NORTHEASTERN JAPAN MEGA-EARTHQUAKE ALERT SYSTEM BASED ON FORESHOCKS

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Earthquake hazard, risk and loss models are based on earthquake forecasts, which are derived from estimates of the frequency and magnitude of damaging earthquakes in a given area over years, decades, or centuries, based on knowledge of historical seismicity and an understanding of tectonics.

In contrast, earthquake prediction, which is the estimation of the location, magnitude, and time of occurrence of an impending earthquake within useful uncertainty ranges, has not yet been found to be possible.

Consequently, earthquakes are generally characterised as rapid onset events that occur with little or no warning. Warning times for tsunamis in coastal regions that are immediately adjacent to the rupture zones of mega-earthquakes are typically about half an hour once the earthquake has occurred, requiring immediate and very efficient warning systems.

In some locations where the subduction zone is very close to the shore, such as in the Mw 7.7 1993 Okushiri, Hokkaido earthquake, the warning time can be only ten minutes, making evacuation practically impossible. This situation has motivated the development of an alert system in northeastern Japan that will require people and businesses to be prepared to act immediately upon the occurrence of a very large earthquake "mega-earthquake."

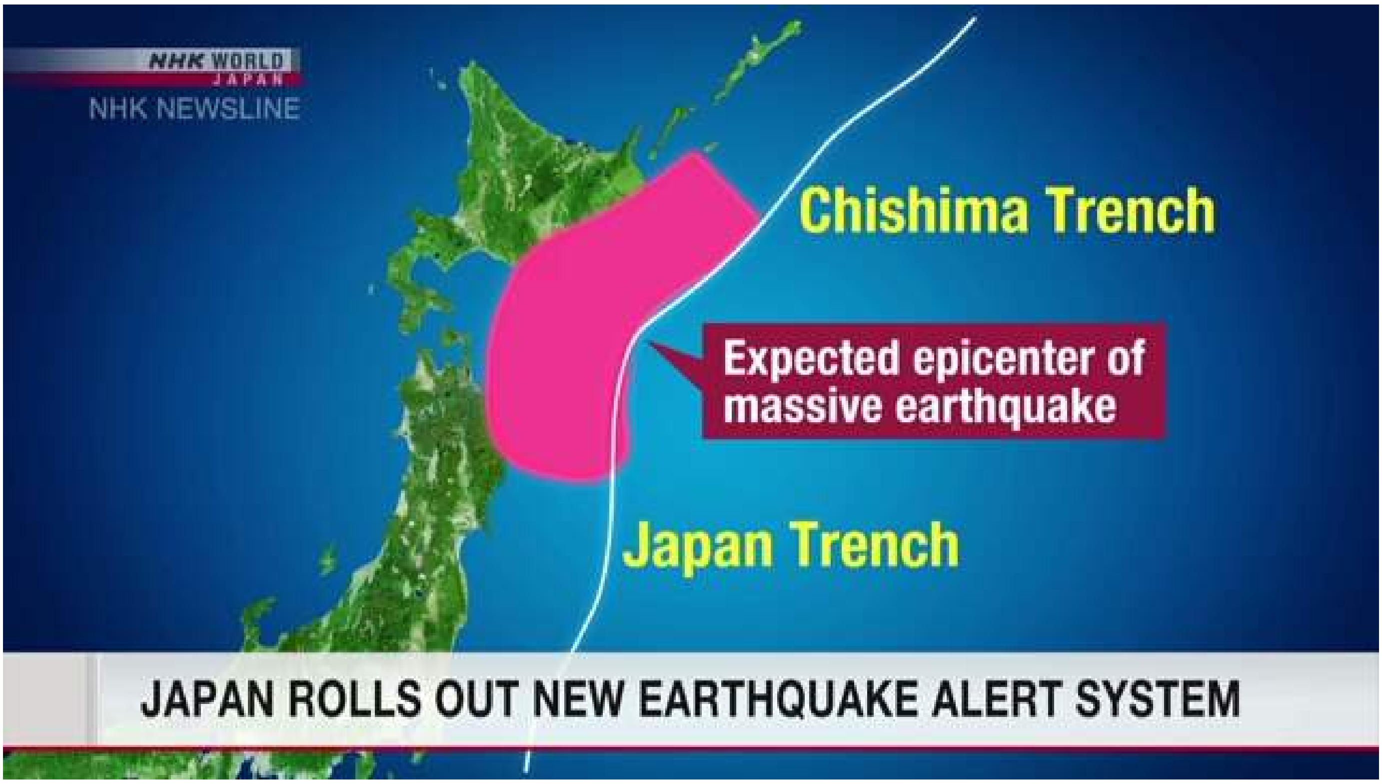

Figure 1. Expected rupture zone (shown in pink; "epicenter" should say "rupture zone") of the large earthquake for which alerts will be given by JMA. Source: NHK News.

The alert is triggered by the occurrence of a smaller earthquake that may be the foreshock of a mega-earthquake. "Mega-earthquake" is not a well-defined term, and is used in this briefing to denote a very large and destructive earthquake, notionally having a moment magnitude Mw of 8.5 to 9.0 or more, in contrast to the magnitude of 7 or more for the potentially triggering foreshock, already large.

On December 16, 2022, the Headquarters for Earthquake Research Promotion (HERP) of the Japanese government Cabinet Office initiated a new alert system for potential large earthquakes (moment magnitude Mw 8 or larger) following magnitude 7 or larger earthquakes in the Japan Trench off Tohoku and the Chishima Trench off Hokkaido in the Pacific coastline of northern Japan.

