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Approaches to post-tsunami coastal reconstruction: Comparisons across Indonesia, Thailand, and Japan

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ABSTRACT

Natural hazards pose significant challenges to affected communities worldwide, yet there remains a lack of comprehensive studies comparing recovery efforts across different countries and cultures. This study addresses the gap by investigating the impact of three devastating tsunami events on four distinct locations: Banda Aceh (Sumatra, Indonesia) and Southern Thailand, both affected by the 2004 Indian Ocean Tsunami, the 20th anniversary of which provided the initial motivation for the study; the Tohoku region of Japan, affected by the 2011 Great East Japan

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Banda Aceh
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Earthquake and Tsunami; and Palu Bay (Sulawesi, Indonesia) affected by the Palu-Central Sulawesi Earthquake and consequent triple disaster. Data for this research was gathered from recovery missions led by the UK Earthquake Engineering Field Investigation Team (EEFIT), working in collaboration with local partners (Tsunami and Disaster Mitigation Research Centre, Tadulako University, Mahidol University and the Asian Institute of Technology). Additional material was provided by the International Research Institute of Disaster Science (IRIDeS) at Tohoku University. This paper evaluates recovery in terms of spatial planning, the development of design codes, evacuation planning, and the reconstruction development of coastal and port structures. A companion paper considers post-disaster recovery of buildings and other structures in Indonesia. Key findings include a variety of responses to planning enforcement in exclusion zones, a reliance on US tsunami codes for building code development rather than the comprehensive Japanese codes, diverse behavioural responses to the use of vertical evacuation structures, and some similarities in the use of multi-layered protection from tsunamis, inspired by Japanese approaches. The investigation provides insights into recovery and reconstruction efforts for: (i) the affected regions where agencies can compare and contrast their approaches with others, (ii) agencies and communities in similarly-affected locations in other parts of the world, and (iii) those at risk of future tsunami inundation.

1. Introduction

Recovery from catastrophic natural hazards can be affected by many factors, including the extent of damage, geographical location, and socio-economic conditions. Studies that compare recovery from major natural hazards across different countries and cultures are relatively few and far between. Suppasri et al. [1] compared and contrasted disaster preparedness across Indonesia, Sri Lanka, Thailand, and the Maldives ten years after the devastating Indian Ocean tsunami of 2004, reporting on the vulnerabilities of the locations. The key similarities between locations were the well-established disaster preparedness education, generally completed reconstruction (except in the Maldives, where building material procurement had been a problem), and severe traffic jams affecting tsunami evacuations (particularly in tourism-dominated areas). The critical differences in preparedness were the different readiness levels of tsunami warning systems. More recently, Maly et al. [2] compared housing recovery in Thailand, India, and Japan following different disaster events that occurred over the period 1995 to 2014. They highlighted the long-term benefits of Civil Society Organisations (e.g., community-based organisations) complementing government-driven housing recovery programmes in India and Thailand. They also recognised the importance of policies and good governance being integrated locally.

The study reported herein investigates the influence of destructive tsunami events on three different countries, seeking to compare and contrast the spatial and temporal effects on coastal reconstruction responses over a period of up to 20 years. It focuses on four locations that have been affected by tsunamis that occurred in the early 21st Century: (i) Banda Aceh (Indonesia) and (ii) Southern Thailand, both affected by the 2004 Indian Ocean Tsunami (IOT), the 20th anniversary of which provided the motivation for the initial field investigation; (iii) the Tohoku region of Japan affected by the 2011 Great East Japan Earthquake and Tsunami (GEJE); and (iv) Palu Bay (Indonesia) affected by the 2018 Palu-Central Sulawesi Earthquake and ensuing triple disaster (severe ground shaking, tsunami and liquefaction-induced mudflows).

The primary sources of material for Indonesia and Thailand were acquired through recovery missions in late 2022, led by the UK Earthquake Engineering Field Investigation Team (EEFIT), working in collaboration with local partners, including the Tsunami and Disaster Mitigation Research Centre (TDMRC), Tadulako University, Mahidol University and the Asian Institute of Technology. The Japanese material was provided in collaboration with the International Research Institute of Disaster Science (IRIDeS) at Tohoku University, and using some material acquired in Japan during April 2023 by the first author. Further material came from subsequent site visits in December 2024 and recently published literature.

The paper first summarises the immediate effects of the tsunamis on the locations and then considers the implications on longer-term redevelopment in terms of design code developments, coastal evacuation planning, and coastal defence design. A companion paper will describe the reconstruction of buildings in the two Indonesian locations [3]. It is possible to make spatial comparisons between the locations but also, to some extent, temporal comparisons within Indonesia, which has suffered from multiple disasters during recent times. The key themes from the comparisons between locations are then presented, with some discussion. It is hoped this will prove helpful for those living in locations at risk from tsunami inundation.

2. Initial impacts of the early 21st century tsunamis

2.1. Indian Ocean Tsunami, 2004

On December 26, 2004 at 00:58:53 GMT (07:58:53 a.m. local time), an enormous earthquake occurred off the west coast of northern Sumatra, Indonesia, which crossed the Indian Ocean, causing damage and life loss in 11 countries. The earthquake, initially reported by the United States Geological Survey to have had a moment magnitude (Mw) of 9.0, has now been attributed a Mw of 9.3 (i.e., 2.5 times greater energy release, [4]). The Boxing Day 2004 earthquake was the second biggest earthquake ever recorded, surpassed only by the Mw 9.6, 1960 Chile earthquake. The associated ground shaking caused damage to buildings in northern Sumatra, Indonesia, and was felt in many countries that were subsequently devastated by the tsunami waves [5]. In Indonesia, confirmed loss of life reached around 130,000 people, with around 37,000 more people registered as missing. The cost of the direct damages were estimated by Munich Re at around 4.8 billion US$, including insured losses. Only light shaking was experienced in Thailand on the Phuket and Khao Lak coast. However, the subsequent tsunami, which arrived about 1.5 h later than at Banda Aceh in Sumatra [5], led to the death of over 5,000 people, with nearly 3,000 missing. About half of the victims in Thailand were Western tourists. The economic loss in Thailand was estimated at 235 million US$ [5]. Sri Lanka and India were also severely affected (35,322 and 16,269 killed or missing, respectively, [6]) but are not considered in this study.

2.2. Great east Japan earthquake and tsunami, 2011

The most powerful recorded earthquake in Japan's history and the fourth most powerful earthquake recorded since modern seismography began in 1900, measuring Mw 9.1, struck at 14:46 local time on Friday, March 11, 2011. It occurred where the Pacific Plate is subducting under the Eurasia Plate beneath northern Honshu Island in the Tohoku region. This seismic event triggered a colossal tsunami, leading to widespread devastation along Japan's entire northeastern coastline [7], most notably in the Miyagi, Iwate, and Fukushima prefectures. The tsunami also caused failures at the Fukushima Daiichi Nuclear Power Plant that led to a meltdown of three of its reactors, the discharge of radioactive water and the evacuation of hundreds of thousands of residents. Although there was less damage caused by ground shaking, a series of tsunami early warnings underestimated the tsunami heights. Updated tsunami warnings were delayed or did not reach coastal residents in time because of power outages in many areas. Tsunami waves in excess of 10 m height overtopped all previously existing tsunami defence structures (i.e. breakwaters, seawalls, and floodgates), causing immense destruction along the coast of the Tohoku region. The official figures released in 2021 reported 19,759 deaths and 2,553 people missing [8], and more than 400,000 buildings damaged or destroyed [9]. On the fourth anniversary, in 2015, a report indicated 228,863 people were still living away from their homes. The maximum recorded tsunami runup was about 40 m, the highest in Japanese history [10]. The nuclear accident caused more than 100,000 people to evacuate [11], and in addition there was possible water contamination that had a significant impact on the agricultural, fishery and tourism industries in Japan. The economic impact of the event, including the nuclear disaster, was estimated at over 211 billion US$ [12].

2.3. Palu-Central Sulawesi triple disaster, 2018

On September 28, 2018 at 17:02 local time, an earthquake of Mw 7.5 [13] hit Indonesia, with an epicentre located 78 km north of the city of Palu on Sulawesi Island. The consequent ground shaking caused significant damage to buildings and infrastructure and triggered extensive flow liquefaction in areas of Palu (Petobo, Balaroa and Sigi Valley). The earthquake was followed by a tsunami that also caused devastation to the Palu Bay coastline, in particular to Palu City and Donggala town. This earthquake occurred on the Palu-Koro left-lateral strike-slip fault, the most prominent active fault on Sulawesi Island, with a total length of around 450 km. Strike-slip faults do not normally trigger large tsunamis. However, submarine landslides were very likely to have been one of the causal mechanisms of the tsunami [14]. There were 3,673 confirmed fatalities (including 1,016 unidentified bodies), with an additional 667 people registered as missing and 92,306 people injured, out of which 4,471 had serious injuries requiring treatment in hospital [15]. Additionally, 223,751 people were temporarily displaced from their homes [16], with 74,044 displaced in 120 sites by October 13, 2018 (WHO, Situation Analysis: Earthquake & Tsunami Sulawesi, Indonesia). The direct damage costs were estimated at 1.22 billion US$ (Indonesia Rupiah 18.48 trillion) by the National Disaster Management Agency (BNPB) on October 28, 2018.

2.4. Tsunami frequency of occurrence period

To assist in comparing recovery across different temporal and spatial scales, we consider the frequency of occurrence of tsunamis in these vulnerable countries. Across the Indonesian archipelago, during the past 100 years, there have been 37 tsunamis of at least 2 m maximum wave height associated with earthquakes, volcanoes, and landslides [17]. Twenty-three of these were in the Indian Ocean, though only the IOT of 2004 affected Thailand [17]. Central Sulawesi (in and around Palu Bay) has been affected by five tsunamis during this period [18]. In Japan, there were 23 tsunamis greater than 2 m in the same period [17].

2.5. Reconstruction sustainability

Recovery and reconstruction are complex processes shaped by socio-economic conditions, governance, and geographic contexts. Each country's approach reflects priorities, resources, and constraints, resulting in varying outcomes. Sustainability is a critical component of this process, as the immediate need for rapid reconstruction has to be balanced with considerations for long-term environmental, social, and economic resilience [19]. Key factors include the availability and management of natural resources, adoption of sustainable building practices, and integration of disaster risk reduction strategies into development plan. Local versus global material sourcing have gained great importance, showing how transportation distances and material sustainability impact carbon footprints [20]. Pre-construction planning and community-driven recovery with participatory approaches are critical success factors [21]), as well as holistic planning that incorporates hazard mitigation and social well-being [22]. A growing trend in recent research is the use of life cycle assessments (LCAs) to evaluate the environmental impacts of reconstruction materials and methods. Evidence from Banda Aceh shows that LCAs are crucial for determining the sustainability of supply chains in resource-constrained areas [20], as the efforts made to establish sustainable supply chain practices for timber procurement during reconstruction in

Banda Aceh. As mentioned before, the integration of nature-based solutions, such as mangroves and coastal forests, into multi-layered defence strategies enhance ecological balance while providing cost-effective and culturally accepted measures [22]. Additionally, advances in disaster-resilient building codes, as seen in Japan, highlight the importance of adapting international standards, despite challenges in their adoption in resource-limited settings [21]. Efficient material procurement and supply chain management, as seen in the Indian Ocean Tsunami reconstruction in Aceh, remains key to mitigating environmental impacts. In Indonesia, Thailand, and Japan, challenges such as resource scarcity, coastal zoning, and the carbon footprint of construction necessitate innovative approaches. Incorporating community-driven initiatives and resilient design codes ensures reconstruction efforts are both effective and environmentally conscious.

