured 33,000 on the beaches of Sumatra and Java without warning. What can be done to provide a warning for such events? Real-time analysis of long-period ground motions recorded by regional seismometers could have determined that a sudden flank collapse of erupting Anak Krakatau volcano was potentially tsunamigenic, giving a basis for tsunami warning.

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On December 22, 2018, a devastating tsunami struck Sunda Strait, Indonesia, without warning in the evening. It left more than 400 dead and hundreds more injured along with the west Java and the southern Sumatra coastlines. The population did not feel any earthquake shaking to alert them to a possible tsunami. The local seismic network only measured a tiny event with magnitude ~3.3 based on the high-frequency ground shaking signals. Tsunami signal back-tracing from four tide gauges in Sumatra and Java triangulates a source in the area around Anak Krakatau volcano, which had been actively erupting that day. Satellite images from the Advanced Land Observing Satellite 2 (ALOS-2/PALSAR-2) from Japan and Sentinel-1A/Sentinel-1B Satellite systems from Europe within days after the tsunami event display dramatic geomorphic changes in the southwestern part of Anak Krakatau, suggesting the tsunami could have resulted from the flank collapse of the volcano. As the landslide slipped into the sea, little high-frequency seismic radiation was produced, thus perceptible precursory ground shaking did not provide any natural tsunami warning for people on surrounding coastlines.

This is not the first time that volcanic activity has generated a large tsunami. In 1883, The caldera-forming eruption of Krakatau volcano devastated the same region with a tsunami that took over 35,000 lives. In 1792, volcanic-landslide tsunamis at Shimabara, Japan, killed ~15000 people. Smaller slides like the 2018 Anak Krakatau flank collapse occur much more frequently, so improving the warning capabilities for future events is very desirable.

We analyzed the local seismic network data in Indonesia and we found that clear long-period ground shaking was recorded over the entire archipelago. Analysis of the long-period seismic signals using a standard rapid procedure to rapidly determine the geometry and size of faulting indicates a very shallow, shallow-dipping extensional faulting event with magnitude 5.9 near Anak Krakatau. However, the seismic waveform fits are unusually poor for this size event, and the very shallow dip of the fault suggests a different source process. Rather than assume a faulting process, we model the ground motions using a single-force applied to the earth's surface, as has been used for decades to represent landslides. The moving mass of the slide produces a reaction force on the Earth. We find excellent predictions of the waveforms for a nearly horizontal point-force pointing NE, opposite to the SW direction of the landslide. The strength of the force indicates a sliding mass of < 0.2 km3.

This analysis can be operated in real-time and completed within 15 minutes, allowing quantification of the source of the ground motions as a landslide. With a location near an actively erupting island, a clear basis for issuing a tsunami warning would be provided. The tsunami took about 30 to 60 minutes to reach the surrounding coastlines, leaving time for a civil tsunami-warning alert to be activated. Ideally, within 10 to 15 minutes, the beaches could be cleared, and much less loss of life would ensue.

Currently, regional seismic networks focus on high-frequency signals to initiate earthquake location and magnitude determination. Relatively slowly moving landslide sources can be missed, as was the case for the Anak Krakatau collapse. This event was not detected by the USGS/NEIC; a local network detection was made, but a misleading source mechanism was estimated. Thus, it is crucial to implement real-time monitoring using long-period seismic waves for local tsunami warning - especially for regions with high potential for volcanic landslides.