Under this system, the Japan Meteorological Agency (JMA) would issue an alert within about two hours after a magnitude 7 or larger earthquake occurring in that region. Following the alert, residents in the region would be required to prepare for immediate evacuation for about 7 days while continuing their daily lives. (A comparable alert status is used to prepare for fire and flood evacuation in Australia, as discussed further below).

Businesses would be urged to refrain from operating in places that could suffer tsunamis or landslides.

Communities would be asked to help elderly people evacuate and confirm methods of communication among residents.

The alert system is based on worldwide observations of shallow earthquake sequences. There is typically a probability of about 5% that a shallow earthquake will be followed by a larger earthquake, in which case the initial earthquake is described as a foreshock and the subsequent larger earthquake is called the mainshock (Jones, 1994). The probability declines rapidly within a few hours to days.

In implementing the alert system, HERP cites two specific examples in northeastern Japan.

First, the Mw 9.0 Tohoku earthquake of 11 March 2011, whose tsunamis caused the deaths of 18,500 people and initiated the Fukushima Nuclear Power Plant disaster (Risk Frontiers Briefing Notes 217 and 437), was preceded two days earlier by a magnitude 7.3 earthquake at the southern end of its rupture zone (Figure 2).

Second, the Mw 8.5 earthquake of 13 October 1963 off Etorofu, one of the four Russian-held, Japanese-claimed islands off Hokkaido, was preceded by 18 hours by an earthquake of Mw 7.0.

When they do occur, only about half of all earthquakes are preceded by foreshocks (Trugman and Ross, 2019), so for those events that do not have foreshocks it is not possible to provide an alert based on the occurrence of a foreshock.

Figure 2. Public notice describing the alert system. The top panel shows the expected rupture zone of the large earthquake in pink and the rupture zone of the 2011 Tohoku earthquake in the blue ellipse, together with the location of its Mw 7.3 foreshock at the southern end of that rupture zone documented in the beige circle. The lower panel shows the immediate actions required of the public and businesses.

HIGH LIKELIHOOD OF FALSE ALARMS

Based on global earthquake data for the past century reviewed by HERP, only about one in 100 earthquakes with a moment magnitude of 7.0 or higher was followed within a week by an earthquake with Mw of 8.0 or greater within areas up to 500 kilometers from the initial earthquake.