3. Spatial planning and development following the disasters

This section examines the integration of spatial planning and hazard zonation with construction developments across Indonesia, Thailand, and Japan. It outlines the methodologies and outcomes of regional spatial plans, hazard zonation efforts, and specific

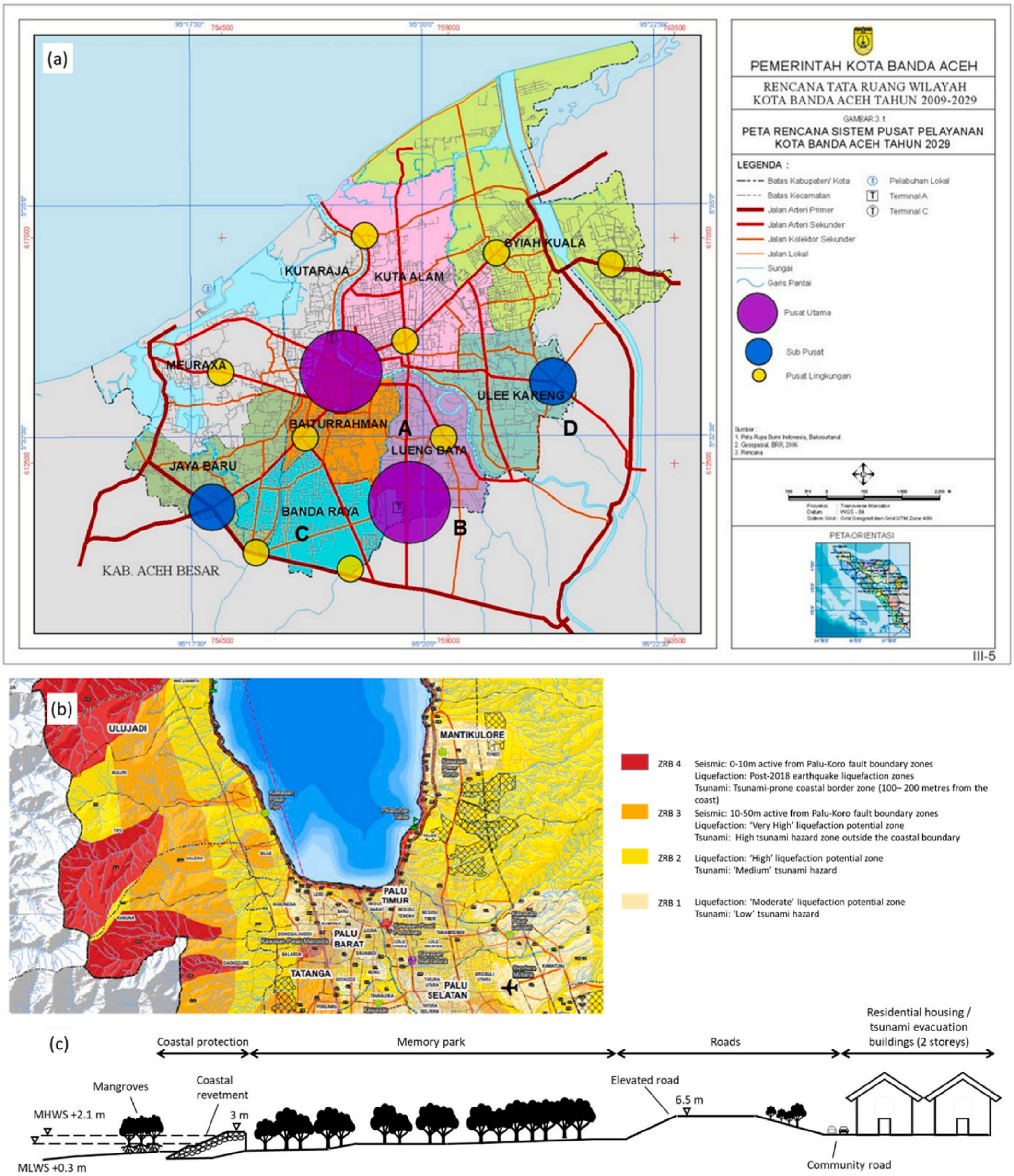


Fig. 1. Spatial planning in Indonesia: (a) Banda Aceh Regional Spatial Plan [24] (b) zoomed-in view of the Palu unified disaster-prone zone mapping [25] (c) Palu City Coastal Rehabilitation Project, from the Asian Development Bank [26].

construction projects aimed at mitigating disaster risk and enhancing resilience in coastal areas. Insights from Banda Aceh, Palu, and other affected locations illustrate the challenges and advancements in integrating disaster risk reduction into spatial development strategies. The detailed analysis of buildings, further elaborated in the companion paper by Baiguera et al., will provide context for understanding the broader landscape of post-disaster reconstruction and development.

3.1. Indonesian spatial planning and development

In Banda Aceh, Indonesia, five years after the IOT, the city government published a Regional Spatial Plan (Fig. 1 (a)). It shows the various centres and sub-centres with circles, and roads, including nominated evacuation roads. The spatial plan includes a 1 km buffer strip, which has been under pressure due to factors such as its relatively lower land price, the desire of people with no lived experience of the IOT moving to the city and investing in homes, and a fatalism that comes from coexisting with other hazards such as volcanoes [23].

The total population of Banda Aceh in 2020 had increased from the 2005 (post-tsunami) figures by 42 %, following the sharp decline of 2004 due to the tremendous loss of life in the IOT. The Banda Aceh population increases are shown in Table 1, using data extracted from Amri et al. [27]. The city is currently approaching its pre-tsunami population. Unfortunately, the population in the sub-districts situated at least partially within the 1 km buffer strip (the red 'evacuation zone' identified by Nubli Gadeng et al. [23]) has grown by 79 % in the same period. During the 2022 EEFIT mission, we saw evidence of a small, high-quality housing scheme within about 500 m of the shoreline: Aiman Regency Alue Naga in the Syiah Kuala sub-district. Finances were advertised on-site by Bank Syariah Indonesia, the state-owned Islamic bank. More reassuring, we were told by a representative from the Spatial Planning Department that the city government plans to relocate their offices to a new centre that has been developed over the last 10 years, away from the coast. This new development effectively moves the centre of activities from the upper purple circle in Fig. 1(a) (above BAITURRAHMAN") to the lower purple circle 7–9 km inland at Batoh. This new hub will hopefully attract new residents away from the tsunami risk zone.

Also, in the last few years, the proposed Banda Aceh Outer Ring Road (BORR) has been the subject of discussion and research. The plans are for a 13.4 km, 30–50 m wide road aimed at improving connectivity and resilience. It would pass through several strategic points (e.g. ports, toll road and airport) and provide an alternative route to the existing main road through Banda Aceh. In addition to alleviating traffic congestion and promoting economic development, the BORR could play a role in disaster resilience with the alternative route providing additional accessibility to support emergency response and evacuation efforts. However, its alignment parallel to the coast could limit its effectiveness in this regard. Furthermore, tsunami inundation modelling undertaken by Syamsidik et al. [28] found that a 3 m elevation BORR would have relatively modest reduction effects on tsunami inundation area (−22 % for 8.5 Mw and −9% for 9.15 Mw earthquake scenarios). A decision on whether the BORR will incorporate the elevated sections is still under discussion in the ministry of PUPR [29], bearing in mind the ongoing relocation of the city centre further inland.

In Palu, Indonesia, just three months after the tsunami, the Indonesian ministries produced a unified disaster-prone zone mapping for the entire Palu Bay region (including Palu City, Donggala and Sigi regencies), which accounts for susceptibility to ground shaking, liquefaction, tsunami, flood, and ground movement in Palu (Fig. 1 (b)). Four zones were identified (ZRB 1 to ZRB 4) in different colours, signifying increasing hazard levels. Focusing in on Palu City, it is striking how much of the land is prone to disasters. The "Palu City Disaster Risk Study 2016–2020" [30] stated that out of 8 sub-districts in Palu City, seven were in the high tsunami disaster zone category and only one sub-district in the low category. Meanwhile, according to this study, the total area in danger of a tsunami reaches 1785 ha or 4.5 % of Palu City's total land area. Several businesses on the Palu City coast (including the collapsed Mercure Hotel) remain shut down as re-development is prohibited (ZRB 4). Still, they are also awaiting the completion of the Palu Coastal Rehabilitation Project, which will reconstruct the collapsed Palu IV bridge [16], construct a 7.2 km long coastal revetment, and a 4 km long elevated road [31]. A cross-section of the western part of the bay, which indicates the relative locations of these structures, is shown in Fig. 1(c). A tsunami-prone exclusion zone has been established (at least 100–200 m from the highest tide point, 100 m zones around Palu Bay, except in Lere, West Besusu, and Talise, which were set at 200 m). There was coastal-fishing village relocation inland (e.g. West Mamboro Village) with houses having open ground floors to allow tsunami flow. However, as noted in the 2022 EEFIT visit, daytime dwellings of fishing people continue to be occupied within the exclusion zone, and the open ground floors have often been converted to living spaces (see Baiguera et al. [3] for more detailed discussion). There is also a significantly-sized reconstructed mosque within or near the tsunami exclusion zone (Baiturrahman Mosque).

Table 1
Increase in Banda Aceh population following IOT.

Year	Total Banda Aceh (BA) popn.	Increase in total BA popn. since 2005	Popns. of BA sub-districts at least partially in the red zone				Total popn. of sub-districts with areas in the red zone	Incr. in red zone sub-district popns. since 2005
			Meuraxa	Kuta Raja	Kuta Alam	Syiah Kuala		
2004	265,098		34,592	21,632	54,718	32,590	143,532	
2005	177,881		2221	2978	35,033	25,418	65,650	
2010	223,446	26 %	16,484	10,433	42,217	34,850	103,984	58 %
2020	252,899	42 %	26,861	15,291	42,505	32,969	117,626	79 %

3.2. Thailand spatial planning and development

One year after the IOT, Thailand regulatory institutions [32] issued restrictions on construction in the coastal zones of the Phang Nga and Krabi provinces affected by the tsunami. These included the requirement that all buildings must be designed by civil engineers according to relevant building design codes, and they must use reinforced concrete (RC). Recent advancements in remote sensing technology have allowed for the collection of high-resolution satellite imagery. This technology provides detailed information about the built environment, crucial for analysing exposure growth and identifying vulnerable areas.

Worryingly, Fig. 2 shows that the population of Khao Lak within the IOT inundation zone has grown by 212 % between 2008 [33] and 2019 [34], as evidenced by the increase in number of building footprints from 1,502 to 4,604. The results also reveal that permanent residents live further inland than in the tourist areas.

3.3. Japan spatial planning and development

Following the GEJE 2011, Japan's coastal defence planning went through something of a paradigm shift [35]. Two different levels of tsunami would now be considered, depending on their frequency of occurrence. Coastal defence structures should resist Level 1 tsunamis, but Level 2 tsunamis should only be tackled with a combination of disaster management approaches. Many locations affected by the GEJE now have designated disaster risk areas; these restrict residential housing construction, permitting only commercial/industrial construction [35]. However, there are further measures, as exemplified in Sendai City, home to the IRIDeS at Tohoku University. The Sendai City Earthquake Disaster Reconstruction Plan [36] combines multiple defence, evacuation, and relocation strategies (see Fig. 3). Sendai City is vulnerable to tsunamis due to its flat topography; those who survived the GEJE evacuated to the top of tall buildings and elevated roads. The new defences are based upon tsunami simulations of the GEJE, with the most seaward wall designed to withstand 150-year return interval tsunamis and 50-year storm surges [35]. An additional prefectural road has been constructed, closer to the shoreline, to provide multiple functionality as a levee. It has a height of 7.0 m T.P. (Tokyo Peil), with a width that can accommodate three large vehicles to ensure two lanes of moving traffic if a car breaks down. Junctions in the road are at elevated heights rather than running underneath the road to prevent the tsunami from travelling through the openings. One-way flap-gates are also provided to ensure that land on the leeward side can drain towards the coast in times of high rainfall. Another layer of defence is provided by a replanted coastal forest. The purpose of the previous disaster prevention forests had been to reduce coastal winds and wind-blown sand and protect from high tides and coastal fog. However, most of the forests were destroyed by the tsunami due to the shallow roots of the trees, which are thought to have occurred because of a high-water table. Therefore, the land level has been increased by 2–3 m and replanted. The trees are also valued from an ecological perspective. Vertical evacuation structures and evacuation hills are also located in this area. Finally, in addition to the structural countermeasures, residents were encouraged to move inland. Pakoksung et al. [37] show that the comprehensive combination of countermeasures, comprising coastal

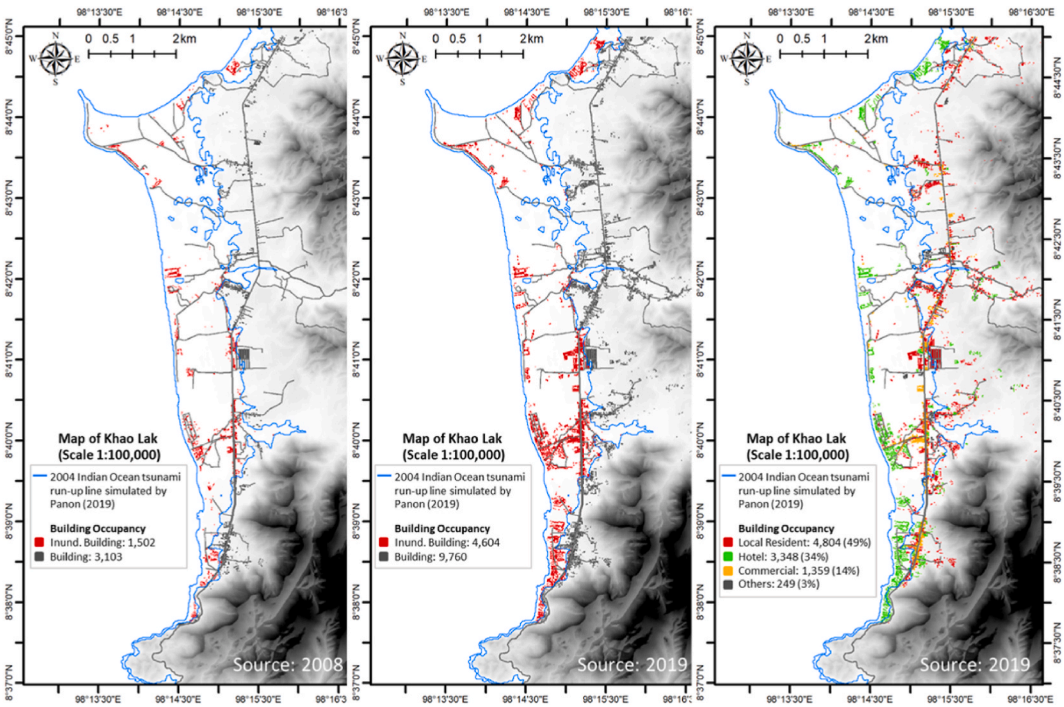


Fig. 2. Khao Lak buildings exposure growth.

