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Introduction to "Historical and Recent Catastrophic Tsunamis in the World: Volume I. The 2011 Tohoku Tsunami"

KENJI SATAKE,[1] ALEXANDER B. RABINOVICH,[2] DALE DOMINEY-HOWES,[3] and JOSÉ C. BORRERO[4,5]

Abstract—Twenty-one papers on the 2011 Tohoku, Japan tsunami are included in Volume I of the PAGEOPH topical issue "Historical and Recent Catastrophic Tsunamis in the World." Two papers discuss seismological aspects of the event with an emphasis on tsunami generation and warning. Five papers report the impacts and effects in Japan through field surveys of tsunami heights, building damage, and tsunami deposits or analysis of satellite data. Eight papers report the tsunami effects on other Pacific coasts, including the Kuril Islands, the USA, French Polynesia, the Galapagos Islands, Australia, and New Zealand. Three papers report on analyses of the instrumental records of the 2011 Tohoku tsunami, and two more papers report their modelling efforts of the tsunami. Several of the above papers also compare the 2011 Tohoku and 2010 Chile tsunamis.

Key words: Tsunami, 2011 Tohoku earthquake, source parameters, Pacific Ocean, DART, tsunami records, seiches, tsunami modelling, spectral analysis.

1. *Introduction*

The Tsunami Commission was established within the International Union of Geodesy and Geophysics (IUGG) following the 1960 Chile tsunami, generated by the largest (*M* 9.5) instrumentally recorded earthquake. The 1960 tsunami propagated throughout the Pacific Ocean, affecting areas far from the source. Since then, the Tsunami Commission has held biannual International Tsunami Symposia and published special volumes of selected papers (e.g., SATAKE *et al.* 2007, 2011a, b; CUMMINS *et al.* 2008, 2009). Tsunami science and research, as well as warning and hazard mitigation systems, have dramatically developed and improved as a result of the catastrophic 2004 Indian Ocean tsunami produced by the Sumatra–Andaman earthquake (*M* 9.1), which was the worst tsunami disaster in recorded human history. Several other destructive events occurred between 2005 and 2010, including the 2006 Java, 2009 Samoa, 2010 Chile and 2010 Mentawai tsunamis. The Tohoku (East Japan) tsunami of 11 March 2011 was a tragic continuation of this chain of devastating events.

The 25th International Tsunami Symposium was held from 1 to 4 July, 2011, i.e., only four months after the 2011 Tohoku tsunami. The symposium occurred within the framework of the Joint Association Session JS01 "Advances in Tsunami Science, Warning, and Mitigation", during the 25th General Assembly of the International Union of Geodesy and Geophysics in Melbourne, Australia. Sixty-five oral and thirty poster presentations comprised the symposium. At the business meeting of the Tsunami Commission, it was decided to publish selected papers presented at this symposium, as well as other papers on related topics. Out of 48 submitted papers, 39 papers have been accepted and published in two volumes. Volume I contains 21 papers on the 2011 Tohoku, Japan tsunami, while Volume II contains 18 papers on other tsunamis and related topics.

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[1] Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan. E-mail: satake@eri.u-tokyo.ac.jp

[2] P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovsky Pr., Moscow 117997, Russia. E-mail: a.b.rabinovich@gmail.com

[3] Australia-Pacific Tsunami Research Centre, Natural Hazards Research Laboratory, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney NSW 2052, Australia. E-mail: dale.dh@unsw.edu.au

[4] eCoast Ltd., Box 151, Raglan 3225, New Zealand. E-mail: jose@ecoast.co.nz

[5] Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, USA. E-mail: jborrero@usc.edu

Birkhäuser

2. *The 2011 Tohoku Earthquake*

The 11 March 2011 Tohoku earthquake (official name: "off the Pacific coast of Tohoku earthquake") was the largest instrumentally recorded earthquake (M 9.0) in Japan. It caused devastating tsunami damage on the Pacific coast of Japan, including the serious accident at the Fukushima Dai-ichi nuclear power station. As we write this Introduction, the earthquake and tsunami is reported to have caused nearly 20,000 casualties in Japan, of which approximately 90 % were associated with drowning.

Numerous papers have been published for the Tohoku earthquake and tsunami, including special issues in *Earth, Planets and Space* (Vol. 63 No. 7, Editors: Kanamori and Yomogida 2011), *Geophysical Research Letters* (Vol. 39, No. 7, 2012), *Coastal Engineering Journal* (Vol. 54, No.1, Editor: Sato 2012), among others. Results from many seismological analyses of the Tohoku earthquake suggest that a very large slip, approximately 50 m, occurred on the shallow interface of the subducting Pacific plate near the trench axis. This was confirmed by several submarine geophysical measurements (see papers in the above special issues). In this volume, two papers discuss seismological aspects of the 2011 Tohoku tsunami.