HERP expects that alerts will be issued about once every two years, and in most cases they will be false alarms. Further, as noted above, only about half of all shallow earthquakes are preceded by foreshocks. HERP explains that, despite this high level of uncertainty, the new system is expected to be effective in mitigating casualties and damage from earthquakes because it will help people become more vigilant.

Until now, the JMA has used the local Japanese magnitude scale, MJMA, which is simply measured from the amplitudes of seismic waves, to describe the size of earthquakes in Japan. However, in the course of the 11 March 2011 earthquake, JMA's initial measurement of MJMA 7.9 greatly underestimated the actual Mw of 9.0, and may have delayed the tsunami evacuation response because an earthquake of magnitude 7.9 typically generates tsunami heights of a few metres, in contrast to the ten metres or more generated by the Mw 9.0 event in many locations. The moment magnitude scale (Mw) is based on the physics-based modeling of seismic wave amplitudes, and although it takes longer to calculate, it provides a more reliable estimate of the size of the earthquake. JMA is now using Mw for tsunami warnings.

PREVIOUS LARGE EARTHQUAKES IN NORTHEASTERN JAPAN, INCLUDING THE 1896 SANRIKU TSUNAMI EARTHQUAKE

The only earthquake with a magnitude comparable to the 11 March 2011 earthquake that is known to have occurred in northeastern Japan is the 869 Jogan earthquake (Minoura et al., 2001).

The magnitude of this earthquake is estimated to have been at least Mw 8.6 (Namegaya and Satake, 2014).

There was a growing realization of the significance of this earthquake in the decades preceding the 2011 event, but the failure to act upon it by increasing the height of the tsunami sea wall resulted in the Fukushima Nuclear Power Plant nuclear disaster (Risk Frontiers, Newsletter Vol. 18, Issue 4, Sept. 2019).

This suggests that the recurrence intervals of mega-earthquakes in the zone ruptured by the 2011 Mw 9.0 earthquake shown in Figure 2 is about 1,000 years.

The 1896 Sanriku earthquake (Satake et al., 2017), which also occurred in the rupture zone of the 2011 earthquake (shown in Figure 2), was a “tsunami earthquake” (Kanamori, 1972) whose tsunami magnitude Mt of 8.2 was much larger than its estimated conventional magnitude of 7.2.

Tsunami earthquakes produce large tsunamis but weak ground motions, due to very low fault rupture velocities in the accretionary wedge of the shallow subduction zone. The 1896 earthquake was felt, but generated little concern because it was so weak, and many small tremors had also been felt in the previous few months. However, 35 minutes later, the first tsunami wave struck the coast, producing tsunami wave heights comparable to those of the 2011 earthquake in the northern region (Satake et al., 2017), and estimated deaths of 27,122 people, exceeding the estimated 18,453 deaths in the 2011 earthquake (Matanle et al., 2019).

Since the year 1500, the deaths caused by each of these two earthquakes were exceeded in Japan only by the 105,385 deaths caused by the Great Kanto earthquake of 1923 in Tokyo, 87% of which were attributable to fire following the earthquake (Moroi and Takemura, 2004).

The 1896 Sanriku earthquake illustrates the special challenges to tsunami evacuation presented by a tsunami earthquake. People who are vulnerable to tsunamis are instructed to evacuate upon feeling an earthquake without waiting for an evacuation order. However, the weak ground motions generated by tsunami earthquakes like the 1896 Sanriku earthquake may not be felt or may not be sufficiently alarming to trigger an evacuation response. In this situation, the HERP plan for an alert triggered by a foreshock of a mega-earthquake may be of special value for tsunami earthquakes.

THE CHALLENGES OF MEGA-EARTHQUAKE TSUNAMI WARNING AND HAZARD AND RISK MITIGATION

As noted in the introduction, the motivation of the newly implemented alert system in northeastern Japan is to enable people and businesses to be prepared to act immediately upon the occurrence of an earthquake, because there is very little time to evacuate before the tsunami strikes after the earthquake has occurred.