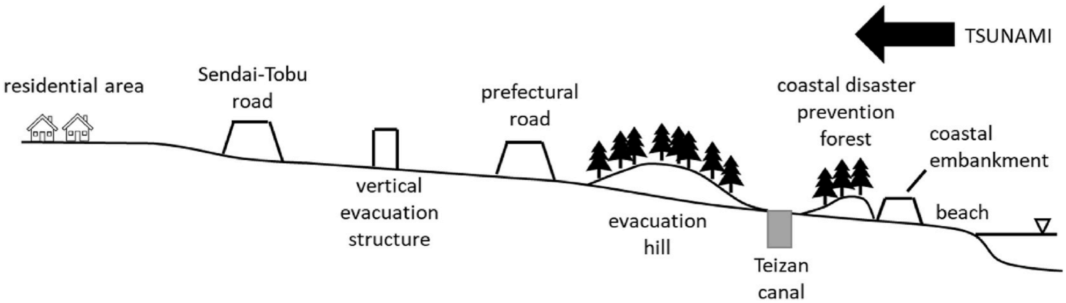


Fig. 3. Conceptual image of the Sendai City multi-layer tsunami mitigation measures (after [38]).

levees, a coastal disaster prevention forest and an elevated road, may reduce the area inundated by the tsunami by 20 km^2.

In Kesennuma City, Miyagi prefecture, which was devasted by the 2011 GEJE, there was an initial reconstruction plan to build a large seawall (trapezoidal revetment) inland of which is the Japanese Railway line (JR, Fig. 4). However, for the crest to be high enough to provide sufficient protection, the revetment would need to be extremely wide, significantly reducing the width of Ooya beach. A revised plan was devised to move the revetment further inland, preserving the beach. The route of the JR line was also moved inland and was turned into a bus rapid transit (BRT), connecting settlements along that stretch of the coast. The bus route, road and buildings would all be at the new revetment elevation, as shown in Fig. 4.

Another approach is evident in Yuriage, a coastal neighbourhood in Natori city situated south of Sendai Airport that was devastated by the tsunami. In Yuriage, residential housing has been permitted in the previous inundation area, but only along a 750 m wide strip inland of the canal that has been elevated by 5 m [40].

4. Development of tsunami design codes in Indonesia, Thailand and Japan

The development of design codes for tsunami loading has significantly evolved over the years, reflecting a growing understanding of the risks posed by tsunamis following major events such as the Indian Ocean Tsunami. Fig. 5 shows the evolution of design codes in Indonesia, Thailand and Japan for tsunami loading and effects since the IOT. In Indonesia, whilst they have had seismic codes dating back to the 1960s (PBI 1966 – The rule of concrete construction in Indonesia), but codes addressing design for tsunami loads were not published until 2020 when SNI 1727 adopted ASCE 7–16. Similarly, in Thailand, building codes for seismic actions date back to the 1980s (Uniform Building Code, 1985) and tsunami loads were introduced later (2008), partially based upon the US Construction Manual (FEMA-55, 2000) and the City and Council of Honolulu Building Code (CCH, 2000). During the 2022 EEFIT mission to Thailand, compliance with these codes was observed in a hotel we surveyed (The Waters, Khao Lak). Finally, Japan has the most highly developed building codes for seismic and tsunami load considerations [41,42] with significant developments/revisions following the IOT and the GEJE, including a guideline concerning structural damage to tsunami evacuation buildings etc. [43]. Their guidelines consider factors such as buoyancy forces that can lead to overturning, including RC buildings [44], sliding, the effect of building openings, pile extraction, scour, and debris loading. However, there has apparently been no significant impact from these comprehensive codes in Indonesia and Thailand. It should be noted that all these codes cover only engineered buildings, not small-scale residential units.

5. Coastal evacuation planning in Indonesia, Thailand and Japan

Successful coastal evacuation planning should cover warning systems, effective training, and evacuation infrastructure and mechanisms. In this section the processes and strategies for coastal evacuation planning within Indonesia, Thailand, and Japan are described. From the introduction of the Indonesian Tsunami Early Warning System (InaTEWS) following the IOT to the evolution of Thailand's real-time seismic and sea level monitoring networks, and Japan's advanced tsunami early warning protocols, this comparative analysis evaluates the effectiveness and adaptability of these strategies. The discussion also includes the effectiveness of community training and preparedness exercises, and the establishment of evacuation routes and structures designed to safeguard populations during such events. By detailing the advancements and challenges encountered in Indonesia, Thailand and Japan, this

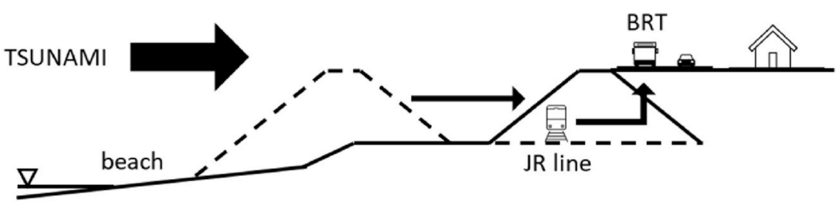


Fig. 4. Initial and revised Kesennuma coastal defences and transport infrastructure plan, dashed lines representing the initial plan (after [39]).

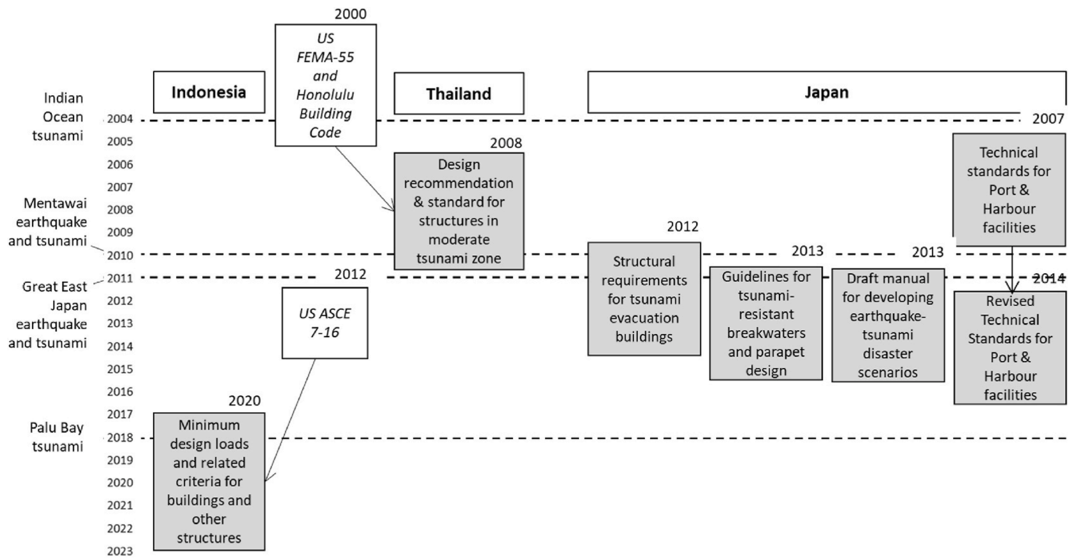


Fig. 5. Development of tsunami-engineered building codes in Indonesia, Thailand and Japan with links to US codes alongside critical disasters.

overview provides a description of technical and operational aspects of coastal evacuation planning, also highlighting the collaborative efforts between governments, local communities, and international bodies.

5.1. *Tsunami early warning systems*

Before the 2004 IOT, there was no tsunami early warning system in the Indian Ocean region, and many countries did not have the capability to detect and warn populations in their low-lying coastal areas. The absence of such a system contributed to the high death tolls in southern Thailand, even though there was a delay of up to 120 min between the earthquake and the first tsunami arrival in Khao Lak and Phuket, which would have been sufficient time to issue an effective warning. Consequently, implementing adequate warning systems is valuable in enhancing the resilience of populations susceptible to tsunami impacts.

5.1.1. *Early warning systems in Indonesia*

Following the 2004 IOT, various efforts have been made to mitigate the impact of tsunamis in Indonesia. Principally, there is now the Indonesian Tsunami Early Warning System (InaTEWS). It is a complex people-centred system which requires communications between various agencies and ministries. It includes four key elements [45]: risk knowledge, risk monitoring, dissemination, and response capability. Several institutions have a role in the InaTEWS: the National Tsunami Warning Centre at the BMKG office, BNPB, local governments, Indonesian Military, National Indonesian Police, television and radio stations, communities at risk, cellular service providers and Hotel Managers. The warnings in InaTEWS are delivered in four stages, as shown in Fig. 6(a).

Within the first 2–5 min, due to the proximity of coastal areas to the earthquake sources, a tsunami warning is essential. Note that the Palu tsunami inundated the coast within 5 min of the earthquake [14]. The InaTEWS is based upon three sensor types: (i) 159 seismic stations, which provide information on the epicenter location, depth, and the Mw; (ii) a 22 GPS systems comprising more than 20 real-time stations; and (iii) approximately 100 tide gauges. Offshore wave buoys were formerly part of the system, but they are no

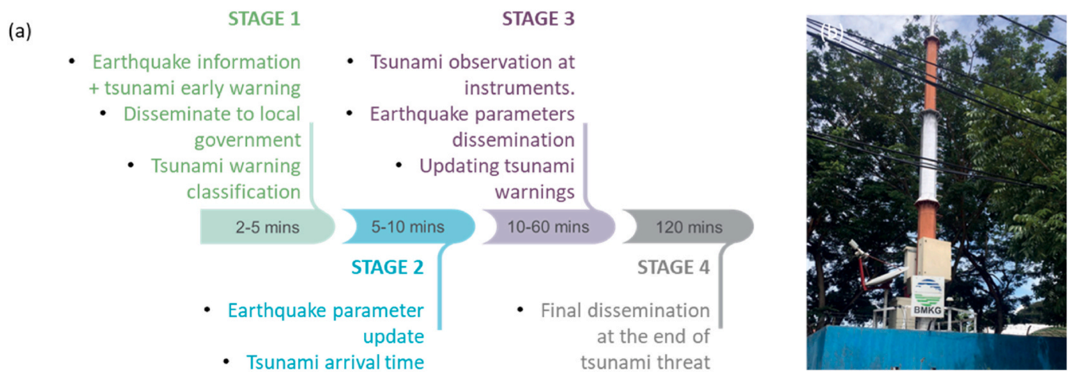


Fig. 6. Indonesian tsunami early warning system stages (a) and photo of a siren (b).

longer relied upon due to their lack of reliability and high economic cost [46]. There are 4,470 pre-calculated tsunami scenarios automatically matched to the measured data, first by seismic information, then with either or both the GPS and tide gauges [47]. Based upon the most closely matched scenario, a warning is then issued according to the estimated wave height (EWH) [46]:

- Advisory EWH <0.5 m;
- Warning 0.5 m < EWH <3 m;
- Major warning EWH >3 m.

However, landslide-generated tsunamis, responsible for the Palu Bay event, are not modelled in these scenarios. Since its launch in 2008, InaTEWS has issued warnings following 22 earthquakes, two of which had significant tsunami impacts, namely the 2010 Mentawai Islands tsunami (with 504 tsunami victims) and the 2018 Palu Bay tsunami (with more than 1000 tsunami victims) [14]. Another two were overseas tsunamis, namely from Japan on March 11, 2011 (with one victim in Papua) and from Chile on February 27, 2010.

The system was also tested by the April 11, 2012 earthquakes that affected Banda Aceh (8.2 Mw followed by 8.6 Mw just over 2 h later). Only modest tsunami waves were generated by the earthquakes (~1.06 m in Meulaboh in the issued warning), but widespread panic ensued. A joint rapid assessment of the situation followed [48], involving many Indonesian institutions, but also including UNESCO, UNDP and Tohoku University (Japan). They conducted interviews, circulated questionnaires (up to 800 respondents in Aceh) and conducted focus group discussions. The assessment highlighted issues including: ineffective/unhelpful sirens (local sirens not being activated within an appropriate time window and when finally activated causing panic due to the fear of imminent inundation), traffic congestion (families travelled in cars to find members before trying to evacuate to safe locations), the BMKG website crashing after receiving 400,000 visits, procedural/equipment issues [48]. Furthermore, only a few dozen people ran to the escape buildings, despite the drills [49].