Okal (2013) reports that the real-time estimate of mantle magnitude indicate that the seismic moment of this earthquake was 4×10^{22} Nm. The slowness parameter Θ, a ratio of energy release to seismic moment, was -5.65, which suggests that this earthquake was a 'normal' earthquake, without any slow-rupture characteristics. This is unlike other great earthquakes such as the 2004 Sumatra–Andaman earthquake, which exhibited some slow characteristics as indicated by a Θ value of -6.40. He also estimated the short-rupture duration (average 65 s) from short-period (2–4 Hz) P waves, and that the seismic moment of the Earth's free oscillation (the gravest period nearly 1 h) was similar to the one from the shorter-period mantle magnitude. He then concluded that the 2011 Tohoku earthquake was a relatively fast earthquake, and no seismic moment was hidden in the long-period band.

Within 3 min of the earthquake, the Japan Meteorological Agency (JMA) issued a tsunami warning (Ozaki 2011). While the tsunami warning saved many lives in Japan, the initial estimates of the tsunami heights, between 3 and 6 m, based on the preliminary magnitude (M 7.9), significantly underestimated the actual tsunami heights. Hirshorn *et al.* (2013) examined a method to estimate the moment magnitude from P waves, M_{wp}. The Pacific Tsunami Warning Center (PTWC in Honolulu, Hawaii) has adopted M_{wp} for the first estimation of earthquake size, and their M_{wp} values were 8.1 for the 2004 Sumatra–Andaman earthquake and 8.6–8.8 for the 2011 Tohoku earthquake. They calculated M_{wp} values from seismograms recorded in Japan (distance range of 2 and 15 arc degrees) and found that the M_{wp} underestimated (7.7–8.4) in the distance range <5 arc degrees, but became 9.1–9.3 if the records at >10 arc degrees were used. The authors conclude that a reliable estimate of magnitude is possible within 4–5 min of the earthquake.

3. *The 2011 Tsunami and its Effects in Japan*

The 2011 tsunami caused severe damage in Japan. The tsunami heights on the Japanese coasts were measured by the Joint Survey Group that consisted of ~300 researchers from 60+ organizations. Their results were compiled and are available at http://www.coastal.jp/tsunami2011/. The total number of measurement points exceeded 5,300. The density of measurements far exceeds that of any previous event and provides invaluable data for future research. For comparison, the dataset collected by international research teams following the 2004 Indian Ocean tsunami, which affected more than 14 countries around the Indian Ocean, contains approximately 1,000 points in the NOAA/WDC tsunami database at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml.

Suppasri *et al.* (2013) investigated the effects of the 2011 Tohoku tsunami on coastal defence structures and different building types in Japan. Although the Japanese coasts were well protected by tsunami countermeasures, such as sea walls or flood gates, they were often either insufficient to prevent significant overtopping or were damaged badly themselves by the tsunami. The authors explore and discuss the impacts of the tsunami on residential buildings and, importantly, buildings designated as safe evacuation sites. This analysis is insightful since it highlights the problematic issue of the complacency that can arise as people assume that such structures will afford them safety during a tsunami. The take-home lesson from this study is that no matter how much effort is focused on early warning systems and hard engineering approaches, they cannot and must not be at the expense of socially-oriented approaches to risk reduction. That is, public awareness efforts and community engagement are critical for helping reduce human casualties during tsunamis.

Also focusing on the tsunami effects on engineering constructions is the paper by Yeh *et al.* (2013) who present observations of damage to buildings and coastal structures. They discuss building failures through mechanisms such as the rotation of a structure due to the tsunami flood, the entrapment of air inside a structure, and failure due to soil liquefaction around building foundations. The paper also discusses the spatial distribution of structural damage and suggests that some weaker constructions survived the tsunami as a result of shadowing from larger and sturdier buildings. They also show that high-speed flows induced in the gaps between structures that survived the tsunami led to enhanced and more destructive flows in these areas.