The alert is triggered by the occurrence of a smaller earthquake that may be the foreshock of the mega-earthquake.

A massive tsunami seawall construction program is now underway in northeastern Japan to mitigate tsunami hazards (Figure 3, Kurtenbach, 2015; UNDRR, 2017; Matanle et al., 2019). Opponents of the $AUD10 billion program argue that the massive concrete barriers will damage marine ecology and scenery, hinder vital fisheries, and do little in reality to protect residents who are mostly supposed to relocate to higher ground anyway.

Figure 3. A new 14-metre-high seawall near Toni in the city of Kamaishi, Iwate Prefecture. The old seawall was 12 metres high but could not withstand the 2011 tsunami.
Source: Kurtenbach (2015).

Some investigators have suggested the benefits of various kinds of social infrastructure to augment the ongoing "grey infrastructure" component of tsunami mitigation. Aldrich (2022) claims to have quantitatively demonstrated how cultural centres, libraries, community centers, and other social infrastructure facilities are correlated with improved survival rates for vulnerable populations affected by the 2011 tsunami, after taking into account the area of the neighbourhood, height of the seawall, height of the tsunami, distance to the sea, and education and home ownership of the people.

However, additional aspects of social infrastructure that have been described by Hasegawa (2013) may have had significant impacts that were not considered by Aldrich (2022).

First, in many locations, the tsunami warning loudspeaker in the neighborhood was not operational, so evacuation began upon seeing the tsunami.

Second, the initial warning predicted an underestimate of the ultimate tsunami wave height, suggesting inaction was a viable response. Initial estimates of 3m wave height 3 minutes post-earthquake became 10m+ 44 minutes post-earthquake, and actual heights ranged from 10.1m to 21.4m (Matanle et al., 2019, Table 3).

Third, the warning was not always delivered with sufficient urgency to prompt action; some were expressed as requests, not as orders. In implementing the new alert system, HERP hopes that by making people more vigilant, some of these shortcomings will be avoided and the mitigation of casualties from future mega-earthquakes in northeastern Japan will be enhanced, even though it will result in many false alarms.

RELEVANCE FOR AUSTRALIA: EVACUATION ALERTS FOR SLOW AND RAPID ONSET EVENTS

The HERP tsunami evacuation alert system described here is comparable to those used to prepare for fire and flood evacuation in Australia: people are advised to be fully prepared for immediate evacuation when advised to do so. However, those Australian hazards have slower onsets than earthquakes, and the hazardous event is already underway when the warning is given. This enables the public to monitor the situation and the progression of the warning status.

In contrast, earthquakes are sudden onset events, and for ground shaking hazard there is usually very little time (a few seconds to a minute at most) within which to respond to an alert for imminent ground shaking based on the detection of the earthquake. This is because seismic waves travel through the Earth at several kilometres per second, in contrast to the near-shore wave speeds of a few tens of metres per second for tsunamis, providing much more warning time for tsunamis.

Warnings of imminent ground shaking have been implemented in Japan, China, Taiwan, Mexico (where special conditions in Mexico City provide up to one minute of warning), Turkey, Romania, and recently in California and the Pacific Northwest of the United States and Canada.

These "shakealerts" are early notifications of imminent ground motions from earthquakes that have already occurred and been detected.

In Japan, they have mostly been used to slow down bullet trains, but there have already been two derailments of bullet trains by earthquakes, one in the 2011 earthquake and the other in the Mw 6.6 2004 Chuetsu earthquake, in both cases because the warning time was too short to enable sufficient braking of the train.

Although earthquakes are sudden onset events, two conditions provide some degree of slow onset for tsunami evacuation.

First, the HERP alert of a possible mega-earthquake from foreshocks preceding about half of these events provides time to prepare for evacuation in those cases.

Second, the time taken for the tsunami to arrive following the earthquake provides some time to evacuate once the earthquake has occurred. This suggests that some human behavioural aspects of evacuation alerts may be transferrable between Australia and Japan.