The large number of tsunami fatalities in Palu Bay in 2018 sparked polemics and criticism of the effectiveness of InaTEWS. Various national and international media criticized the InaTEWS system, which was considered not to work optimally, thus failing to provide early warning to the community in the affected areas. Facing this criticism, BMKG, as the operational implementer of InaTEWS, stated that the early warning system had actually been running well. It was stated by Dr. Daryono, Head of the BMKG's Centre for Earthquake Information and Early Tsunami Warning, that BMKG had followed the established standard operating procedures (SOP) in providing earthquake information services and tsunami early warning. There was no human error or instrument error by the BMKG in issuing an early warning for a tsunami Palu [50]. UNDRR and UNESCO-IOC [14] make the point that responses to the early warnings issued by BMKG are the responsibility of the local government. Their investigation found that the warning bulletin issued by InaTEWS was not conveyed to the local Palu community. They concluded that too many agencies and institutions are involved in the early warning chain at the regional level [14]. In Palu Bay the response was further complicated by the fact that, at that time, BKMG issued warnings based

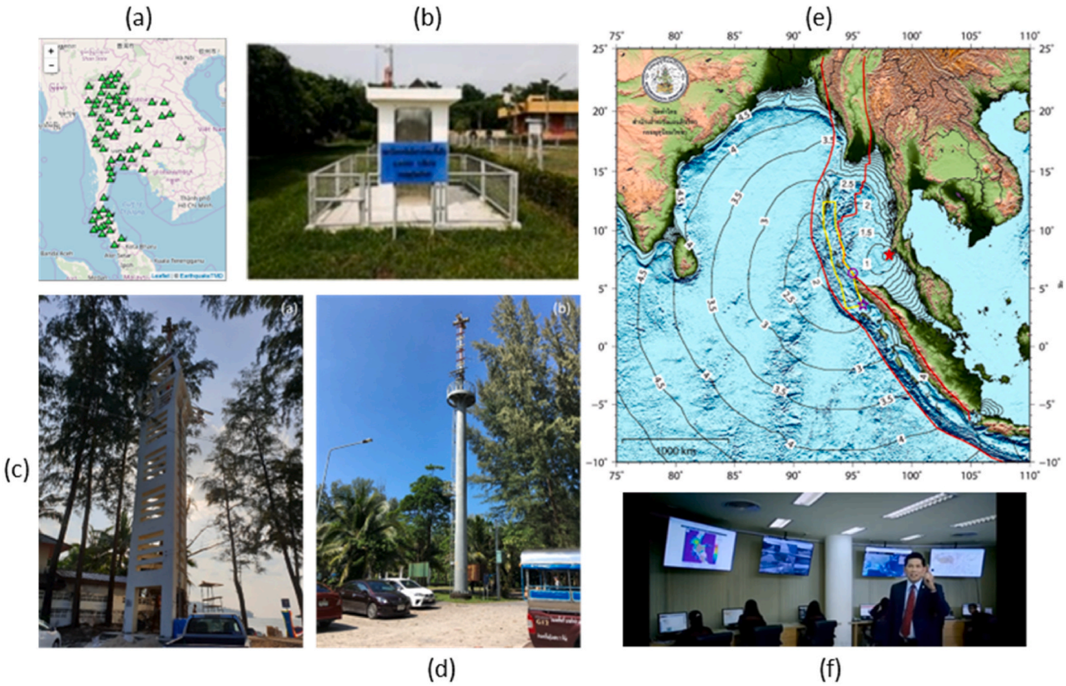


Fig. 7. Thai early warning systems: (a) location of digital seismic stations; (b) example digital seismic station; (c) and (d) example warning towers; (e) tsunami arrival time map; (f) testing of the warning system.

on the Mamuju tide gauge station located much further to the south, not the Pantoloan Port tide gauge within Palu Bay itself [51].

In terms of hardware, the city of Palu has one tsunami siren (Fig. 6(b)), installed by the BMKG in 2011, located in the city centre, about 1.9 km from the beach. There is a general understanding of what the siren does. According to the BMKG mandate, on the 26th day of every month, there is an audible test of the siren. Some of the local inhabitants, questioned during the EEFIT visit in November 2022, said that the tsunami siren had not sounded in drills in the months before the 2018 earthquake and tsunami. During the earthquake, the siren did not sound due to power outages (including failures of the backup power supply) and telecommunication disruptions following the earthquake [14]. In the 2018 EEFIT Palu mission conducted by some of the same team [16], it was notable that all interviewees evacuated based on their own observations: the ground motions and the sight of the water, with two interviewees also mentioning strange animal behaviours (moving away from the sea) and none mentioned early warning systems. Furthermore, 'fake' tsunami warning towers (actually, standard telecommunication towers) are also said to have led to deaths, as residents were waiting for them to issue an alert before they would start their evacuation. This telecoms tower was installed by contractors who wrongly conveyed its purpose [14]. The city of Banda Aceh has five warning siren towers around the city. In Palu, there were also delays in the reception of warning messages via SMS. An example was given of residents returning to the coast (having evacuated inland, based on previous experience) 2.5 h after the first (more minor) earthquake. They then picked up messages via SMS and social media to say that there was no tsunami risk from the earthquake and were then caught up in the subsequent large earthquake and tsunami [14].

5.1.2. Early warning systems in Thailand

Real-time seismic and sea level monitoring networks in Thailand have been developed and maintained by the Thai Meteorological Department (TMD) since 2005. TMD is a governmental organization responsible for monitoring, analysing, and warning for natural hazards, including earthquake information and tsunami warnings. As of January 2018, TMD is operating around 80 digital seismic stations (Fig. 7(a) and (b)). They will provide a real-time tsunami warning to the National Disaster Warning Center (NDWC) within 15 min of any earthquake. Two wave buoys [52] also provide data; one buoy (No. 23461), located 340 km off the coast of Phuket, stopped sending signals in January 2024. The Department of Disaster Prevention and Mitigation (DDPM) planned to replace it between July and October 2024 [53].

Unlike in Indonesia and Japan, the warning types do not differ based on wave size. Instead, a first warning is issued after detecting an earthquake within seismic awareness zone 1 (Thailand, Myanmar, Malaysia and northern Sumatra) with a magnitude greater than 7.8 and a focal depth of less than 100 km. The second warning is issued after detecting a tsunami wave from a tidal station or tsunami buoys [54]. NDWC acts as the centre coordinating with other governmental agencies and is responsible for making decisions, announcing all warnings, and evacuating people in high-risk areas. NDWC plan to disseminate warning messages via television, radio, e-mail, SMS, and warning towers. During a follow-up visit in December 2024, the cell broadcast system (CBS) had been tested but was still not operational. When CBS works it will send instant emergency alerts to all mobile phones in high-risk areas, covering all service providers without requiring pre-registration in 5 languages (Thai, English, Chinese, Japanese, and Russian). There are now 130 warning towers [55] in six tsunami-affected provinces (Krabi, Phang Nga, Phuket, Ranong, Satun, and Trang) (Fig. 7(c) and (d)) installed in popular tourist and low-lying coastal areas along the Andaman Sea. These towers are maintained by the Department of Disaster Prevention and Mitigation (DDPM). Routine weekly tsunami warning practices are scheduled from these towers by playing the Thai National Anthem at 8 a.m. every Wednesday to confirm there are no operational problems. However, this was not audible during the two Wednesdays that a sub-set of the EEFIT team was in Phang Nga in 2022. At the Outrigger Hotel in Khao Lak, the manager said that warnings would be provided to hotels, and cars with loudspeakers would warn people on the main highway. These warnings would come via local NDWC and DDPM staff and be propagated further by local civil staff. In rural areas, it is common to have loudspeakers for community announcements (e.g. annual vaccine programme, local sports, local election, etc.).

TMD has also developed tsunami source inversion with time reverse imaging to forecast tsunami arrival time from other potential earthquake sources. Tsunami arrival time maps (Fig. 7(e)) from different tsunamigenic sources, which might directly impact the Thai coastlines, both in the Gulf of Thailand and the Andaman Sea, have been pre-determined for warning purposes. As shown in Fig. 7(f), the tsunami early warning system is tested and validated in the SOPs for routine checks by the NDWC.

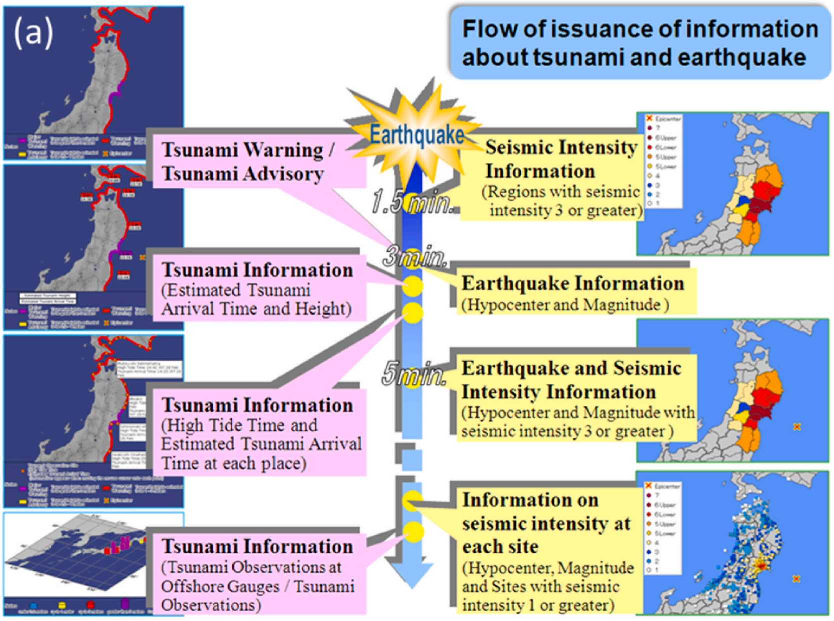
5.1.3. Early warning systems in Japan

The Japan Meteorological Agency (JMA) has operated its tsunami early warning system since 1952. They began using quantitative methods for the warning in 1999 [56]. This method is based upon pre-simulated assumed earthquake magnitudes and related fault parameters stored in a database, which enables the estimated tsunami arrival time and height to be announced from the real-time observation of earthquake-related information within a few minutes. This approach is used because simulating a tsunami immediately after the occurrence of an earthquake requires much computational time, so the JMA cannot announce the warning before the actual tsunami arrives. This tsunami database is validated using historical tsunami events. It has been improved over time with measures such as the use of finer simulation grid size, the adjustment of roughness coefficients, the addition of more cases of the assumed fault parameters, and the increased accuracy of the tsunami height estimation [57–59]. Several offshore tsunami buoys existed before the 2011 tsunami, but they were not sufficient in number. Japan's National Research Institute for Earth Science and Disaster Resilience (NIED) have subsequently installed the "seafloor observation network for earthquakes and tsunami along the Japan Trench" (S-net), consisting of 150 sensors which cover the area of the 2011 earthquake and its surrounding areas [60,61]. The sensors comprise ocean bottom pressure sensors (for tsunami detection) and seismometers. This dense real-time observational system will support the accuracy of the tsunami warning. It is not only the above-mentioned technical improvements but also an operational perspective. JMA decreased the tsunami warning category from eight to five quantitative expressions. It will use qualitative expressions when it takes time to determine the exact earthquake magnitude scale [62]. An infographic showing how information will be conveyed is shown in Fig. 8(a).

There are three levels of tsunami warnings [65]:

- Major Tsunami Warning – Over 10 m or 5–10 m or 3–5 m;
- Tsunami Warning – 1 m-3m;
- Tsunami Advisory – 0.2 m–1 m.

In coastal areas of Sendai City, 79 outdoor speakers will broadcast tsunami evacuation information. The poles supporting the transmission systems have been redesigned since the GEJE 2011 when 38 poles were damaged: revised battery height (8 m), operation time (72 h), and pole diameters (319 mm). Warnings will also be issued by other mechanisms, including mobile phone and landline [66], email, the Sendai City website, and Tweets from the Sendai City Crisis Management Bureau. Fire engines and helicopters will also make announcements, and there have been recent trials with announcements from drones in coastal areas [65]. Furthermore, people are encouraged to either go inland or into a designated evacuation site on foot when they experience strong ground shaking, not waiting for a tsunami warning [66]. At the time of writing, there have been reports of the successful issuance of a tsunami warning (later downgraded to tsunami advisory) in the 2024 Noto earthquake, including by an overseas visitor who received a message in



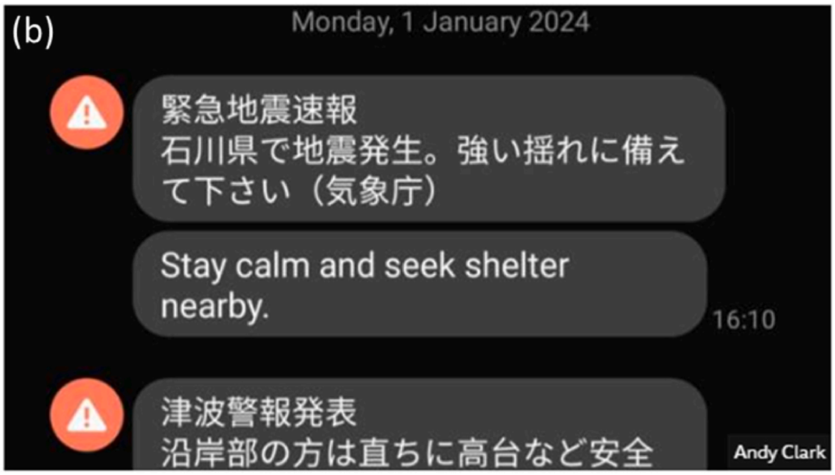


Fig. 8. Japanese early warning systems: (a) flow of information [63] and (b) message received by English visitors caught up in the 2024 Noto Peninsula, Japan Earthquake [64].