Liu *et al.* (2013) report on their detailed tsunami survey in the city of Rikuzen Takata. Located along the southern Sanriku coast, this city has experienced several destructive local tsunamis in the past, such as the 1896 Meiji and 1933 Showa Sanriku tsunamis and even far-field events such as the 1960 Chile tsunami. Compared to these past events, the 2011 tsunami caused much greater damage in this city, as well as 1769 casualties. The representative water height in 2011 was 15 m, compared to just 5 m during past tsunamis, and the inundation area was 13 km^2, compared to 5.3 km^2 from the Chile tsunami and less than 2 km^2 from the two Sanriku tsunamis. The tsunami travelled upstream some 8 km along the Kesen River. A “tsunami control forest” with 70,000 pine trees along a 2 km long and 200 m wide beach was completely overrun by the waves and only one single pine tree survived. Furthermore, a tsunami shelter was located too close to the coastline and at too low elevation, and nearly 100 evacuees lost their lives.

Yoshii *et al.* (2013) examined the chemical properties of soils in the tsunami inundation areas in Sendai plain, and showed that sediments affected by tsunami appear to preserve clearly identifiable and distinctive geochemical signatures—specifically, increased concentrations of water-soluble ions, compared to those in non-inundated areas. They also report similar results from the Talcahuano coast of Chile for the 2010 Chile tsunami. Although water-soluble ions may be washed away by rain, their method provides an independent way to estimate the inundation area, where tsunami deposits are not left. Tsunami geology and geochemistry is a rapidly developing field of scientific enquiry, and numerous researchers are utilizing multiple techniques for identifying and categorizing the size and effects of past tsunamis.

Tsunami inundation and runup in Rikuzen Takata and the Sendai plain were estimated remotely using satellite images. Ramírez-Herrera and Navarrete-Pacheco (2013) report that the maximum runup height in Rikuzen Takata was estimated as 39 m from satellite images and Digital Elevation Models, and this value was very similar to the ground-truth reported by land surveys referred to in their study. They also estimated inundation distances of ~ 6 km on the Sendai plain, which is also in agreement with field surveys. They note however, that in some areas, their forecasts of runup and inundation were larger than those actually measured in the field and they discuss the various reasons for this. In places where tsunamis have caused extensive destruction, where the focus of in-country emergency workers are the affected populations, and/or where field conditions are dangerous, the remote assessment methods are especially useful.

4. The 2011 Tsunami and its Effects in Other Locations

The 2011 Tohoku tsunami also affected the coastlines of other countries around the Pacific and caused two fatalities outside Japan: one in the USA and one in Indonesia. Vivid images of the tsunami destruction in Japan were rapidly broadcast around the world, alerting the public and emergency management officials of the severity of the event. It is possible that these images may have prompted more urgent action, particularly in California (Wilson *et al.* 2013). This is in contrast to the 2010 Chile tsunami that occurred in the pre-dawn hours in a society not as digitally connected as Japan. We editors speculate about whether without such images the tsunami casualties may have been much greater. Nine papers report the tsunami effects elsewhere including in the Kuril Islands, the USA, French Polynesia, the Galapagos Islands, Australia and New Zealand.

Razjigaeva *et al.* (2013) describe the coastal deposits and sediments left by the 2011 Tohoku tsunami in the South Kuril Islands, where the tsunami runup heights were mostly 3–4 m and the inundation distance was 50–80 m. A very unique and important aspect of their study is that they made surveys at the same sites where the 1994 Shikotan tsunami and the 2006–2007 storms were studied. They did not find the 2011 tsunami deposit at the locations where the 1994 tsunami and 2006–2007 storms left deposits. The 2011 tsunami deposits were found only in closed bays, which were covered by sea ice. The sea ice eroded the coasts and left deposits. Microfossil (foraminifera and diatoms) in tsunami deposits indicates that they are near-shore origin.

Kaistrenko *et al.* (2013) report the tsunami runup heights and their effects throughout the entire Kuril Islands chain. The maximum tsunami runup heights along the islands were approximately 5 m. During the tsunami arrival, most seas were covered by sea ice that was transported on land by the tsunami, although no severe damage was caused. This is in contrast to the 23 April 1923 Kamchatka earthquake and the 4 March 1952 Tokachi-oki earthquake, when sea ice transported by the tsunami caused significant damage.

Three papers describe the tsunami on the US west coast. Tolkova (2013) examined some physical properties of the 2011 Tohoku tsunami as it propagated more than 100 km upstream in the lower Columbia River, along the border between the states of Oregon and Washington, USA. Analysis of tide gauge records indicates different tsunami-tide interactions at lower and upper estuaries. A numerical model reproduced the observed interaction between the tides and the 2011 tsunami propagating up the river, and demonstrated possible amplification of a tsunami wave crest propagating right after the high tide. Similar amplification was also observed at the time of the 1964 Alaska tsunami.