TSUNAMI HAZARD IN AUSTRALIA FROM EARTHQUAKE SOURCES

The probabilistic tsunami hazard in Australia from earthquake sources was estimated by Davies and Griffin (2018).

The near shore wave heights shown in Figure 4 for a set of return periods do not account for onshore runup effects, and, even for low wave heights, flow velocities in ports and harbours can be large and do significant damage.

Coastal impacts can also be increased by high tides, storm surge and sea level rise, and the number of exposed properties increases rapidly with height above sea level (Somerville et al., 2009). However, near shore wave heights exceeding 3m are confined to the northwest coast of Western Australia for return periods of 2,500 years and longer in Figure 4.

The Australian coastline is sufficiently distant from the source zones of major subduction zones that, for all of the major coastal cities, there will be several hours of warning time between the issuance of a tsunami warning and the arrival of the tsunami on shore, providing adequate time for evacuation in most situations.

Even in northern Queensland and the northwest coast of Western Australia, the distances to tsunami sources are quite large, and the shallow bathymetry of the continental shelf in these regions will retard tsunami propagation speed.

The coral reefs and mangroves in northern Queensland present an additional impediment to tsunami propagation.

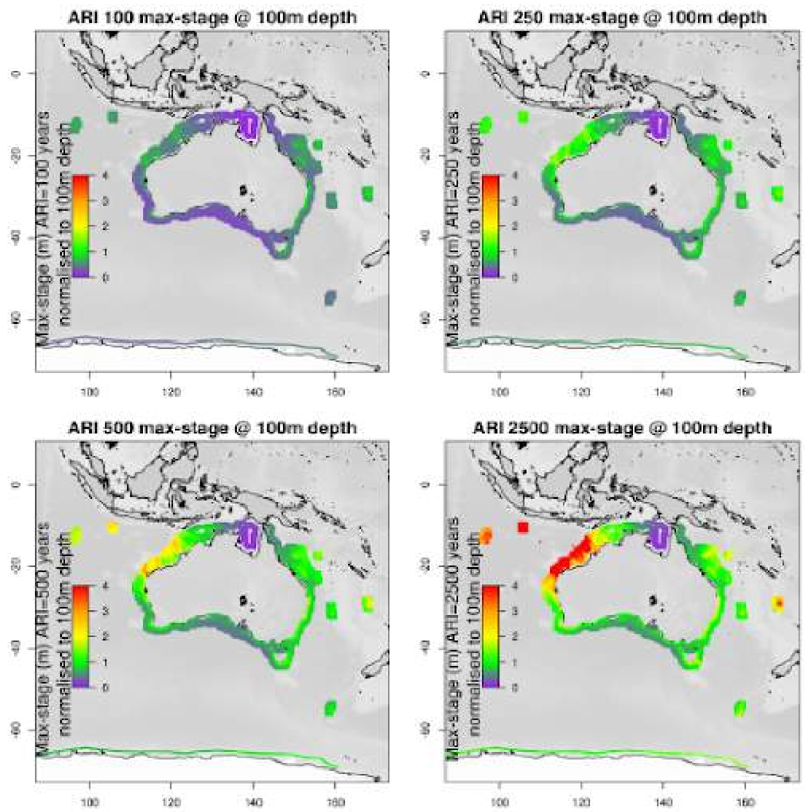

Figure 4. Tsunami height in Australia from earthquakes, normalised to 100m depth, for a range of average return periods (100, 250, 500 and 2500 years). Source: Davies and Griffin, 2018.

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Paul is Chief Geoscientist at Risk Frontiers. He has a PhD in Geophysics, and has 45 years experience as an engineering seismologist, including 15 years with Risk Frontiers. He has had first hand experience of damaging earthquakes in California, Japan, Taiwan and New Zealand. He works with Valentina Koschatzky in the development of QuakeAUS and QuakeNZ.