English (Fig. 8(b)). Notwithstanding this effective communication, a visit by an EEFIT member to Japan in 2022 was made with no advanced notification of hazards in different areas, e.g., the requirement to download a smartphone hazards app.

5.2. Tsunami preparedness training

Conducting routine training is crucial for identifying weaknesses in tsunami evacuation preparedness. Exercises and drills can raise awareness among various stakeholders at risk and suggest how warning systems should function.

5.2.1. Training in Indonesia

Tsunami and broader disaster education is incorporated into the school curriculum; an approach known as *Satuan Pendidikan Aman Bencana* (Disaster Resilient Education) is explicitly implemented for elementary and junior high schools. University academics have been involved in the concept and development phases of the formal guidelines [67]. TDMRC has been actively engaged in school disaster education, e.g. art workshops on disaster mitigation and preparation of school tsunami evacuation maps and drills. The involvement of local partners is critically important; Sakurai et al. [68] found that those Banda Aceh schools with externally-driven (i.e. donor) disaster-preparedness activities did not continue them due to a lack of ownership/funding.

Within the wider community, concerning the City of Palu Contingency Plan (2012), the city of Palu held a National Rehearsal for Tsunami Disaster Management in 2012 (Fig. 9). The National Disaster Mitigation Agency (BNPB) organised the activity with various agendas: discussions on disaster topics, exhibitions, and film screenings of simulations dealing with a tsunami [14]. The people who attended the three-day training were then asked to become Community Disaster Preparedness Groups (KSB) for each village. During the training, residents received instructions to take part in a tsunami evacuation drill. Some *kelurahan* (city wards) participated in the self-evacuation activities a few days earlier, which were facilitated by a consortium of non-governmental organisations. In the scenario, women, children, the elderly and pregnant women were transported by car or motorcycle. Sirens sounded as a sign of an earthquake and that it was time to run for safety to a safe place. But when the actual tsunami happened, the scenario that was taught did not work. Some people still remembered what was done during the drill, which mostly resembled a dramatization of an earthquake incident rather than a preparedness exercise.

Moreover, not all people in Palu had participated in evacuation training [14]. On the EEFIT mission we heard first-hand that this was the case in Banda Aceh, where only a representative from a (school) community was required to engage with the evacuation activity. Syamsidik et al. [69] also report that the preparedness of some schools and health centres in the Aceh region of Indonesia was compromised due to insufficient drills and operational guidelines. Furthermore, the external disaster education group training provided to communities subsequently affected by the Palu event was based on characteristics of the IOT, where the sea receded, and there would be 20–30 min between the earthquake and tsunami [14]. This sequence of events did not happen in Palu, which may have led to some of the tsunami casualties.

The latest official tsunami preparedness simulation guidelines were published in 2014 by Indonesia's National Disaster Management Agency [70]. However, frequent training is still being conducted by both BPBA (Aceh Disaster Management Board) and BPBD (Aceh Disaster Management Regency). Activities include training sessions or workshops related to emergency response and JITU PASNA (Post-Disaster Needs Assessment). The programmes serve as part of building a more resilient community and trying to ensure a well-coordinated disaster response.

5.2.2. Training in Thailand

Most areas in Thailand affected by the IOT have emergency response plans and countermeasures which follow international guidelines or prescriptive designs. Current practice is limited to raising awareness among people about proper response and maintenance processes, as shown in Fig. 10(a) (government level) and (b) (local community). The EEFIT team that visited Phuket in 2022

Fig. 9. Evacuation training in Palu City, Indonesia, in 2012 UNDRR and UNESCO-IOC [14].

had made a previous visit in 2019, noting confusing evacuation signage [71]. Major improvements were evident in 2022, but there was still a little ambiguity, particularly for visitors unfamiliar with the geography. Many of the hotels we surveyed had evacuation plans, some including details about how staff would pick up food from the kitchens to provide for their guests.

The Department of Disaster Prevention and Mitigation (DDPM) are responsible for organising annual evacuation drills for local people in Phuket and Khao Lak. These focus on building awareness, but they cannot fully assess the readiness of evacuees and do not reflect reality accurately. In one drill, participants only started from the beach (Fig. 10(c) and (d)), but evacuations would more realistically start from different locations. In addition, decisions to evacuate would change based on the time of day and the type of information provided. The evacuation routes are generally designed for on-foot evacuations, but most people would choose to evacuate by vehicle, which could be controlled by traffic systems. Realistic evacuation drills are not practiced due to several factors, including commitment to participate, time, and budget constraints. In December 2024 on a site visit to Ban Nam Khem, we learned about some good practice developed by the community itself. Here the residents are very exposed to tsunami inundation, with a roughly 3 km journey to safety. When they first conducted evacuation drills, from a central location, it took ~40 min. Now, with further practice they can evacuate to safe areas, *from their normal place of work/activity*, in just 17 min. Some hotels practice their own drills, e.g. the Outrigger Resort in Khao Lak had a drill of evacuation procedures every three months. In general though, infrequent exercises and drills are indicators of weaknesses in evacuation preparedness that need to be addressed. During the same visit in 2024 we also observed Disaster Preparedness Workshops at an elementary and junior high school, led by Yasuda Mari from Tohoku University. They comprised an informative lecture, an activity of turning a large handkerchief (printed with evacuation instructions) into a versatile bag, and a disaster awareness game. More than 400 of these workshops have been undertaken in Thailand, Japan, Hawaii and elsewhere. The Thailand Tsunami Museum in Khao Lak also fulfils an educational role in the region.

An alternative approach to realistic drills, agent-based modelling, has been undertaken by two of the Thailand EEFIT team members. Their investigation [72] considered two locations in Khao Lak: Ban Nian, where 80 % of the population was assumed to be visitors and Tab Lamu, where only 40 % were visitors. Assumptions about factors such as evacuation preferences, shelter recognition, etc., were based on questionnaire responses, and others, such as warning times, were based on previous evacuation events. The results revealed the dependence of successful evacuations on warning time, preparation time and shelter recognition. It also highlighted the fact that there is insufficient provision of vertical evacuation shelters. Therefore, local and tourist populations alike remain vulnerable.

5.2.3. Training in Japan

Japan has well-developed training programmes for populations living within tsunami hazard zones, with officials and residents all involved. In the Miyagi prefecture, where there are extensive low-lying coastal plains and previous inundation was up to 5 km inland, drills began in 2012, shortly after the GEJE in 2011. In Yamamoto Town, vehicle evacuation was intentionally incorporated into a drill as the location was, at that time, experiencing significant truck movements associated with rebuilding the seawall. As expected, the

Fig. 10. Tsunami evacuation training in Thailand: (a) government level; (b) local community level; (c) and (d) evacuation drills.

drill resulted in long queues of up to 400 m at road junctions. Based upon this, traffic regulation was identified as an important area to resolve [73]. In Iwanuma, drills have improved the proportion of people alerted by tsunami sirens and increased the number of people evacuating on foot [73].

In Sendai, there are annual drills on World Tsunami Awareness Day (05 November), where people actively use the evacuation facilities [65]. Hazard maps are a key feature of preparedness in Japan. Dedicated map workshops are held several times a year, ensuring that any revisions are conveyed to affected communities. Maps are distributed annually so that those who have recently moved to Sendai City are informed [65] with an English language version available. Maps are also used in the dedicated drills and volunteer workshops. The visually engaging maps indicate the tsunami inundation areas, evacuation facilities, and sites. The maps indicate two zones in Sendai, split by the newly constructed/elevated road; both sides of the road were inundated in 2011. On the seaward side of the road, people need to evacuate when there is a Tsunami Warning, but on the inland side of the road, people only need to evacuate for a Major Tsunami warning. On the reverse of the map is a ‘Tsunami Evacuation Guide’ with helpful information/reminders. It was prepared under the supervision of IRIDeS, the Tohoku University research institute [66]. The 6th edition map in 2022 used the Prefectural tsunami flood estimates and took into account the tsunami increasing the river levels [66] with a ‘floodwater’ line based on GEJE 2011.

5.3. Evacuation routes and structures

In tsunami-prone regions, the effectiveness of evacuation routes is critical for minimising casualties and ensuring public safety. Nevertheless, several challenges remain in optimising these routes, with factors such as human behaviour, terrain, and infrastructure limitations significantly influencing evacuation success. One prominent issue is the delay known as "milling time," where individuals hesitate or seek confirmation before evacuating after receiving an alert. This hesitation can severely reduce the chances of reaching safety, particularly in events where time is constrained. Research has demonstrated that even a 10 to 15-min delay can substantially increase mortality rates in near-field tsunami events, underscoring the need for enhanced public education and training programs to ensure immediate evacuation upon receiving warnings [74]. Moreover, evacuees often prefer familiar or primary routes, which can

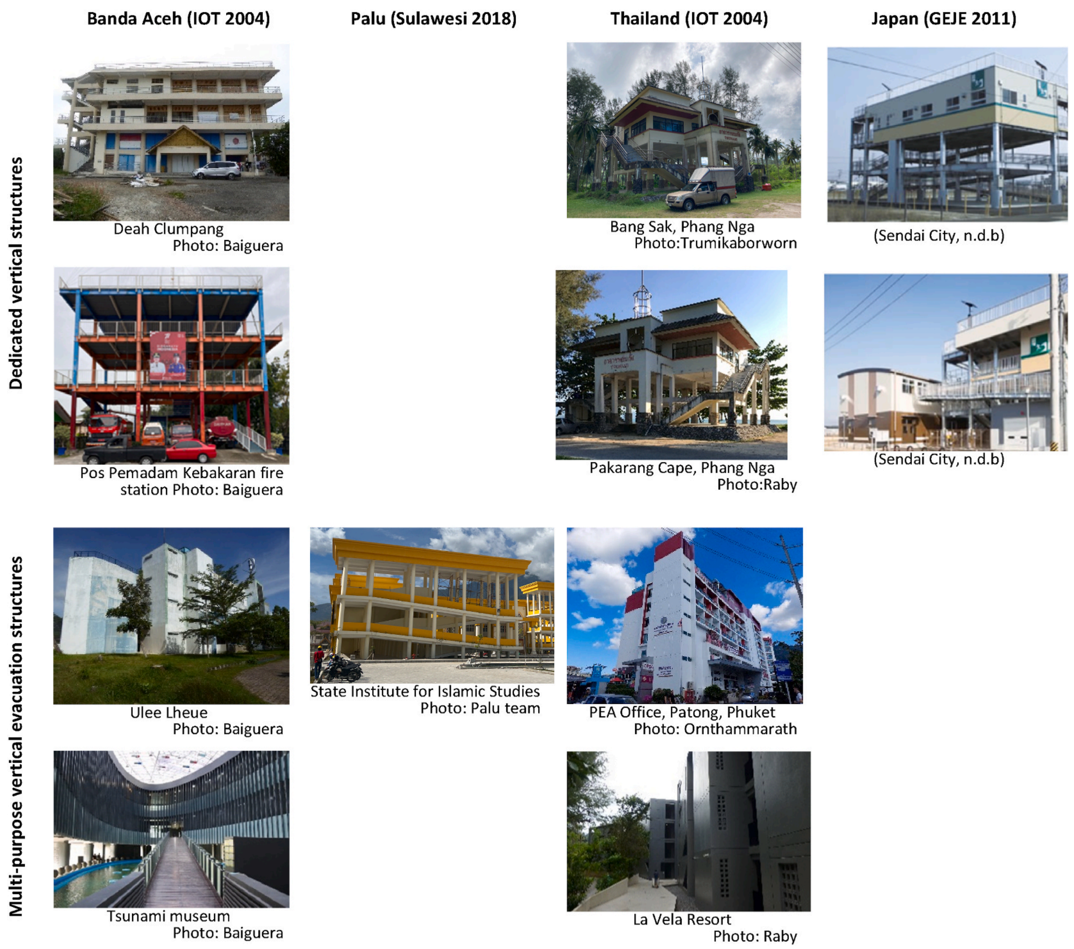


Fig. 11. Examples of vertical evacuation structures in Banda Aceh, Palu, Southern Thailand and Japan.

result in congestion, particularly in regions where vehicular evacuation is prevalent [75]. Although recommendations emphasise evacuating on foot, many individuals still choose to use vehicles, exacerbating traffic problems and delaying the overall evacuation process. To address these challenges, recent advances in technology now allow for the modelling and simulation of evacuation behaviours, providing planners with tools to predict bottlenecks and adjust routes dynamically or to implement mixed-mode evacuation strategies that incorporate both pedestrian and vehicle pathways [76]). Evacuation efficiency depends greatly on terrain and environmental conditions. While well-maintained roads enable faster movement, unpaved or difficult terrain, such as sandy areas, can hinder evacuation efforts. Consequently, effective planning must consider the local landscape to minimise travel over challenging terrain. Recent advancements in evacuation planning include digital tools and simulation-based training, which offer communities the opportunity to practice evacuations in realistic settings. These tools not only familiarise residents with evacuation routes but also enable planners to test and refine these routes based on real-world data, enhancing the efficiency and speed of evacuations. Integrating these technologies into public preparedness programs has been shown to improve the success of evacuations significantly, ultimately reducing the risk of casualties.