Wilson *et al.* (2013) report the observational aspects of the two recent tsunamis: the 2010 Chile tsunami and the 2011 Tohoku tsunami. Both arrived at the US west coast during low tide and did not cause significant inundation of dry land. However, both events induced resonant oscillations and associated strong currents within harbours that created extensive damage in a number of harbours and bays of California. During the 2010 tsunami, maximum tsunami amplitude was 1.2 m at Pismo Beach, and over $3 million damage to boats and docks occurred in nearly a dozen harbours in California. During the 2011 tsunami, the maximum amplitude was 2.47 m at Crescent City with over $50-million damage to more than 20 harbours. One fatality occurred at the mouth of the Klamath River. The authors indicated that because tsunami-induced currents were responsible for most of the damage in these two events, modelled current velocity estimates should be incorporated into future forecast products from the warning centres.

Xing *et al.* (2013) examined the response of three California harbours (Crescent City harbour, Los Angeles/Long Beach Port, and San Diego harbour) to six significant tsunamis (both near-field and far-field) generated between 2005 and 2011. They used a hybrid finite element numerical model in the frequency domain that incorporated effects of wave refraction, diffraction, partial reflection and energy dissipation. The computed resonant periods of the harbours are in good agreement with the periods of the principal spectral peaks of tsunami waves observed inside these three harbours during the six events. The simulated tsunami-induced currents are also in qualitative agreement with those known from eyewitness reports. The results show that each harbour responded differently to arriving waves and significantly amplified harbour oscillations at certain periods according to the shape, topography, characteristic dimensions and water depths of the respective harbour basins.

Reymond *et al.* (2013) describe the effects of the 2010 and 2011 tsunamis in French Polynesia, as well as the timeline of the warning procedures, the information flow in the warning centre and to the local authorities. The maximum runup height from the

2011 tsunami was approximately 4 m; several houses were flooded. The tsunami heights from the two tsunamis at the same locations were not correlated, suggesting that the local responses are controlling factors for the tsunami heights. Their discussion highlights important issues, such as the extended duration of a tsunami hazard, which was illustrated during the 2011 event when the highest water level occurred *after* the official "all-clear" was issued, prompting the reinstatement of the tsunami alert for the islands.

Lynett *et al.* (2013) report on the effects of the 2011 tsunami in the Galapagos Islands. This report is the first-ever post-tsunami field survey in the Galapagos and highlighted the variability of tsunami effects over a relatively small area. Their observations included areas that experienced little tsunami activity, with wave heights that did not exceed typical high water tidal levels as well as other areas that experienced tsunami heights in excess of 6 m and corresponding structural damage and coastal inundation. Their survey also recovered important instrumental data for the tsunami including water levels and current measurements. These data were compared to numerical modelling results and highlighted the need to record current data (speed and direction) at sufficiently high temporal resolutions to be used in meaningful modelling assessments.

The tsunami also affected the Australian and New Zealand coasts. Hinwood and McLean (2013) examined the 2011 tsunami records at three bays, Port Kembla, Twofold Bay and Spring Bay, sparsely spread over 1,000 km along the coast of SE Australia. The amplitudes were up to 0.5 m, but the tsunami persisted for more than 2 days, largely caused by wave travelling along different pathways around Australia and New Zealand. They found that the waves were largely unaltered by the continental shelf and then were transformed by bay resonances. Cross-correlation in moving time windows was applied to separate tsunami waves that arrived at the observational sites following different pathways. The tsunami waves at 65-min period were the most energetic. Three possible types of harbour responses are discussed and classified. Despite its small height in this region, the tsunami put several swimmers at serious risk and generated significant harbour oscillations accompanied by strong currents that should be considered by the Tsunami Warning Service.

Borrero *et al.* (2013) describe the effects of the 2011 tsunami in New Zealand. The positive tsunami amplitudes recorded by approximately 30 tide gauges were less than 1 m, but the tsunami signal was evident for more than 2 days. Tsunami effects consisted primarily of rapid changes in water level and associated strong currents that affected numerous bays, harbours, tidal inlets and marine facilities, particularly on the northern and eastern shores of the North Island. The tsunami caused moderate damage and significant overland flooding at one location. Real-time analysis and modelling of the tsunami was used as a basis for elevating the predicted threat level for the northern region of New Zealand. A comparison to recorded data following the tsunami shows that these real time prediction models were accurate despite the coarse near-shore bathymetry used in the assessment, suggesting the efficacy of such techniques for future events from far-field sources.

5. *Tsunami Data Analysis and Modelling*

The 2010 Chile and 2011 Tohoku tsunamis were recorded by many coastal tide gauges and mid-ocean bottom pressure gauges of the Deep-ocean Assessment and Recording of Tsunami (DART) system, and provide invaluable data to examine the characteristics of the trans-Pacific tsunamis.

Borrero and Greer (2013) analyzed the tsunami waveforms recorded by coastal tide gauges in New Zealand and California, as well as DART data, to explore far-field characteristics of two major trans-Pacific tsunamis, the 2010 Chile and 2011 Tohoku events. The maximum tsunami energy from the Chile tsunami was toward Japan, and that from the Tohoku tsunami was toward Chile. The locations of New Zealand and California relative to the tsunami sources are similar in that they are situated in opposite corners of the Pacific Ocean basin relative to the two source regions. The Fourier and wavelet analyses indicate that while the spectral contents of the two tsunamis are basically similar at the same stations, suggesting that local effects around the station dominate, there are nevertheless some important differences due to the source mechanism and directionality. The DART data, free from the local coastal effects, show more differences between the 2010 and 2011 tsunamis.

Heidarzadeh and Satake (2013) also examined the 2011 Tohoku tsunami records from a number of coastal tide gauges and DART stations throughout the Pacific Ocean. The maximum trough-to-crest tsunami heights were of 3–4 m on the US west coast and the southern Chilean coast. Their analysis indicated that on coastal tide stations, the largest waves were observed several hours after the first tsunami arrival, whereas at most of the deep ocean DART stations, the first wave was the largest. They also noted a distinct difference in the duration of the tsunami, with coastal stations showing tsunami oscillations for approximately 4 days and at DART stations, approximately 2 days. Their analyses identified the dominant tsunami periods in the DART records were at 37 and 67 min and suggest that this is attributable to the width and length of the tsunami source region. The wavelet time–frequency diagrams showed the switches and lapses of tsunami energy at approximately the same period bands of 35 and 65 min. The latter period (65 min) is the same as was found by Hinwood and McLean (2013) to be the most energetic near the coast of Australia.

Fine *et al*. (2013) conducted numerical modelling of the 2011 Tohoku tsunami and compared their results with the tsunami waveforms recorded at open-ocean DART stations, NEPTUNE cabled stations off Canada, and four tracks of satellite altimeter data. After they validated a source model by the observed data, they examined and found that the temporal evolution of the wave energy leads to the wave energy equipartition law, due to multiple reflections and scattering of the tsunami throughout the Pacific Ocean. They also demonstrated that the final near-equilibrium state agrees with such equipartition law; after the passage of the tsunami front, the tsunami wave is inversely proportional to the water depth. Lastly, they demonstrate that the tsunami wave intensity, defined as a product of energy density and depth, is uniform throughout most of the Pacific Ocean.

Wei *et al*. (2013) demonstrate the accuracy of the NOAA's real-time tsunami flooding forecast system in the near field, by conducting numerical modelling of the 2011 Tohoku tsunami inundation on the Japanese coasts. For their study, they used a tsunami source initially derived from the real-time inversion of tsunameter data. This source was further validated against offshore GPS buoy and nearshore wave gauge data not available until well after the event. The computed tsunami runup height and spatial distribution are consistent with post-tsunami survey data collected along the Japanese coastline. The computed inundation areas on 60 m grids also agrees well with the survey data, giving a modelling accuracy of 85.5 % for the inundation areas along 800 km of coastline.

Grilli *et al.* (2013) simulated the 2011 Tohoku tsunami using two tsunami source models and compared the simulations with far-field and near-field data. The first source model (UCSB) was based on seismic wave analysis, while the second model (UA) was based on land GPS and marine geodetic data. Numerical simulations on a series of nested grids with minimum grid spacing of 250 m were performed using the fully nonlinear and dispersive Boussinesq wave equations and compared to the waveforms on DART and GPS wave gauges, and inundation and runup measurements. They performed a sensitivity analysis that compared both instantaneous and time dependent earthquake slip, and initial conditions on the ocean bottom and at the sea surface. While they succeeded in reproducing tsunami waveforms on DART and GPS stations, they could not reproduce the largest runup and inundation on the Honshu coast measured between 39.5° and 40.25°N. They attribute this to either insufficient resolution of bathymetry/topography data, and/or to additional tsunami sources such as splay faults or submarine mass failure.

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