Effective evacuation of people in a tsunami inundation zone can also be achieved through vertical evacuation structures rather than evacuation routes. These structures allow residents to seek refuge in high-rise buildings or other elevated safe zones rather than attempting to travel longer distances inland. The choice will be influenced by estimated tsunami arrival time in the different locations, i.e. when time is short, it will not be possible to travel a relatively long route away from the inundation zone, so the only option will be to ascend a tall structure. A variety of vertical evacuation structures built in the four locations are shown in Fig. 11. They are divided into dedicated and multi-purpose structures. An indication of their spatial distribution is given in Fig. 12.

Banda Aceh lies on a coastal plain with no natural vertical escape options available to most of the city residents. This explains why, during the reconstruction of the city, a total of eight tsunami vertical evacuation (TVE) buildings were constructed. As shown in Fig. 12 (a), most of them are located in the northern sector of the city, where the largest tsunami inundation depths were recorded in 2004 (10–12 m). The dedicated TVE structures include those built by the Local Disaster Management Agency (DMA) in Deah Glumpang

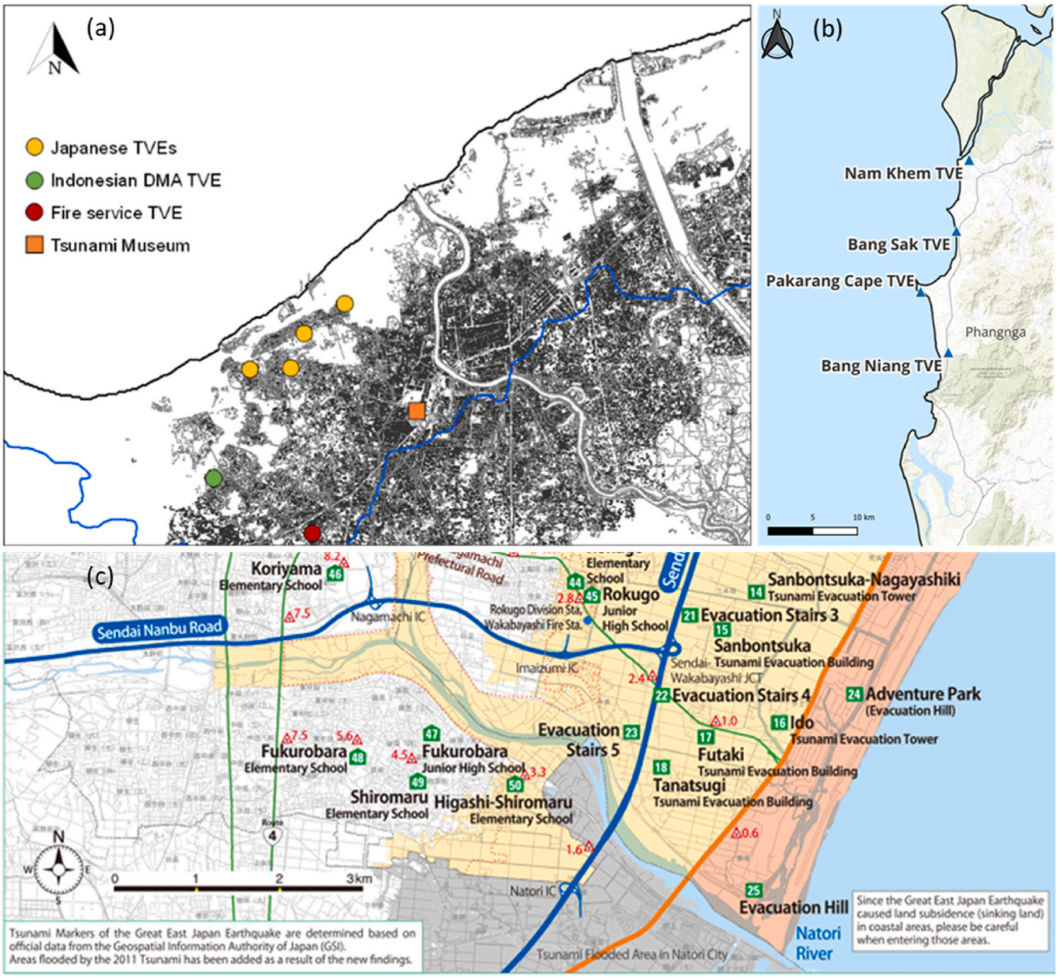


Fig. 12. Spatial distribution of evacuation structures in (a) Banda Aceh (b) Khao Lak and (c) Japan [66].

(Fig. 11) and a three-storey steel building at the local firefighter department (Fig. 11). However, in Banda Aceh, the local population has no affinity with the TVE structures and has not used them in tsunami alerts [69]. The *multi-purpose* TVE structures include the RC structures built with the support of the Japanese government, one of which is located in Ulee Lheue, the area of the former seaport of Banda Aceh. Another is one of the blocks that used to host the Tsunami and Disaster Mitigation Research Center (TDMRC) headquarters in Ulee Lheue prior to moving to the main Syiah Kuala University campus (Fig. 11). This building is a massive reinforced concrete structure, 13 m tall, rectangular in plan, with a dense grid of large square columns (75 × 75 cm in section at the ground floor) and with a refuge roof easily accessible via a system of gentle ramps. The building is strategically oriented to have the short side exposed to the tsunami wave impact. To reduce this further, the engineers designed the front of the building as the bow of a ship. The impressive Tsunami Museum in Banda Aceh City (Fig. 11) is also designated as a multipurpose TVE structure. Most recently, the municipal government of Banda Aceh has been trying to identify tall buildings in the city that would be suitable for vertical evacuation and has produced a detailed map of planned evacuation shelters [77]. Referring back to Table 1, the 2020 data suggests that approximately 118,000 people live in sub-districts closest to the coastal zone and would need to evacuate, either further inland or into shelters.

In several locations in Palu, markers have been made for evacuation routes. The routes are indicated by the white line in Fig. 13. However, not everyone is aware of their function. The newly constructed lecture theatre of the State Institute for Islamic Studies (IAIN) (Fig. 11) has been designed to also serve as a TVE facility for the nearby population. It can accommodate 800 people, protecting occupants from tsunami waves up to 11 m, with wide staircases leading to the roof. Pre-dating the Palu tsunami, researchers from Hasanuddin University planned evacuation routes for Palu City, recognising its vulnerability to tsunamis. They used the ArcCASPER (Capacity-Aware Shortest Path Evacuation Routing) tool [78]. However, there was no evidence during the 2018 EEFIT mission that these routes had become established.

Phuket, Thailand's most densely inhabited area, has steep hills nearby, so the need for TVE structures is lower. In the flatter areas of Khao Lak, Thailand, although dedicated TVE structures are available to reduce evacuation distance, the overall capacity may need to be increased. Their spatial distribution is shown in Fig. 12(c), where structures are situated about 10 km apart from each other. This distance is further than most could quickly evacuate on foot. The structures are showing some signs of decay with rusting railings and, in at least one location, had become home to feral dogs. In Patong, Phuket, the Provincial Electricity Authority (PEA) building (Fig. 11), situated near the edge of the IOT inundation zone, is a nominated TVE structure. Typically, though, government buildings are not constructed within the tsunami hazard zone. Instead, they are designated as horizontal evacuation structures and noted in the tsunami evacuation plan at both the provincial and local levels (sub-district) [79]. Several mid-rise buildings, such as hospitals, schools, and hotels, could be suitable for designated TVE buildings in densely populated areas. However, it is also important to check the design of these buildings with the standard of vertical evacuation shelters. At least two of the hotels in the region had buildings that were five storeys tall. The La Vela Hotel had dedicated one of their buildings as a TVE structure. The roof is accessed via a sliding trap door, and though there is no parapet wall or railings, given the good construction quality of the building, it would be a sensible evacuation site. At the Water's Hotel, just 500 m away from La Vela, their five-storey buildings have not been designated as a TVE structure, and

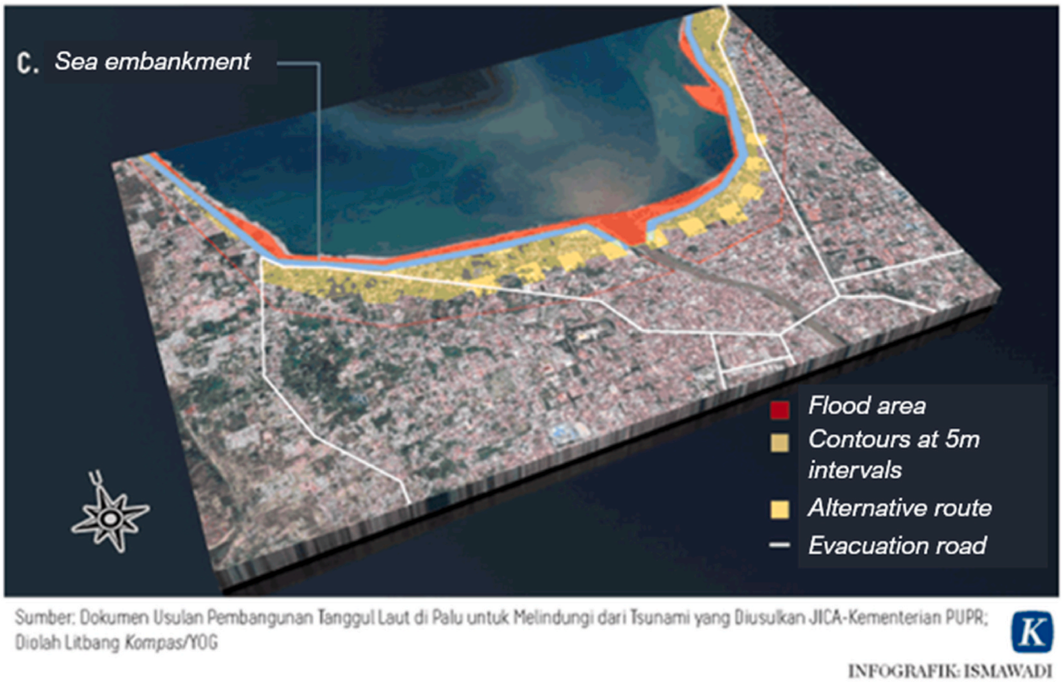


Fig. 13. Palu City evacuation route (in white) [31], with italic text translated to English from original Bahasa Indonesia.

residents would instead have to travel about a kilometre inland out of the inundation zone for a tsunami equivalent to the IOT.

In Japan, during the GEJE 2011, around 106,000 people evacuated to 288 evacuation centres, creating great strain in terms of available food, staffing and privacy [80]. In Sendai City, the capital of the badly affected Miyagi prefecture, there are a large number of evacuation facilities, including six towers, five buildings and five sets of evacuation stairs [65] in addition to constructed hills. The towers have 20 m deep piled foundations, an open ground and first-floor, with external walls on the second floor to provide protection from cold and wind. There is a further area at roof level (10 m). The tower stocks food (to last 48 h), blankets, gas stoves, ropes, life jackets, radio equipment, etc., with lighting provided by PV power. There are balcony areas to allow for rescue of people caught in the wave during the tsunami inundation. Each tower cost about $15 million to construct. The towers and evacuation buildings are locked, with the keys lent to local residents; they can be broken into in an emergency. Evacuation buildings have a dual function as activity centres for the fire corps [65] The recent Noto Peninsula earthquake evidently demonstrated the need to provide support for evacuees over an extended period [81].

6. Development of coastal defence and port structures in Indonesia, Thailand and Japan

Structures along the coastline comprise those that provide some type of defence, preventing waves from engulfing the land, but also those that provide access to the sea for transport, fishing, etc. This section describes the development of both types of structures in the four locations observed by the field teams.

6.1. Coastal defence and port structures in Banda Aceh

After the tsunami struck Banda Aceh city and Aceh Besar Regency, coastal defence structures were constructed along some stretches of the coastline. These structures are in the form of rubble mounds or concrete seawalls. Their purposes are: (a) to preserve the area of Banda Aceh city, as large amounts of the coastal areas which had been used for aquaculture and mangroves, were transformed into a lagoon by the IOT; (b) to protect the land from wave attack and from coastal flooding during Spring tides; (c) to protect the revitalized aquaculture; and (d) to prevent sand deposition over the shoreface and coastal roads. They are not designed to protect against tsunami waves, which have much greater wave height and wavelength compared to storm waves. Forming the rather exposed coastal road connecting the Ulee Lheue Port peninsula to the Tempat Pendaratan Ikan Lampulo Fish Landing port is a rubble mound seawall of 45° shoreward angle with a crest level of about 2 m above the water level (Fig. 14(a)). There are long and wide scour holes along the crest of the wall caused by wave overtopping that has displaced the quarried rock. Gaps have been subsequently filled by much smaller graded rock, giving a fairly level surface for cars but not providing the height needed to prevent overtopping and further damage. This vehicle route is clearly in jeopardy. To the west of the Ulee Lheue Port is an offshore revetment that protects the coastal road connecting the city's main road to the ferry port (Fig. 14(b)). It was the first coastal structure rebuilt after the 2004 IOT, having been badly damaged by the tsunami and severe coastal erosion (probably combined with land subsidence). In addition to protecting the main

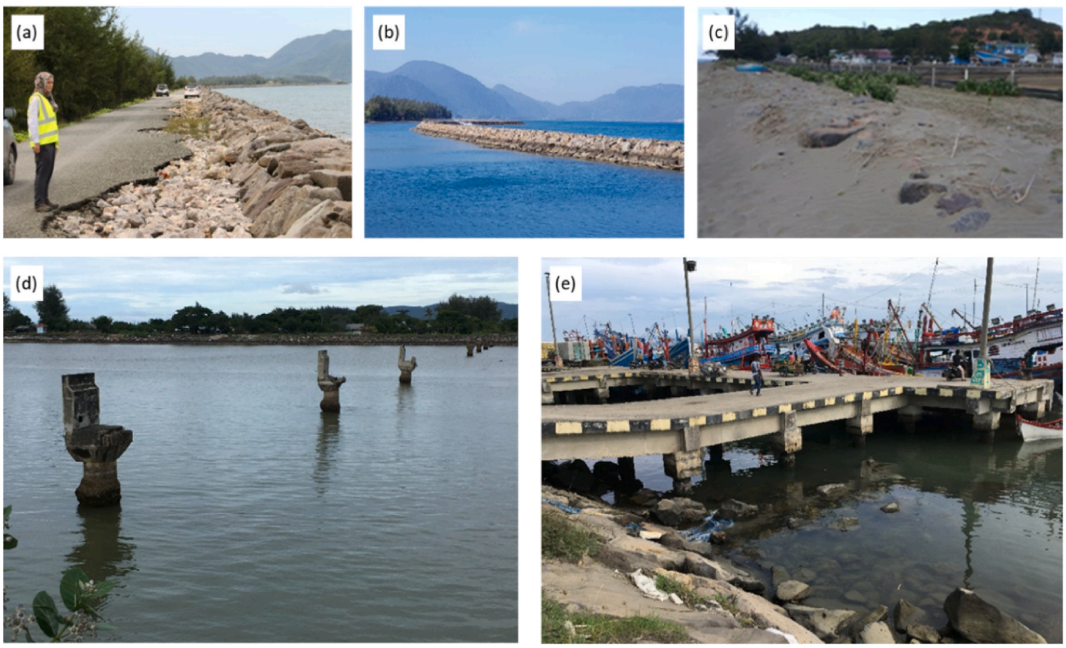


Fig. 14. Coastal defence and port structures in Aceh: (a) coastal road connecting Ulee Lheue Port peninsula to Tempat Pendaratan Ikan Lampulo Fish Landing port; (b) west of the Ulee Lheue Port; (c) Aceh Besar Regency (d) bridge piers across the Aceh river; and (e) jetty in Lampulo fisheries port.

road, it provides calm water for leisure activities, but it is not safe for swimming due to abandoned wells from the former houses. Towards the northeast of the coastal road from Banda Aceh to Ujong Batee at Aceh Besar Regency, more seawall structures are found of rubble mound or concrete types. Some stretches of the seawalls seem to be perched on top of the non-equilibrium shoreface, and some are overtopped by sand accumulation, as shown in Fig. 14(c). The coastline of Aceh has a mixed story of accretion and erosion following the IOT [82]. Also, nowhere in Banda Aceh are mangroves being used as tsunami mitigation; their purpose is just to support aquaculture activities. However, in Palu Bay, Fig. 1(c) (Section 3.1) shows that mangroves are the shoreward line of the multilayer protection plan against tsunamis. Mangrove seedlings have been planted by volunteers on the Palu City shores. Remnants of structures damaged in the IOT are still in evidence in the bridge piers across the Aceh River (Fig. 14(d)), the tsunami having destroyed the deck which carried the road. The extensive Lampulo fishing port, built from internal donor funding, was thriving when we visited (Fig. 14 (e)). However, some of the rubble mound structures and road surfaces were ageing badly.

6.1.1. Coastal defences in Palu Bay

The earthquake and tsunami disaster of September 28, 2018, damaged the facilities and infrastructure of the Palu City coastal area. The destructive force of the tsunami was such, that the coastal protection infrastructure and the physical infrastructure behind (incl. seawalls, reclamation areas, the iconic Palu Bridge IV, education buildings, mosques, monuments (the Floating Mosque), fishing vessels and equipment, houses, and shops) were destroyed or damaged up to a distance of about 200 m inland. The coastline retreated inland, reducing land area and changing the beach slopes. The retreated coastline and the damaged seawalls left Palu City unprotected against coastal erosion and tidal influences. In Palu, the collapse of reclamation land in the Penggaraman area (Tanjung Batu settlement), a part of the old town in Donggala, remains in the state that it was immediately after the disaster. To address these problems and according to a Ministry of Public Works and Housing report [83] the Palu Coastal Redevelopment Program has been created. A part of this program includes the Palu Coastal Protection Project which has been created to address the problems of coastal erosion and high tides [83]. Other elements of the redevelopment program are: (i) construction of an Elevated Road at the Palu City seafront (see Fig. 1 (c)) (ii) reconstruction of the Palu Bridge IV, (iii) mangrove development between Silae and Lere, and (iv) salt production plots. These projects may be constructed together or after the Palu Coastal Protection Project. Protection against tsunamis and sea level rise will be provided in the longer term by the elevated road and mangrove development to be financed by the Japan International Cooperation Agency (JICA). The project location covers from west to east four villages, i.e. Silae (Palu Barat Sub-district), Lere (Ulujadi Sub-district), Besusu Barat (Palu Tiur Sub-district), and Talise (Mantikulore Sub-district). The project consists of constructing a 7 km coastal revetment along Palu beach, including four boat mooring facilities and land acquisition (Fig. 15(a)). According to ADB (2019), the crest elevation of the structure will be 3 m above Mean Sea Level (Fig. 1 (c)), and the width of the coastal protection zone varies, depending on the local elevation, with a minimum of 17.15 m. The four boat mooring facilities will be constructed perpendicular to the coastal embankment, consisting of standing piles with driving piles and pontoons. At the time of the EEFIT mission to Palu in December 2022, limited progress had been made, mainly in the construction of the rock revetment and boat moorings (Fig. 15(b)), but the works for the Palu Coastal Redevelopment Program had not yet started. It was not possible for EEFIT to assess the quality of these works.

The elevated road will restore the coastal road destroyed by the 2018 tsunami. Furthermore, in addition to mangrove protection as the first line of defence, the elevated road will act as a second line of coastal protection. The planned elevated road will have a total length of 4 km along the coast. Tsunami simulation analysis [85], assuming elevated road heights of 3, 6 and 9 m (not accounting for the additional protection provided by the forementioned mangroves), has shown that the elevated road may significantly reduce the tsunami inundation area and delay the tsunami arrival time (four different tsunami scenarios were considered). Tsunami waves do not overtop an elevated road with a height of 9 m. A height of 6 m will reduce the inundation area of Palu Barat and Ulujadi districts by 81.7 % and would also delay the tsunami arrival time. However, an elevated road higher than 6 m has no significant impact in reducing the inundation area.

6.1.2. Coastal defence and port structures in Thailand

Seawalls along the coast of Phang-Nga and Khao Lak were seen to be generally associated with the tourist industry. At the more exclusive southern end of Patong Beach in Phuket is a seawall that protects the coastal road and tourist apartments (Fig. 16(a) and (b)).

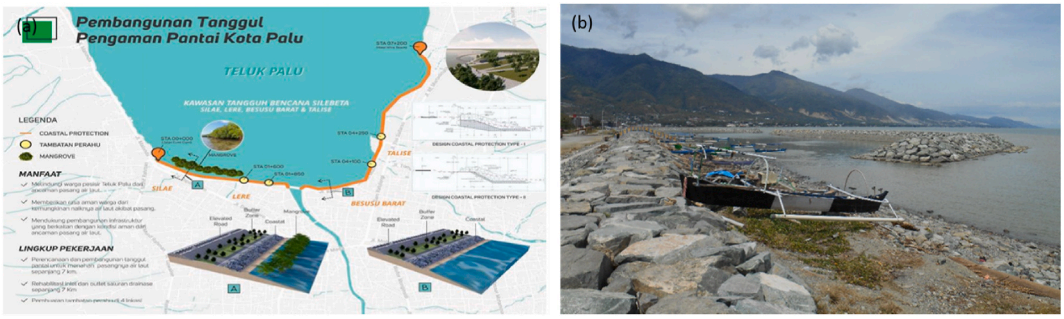


Fig. 15. Palu City coastal defences: (a) Infographic on the Palu Coastal Protection project; the location of the four boat mooring facilities is shown in yellow circles [84]; (b) new revetment and boat mooring facility in Lere in December 2022.

The concrete wall has a recurve shape commonly used as a wave return, but here the wall is some distance from the shoreline (~10 m). Away from smart tourist resorts, Bhan Nan Khem pier has been reconstructed post-IOT, but the remains of the former pier still lie derelict alongside (Fig. 16(c)). Finally, we found many examples of coastal erosion along the Khao Lak coast e.g. Fig. 16(d). Many of the locations have poorly maintained or inappropriate coastal defences. Given the economic importance of beaches to this tourism-dominated region, this is a serious issue.

6.1.3. Coastal defences in Japan

Japan has many coastal defences built to protect populations from tsunamis, or at least reduce their severity. These will also be effective against more common typhoon-driven storm surges. Lessons were learned from the failures of the coastal levees in the Sendai City area, including strengthened heel construction on the leeward side to prevent failure due to scour, increased size of concrete blocks on the crown and slope, and interlocking blocks on the leeward side to avoid their loss [38]. The reconstruction of the destroyed coastal defences was rapid; when EEFIT visited two years after the tsunami, the 7.2 m elevation (with respective to the Toyko Peil datum) concrete revetments defences in Yuriage which protect Sendai airport were complete, and others in Arahama were well under construction [86]. The 22 m elevation walls protecting the Hamaoka Nuclear Power Plant were also complete. Fig. 17 shows details of the Taro seawalls (in Iwate prefecture), one of the most physically impressive of Japan's tsunami defences. The layout of the two defensive lines of walls is seen to form an X-shape from above (Fig. 17 (a)). The height of the 10 m inner wall was based on the 1933 Showa Sanriku tsunami and was completed in 1958. Whilst it was effective in the 1960 Chilean tsunami, the wall was overtopped by the 2011 GEJE tsunami which had a height of 16.3 m at that location. The 2011 tsunami also destroyed a more modern wall closer to the shoreline (Fig. 17 (b)). The destroyed wall has been replaced by a wall with a crest elevation of 14.7 m, the level of the 1896 Meiji Sanriku tsunami (Fig. 17 (c)). Views of this new wall are shown in Fig. 17(d)–(f). The evacuation plans in Taro are based upon a conservative scenario of the 2011 tsunami occurring at high tide with additional land subsidence and no seawalls.

Fig. 18 shows a range of Japanese coastal defences. Along the coastal road in Miyako (in Iwate prefecture), protecting hotels, fuel stations, and businesses is a seawall with a crest elevation of about 3 m above pavement level (Fig. 18(a) and (b)). To preserve the view of the sea, transparent panels are periodically incorporated into the design, and to allow access to the beach, pedestrians may use concrete steps and a waterproof gate. Fig. 18 (c) shows an example of concrete armour units, ubiquitous on the seaward side of coastal defences in Japan, these ones at the Hotel Ragaso, Tanohata, Iwate prefecture. Note the people in the background for scale. Fig. 18 (d) shows a typical river gate situated at the downstream end of the Settai River. The new structure replaced the earlier barrier (13.7 m high, 300 inland from the shoreline) damaged by 2011 GEJE [88]. Only agricultural land is immediately upstream of this huge structure. The landward inundation limit of the 2011 GEJE corresponds to the railway embankment in Settai beyond which lies most of the town of Settai. Controversy is associated with the height of the Kesennuma seawall mentioned in Section 3.3 (Fig. 4). In 2015, residents and the government agreed on a crest elevation of 4.1 m. However, in 2016, the bounce-back rate of the plate that followed the significant subsidence during the earthquake uplift was faster than expected. Hence, the residents requested a 22 cm reduction in the crest elevation, which was agreed upon by the Miyagi prefecture in 2017. Unfortunately, the construction followed the taller original design, angering residents [89]. In sharp contrast to the use of concrete structures, the town of Matsushima has no tsunami defences. This is a result of being relatively unaffected by the 2011 tsunami due to the protection afforded by many small islands [90] and the cultural and economic value of the natural scenery.

In terms of beach erosion, the natural state of the Tohoku coastline before the tsunami was mixed, with some healthy, wide beaches, but others requiring artificial beach nourishment due to net sediment loss. The tsunami caused considerable erosion of the coastline, in some places by several hundreds of meters inland. The sand was deposited offshore by the receding waves, at depths of 5–10 m. The

Fig. 16. (a) and (b) Recurved concrete seawall in front of the Seagull at Southbeach apartments in Patong Beach; (c) Baan Nan Khem pier; (d) severe erosion at the toe of concrete revetment (Lat 8° 40′ 3.13″ Long 98° 14′ 34.87".

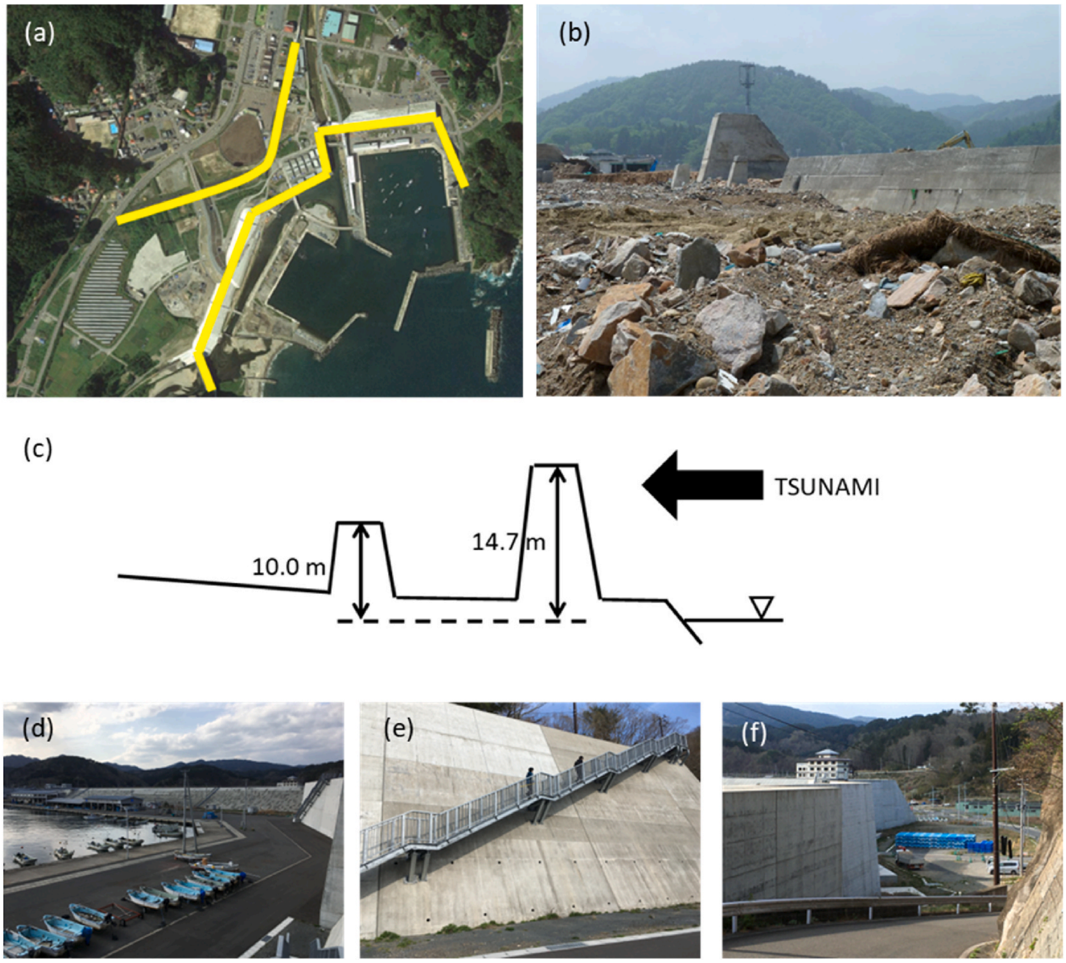


Fig. 17. Taro seawalls: (a) plan layout of seawalls in yellow; (b) remnants of the previous Taro seawall observed during the EEFIT 2011 mission; (c) schematic section through the two seawalls based on Zenshoren [87]; (d) view of the seawall from the western side of the harbour; (e) steps up the offshore side of the western side; and (f) view from the leeside of the seawall.

sediment was naturally transported back to the shoreline, quite rapidly at first (10 m/month immediately following the event), then more slowly (2–3 m/month a year later). Erosion remained a problem in locations which had previously suffered from net loss of sediment [91].

6.1.4. Soft coastal defences

A presentation of tsunami mitigation structures would be incomplete without briefly mentioning the role of vegetation in providing defensive capability. Mangrove plantations were seen by the field investigation teams in Palu Bay, Banda Aceh and Khao Lak, but conversations with local partners suggested that these were not part of dedicated tsunami defences. The interested reader is encouraged to read the associated EEFIT site investigation report which contains our mangrove observations. Furthermore, Benazir et al. [92] provide a comprehensive review of the role of vegetation in tsunami vegetation, including many Indonesian examples.

7. Comparison of recovery and reconstruction across Indonesia, Thailand and Japan

Details of the recovery and reconstruction from each location are summarised in Table 2, using symbols to identify good practice but also areas of concern and critical issues (ticks, exclamation and question marks, respectively). The following points summarise the key differences between locations.

1. In Indonesia and Thailand, financial pressures for housing or economic activity have led to developments within the previous tsunami inundation zone. It is recognised that it is hard to remove historically well-established urban areas across the inundation zones (e.g. the IAIN in the exclusion zone), hence need for TVE structures in such places and good/regular preparedness training.

Fig. 18. Miscellaneous coastal defences in Japan: (a) and (b) waterproof gate and seawall with viewing windows in Miyako (c) armour units in Tanohata (d) gate on Settai river.

Also, in both Japan and Indonesia, elevated roads are playing a role in a multi-layered approach (although only at the planning stage so far in Indonesia).

2. Whilst building codes for tsunamis have been developed/adopted in all countries, the Thai codes for building in tsunami zones were issued in 2008 before other important codes were developed in the USA and Japan. Furthermore, the comprehensive codes of Japan have not been widely conveyed/adopted. However, at least one the new Japanese codes is for dedicated tsunami defence structures ('Guidelines for tsunami-resistant breakwaters and parapet design' see Fig. 5); these structures will not be appropriate for other countries, whether for environmental or cultural reasons.
3. Detection of tsunamis by buoys is losing favour with only Thailand using them, as it is difficult to maintain a sufficient density around a coastline. In terms of on-land warning systems, in Indonesia in particular and possibly in Thailand, there may be insufficient warning sirens.
4. Whilst there is evidence of visitors to Japan receiving automatic warnings on their cell phones, there is no obvious advanced communication of hazards to them, and there is possibly an expectation of them carrying phones of a particular capability. Cell phones warnings are still not operational in Thailand, but will possibly happen in 2025.
5. Disaster preparedness education and/or training involves either an insufficient proportion of the population (Indonesia) or unrealistic scenarios (Thailand). There is evidence of academics contributing to improvements in all locations, including appropriate disaster education by Japanese academics in Thailand. Community-led evacuation initiatives in Thailand have shown some effectiveness.
6. Evacuation structures elicit different responses in different locations: whilst accepted in Japan, dedicated TVE structures are not trusted in Indonesia, leading to the identification of further potential multi-purpose buildings. More buildings are being identified in Thailand, but here due to insufficient capacity of dedicated structures.
7. Beaches in the different locations were in a mixed state, even within regions such as Aceh province. In Palu Bay, parts of the shoreline were lost. In Thailand, there appear to be significant erosion problems. In Japan, there are ongoing erosion problems on some beaches, exacerbated by the tsunami. According to Masaya et al. [93] who modelled the tsunami in Phratong island, Thailand and Sendai, Japan, the tsunami wave characteristics (relative height of the preceding wave) have a strong influence on the sediment movement, and hence the speed of recovery by natural processes.
8. The rate of recovery varies across the locations. The contrast was particularly evident between Japan and Palu Bay. As a highly industrialised nation, Japan's speed of reconstruction in the first two years far outstripped that seen after four years in Palu Bay.

Table 2
Comparisons of recovery for Banda Aceh, Palu, Thailand and Japan: tick (good practice), exclamation mark (area of concern), question mark (area of debate).

<table>
<tr><th rowspan="3">CRITERIA</th><th colspan="4">LOCATIONS</th></tr>
<tr><th colspan="2">Indonesia</th><th rowspan="2">Thailand</th><th rowspan="2">Japan</th></tr>
<tr><th>Banda Aceh</th><th>Palu</th></tr>
<tr><td rowspan="2">Spatial planning and hazard zonation</td><td>✔
1 km buffer zone. Nominated escape roads inland. Development of inland centre.</td><td>✔
Multi-hazard map with exclusion zones. Planned multi-layered response with elevated road.</td><td>✔
Only RC structures permitted in inundation zone. Main road constructed away from tsunami zone.</td><td rowspan="2">✔
Constructed comprehensive multi-layered approach: Restrictions on residential housing in inundation zone; no subsequent inappropriate development; constructed elevated roads.</td></tr>
<tr><td>!
Significant population growth in buffer zone.</td><td>!
“Day-time” residents in exclusion zone. Inappropriate adaptation (ground-floor infilling) of new housing. Newly-constructed Mosque near the exclusion zone and IAIN in the exclusion zone.</td><td>!
High exposure risk for tourists.</td></tr>
<tr><td rowspan="2">Design Codes</td><td colspan="2" rowspan="2">✔
New design codes following ASCE 7-16.</td><td rowspan="2">✔
Design codes last issued 2008 prior to ASCE 7-16 and Japanese codes.</td><td>✔
Comprehensive design codes for range of structures.</td></tr>
<tr><td>?
Apparently low take-up of Japanese design codes in other regions.</td></tr>
<tr><td rowspan="2">Warning Systems</td><td colspan="2">✔
Pre-simulated database of tsunamis for rapid response. Seismic detection and tide gauges. Movement away from wave buoys.</td><td>✔
Pre-simulated database of tsunamis for rapid response. Siren and SMS warnings. Seismic detection and still some use of wave buoys.</td><td>✔
Long-established systems. Pre-simulated database of tsunamis for rapid response. Seafloor detection system. Outdoor sirens, mobile phone messages/mail, tweets etc.</td></tr>
<tr><td>!
~30 minutes arrival time in 2004. Sufficient sirens?</td><td>!
~5 minutes arrival time in 2018. Insufficient number of sirens. Mains-powered warning towers ineffective in 2018. Improvements in local decision-making required.</td><td>!
~120 minutes arrival time in 2004. Sufficient number of sirens for the extensive areas?</td><td>!
~30 minutes arrival time in 2011. Better advanced communication to visitors.</td></tr>
<tr><td rowspan="2">Education Training</td><td colspan="2">✔
Some training undertaken. Involvement of academic researchers e.g. TDMRC.</td><td>✔
Annual training drills, with some strong community-led initiatives.</td><td rowspan="2">✔
Continuous learning from drills. Considerable efforts to communicate information to resident population. Involvement of academic researchers e.g. IRIDeS.</td></tr>
<tr><td colspan="2">!
Insufficient proportion of the population involved.</td><td>!
Unrealistic evacuation scenarios. Tourist populations particularly vulnerable.</td></tr>
</table>

Evacuation structures	! Demonstrated lack of affinity with TVE structures, but additional alternative structures being identified.	! IAIN TVE response untested.	! Limited numbers of TVE structures. Identification of further additional buildings to complement the existing TVE structures.	✓ Apparently, no psychological barriers to their use. More provisions for longer stays.
Coastal defence structures	! Complicated long-term morphological response to tsunamis. Signs that repairs are required to defence structures.	! *Planned* combination of mangroves, 3 m revetment, memory park and elevated coastal road expected to reduce tsunami inundation area but slow progress.	! Sediment erosion in many locations – appropriate coastal engineering schemes being designed?	✓ Defences part of multi-layered approach. ✓ Rapid reconstruction, protecting critical infrastructure. ! Ongoing erosion at some beaches ! Environmental (CO_2) and financial cost of dedicated tsunami defences.
	? No dedicated tsunami defences			? Very large tsunami defences.

Japan clearly needed to address the vulnerability of their nuclear power facilities and also the international airport. However, their ability to deploy considerable resource in a short period of time was still impressive.

9. The issue of dedicated tsunami defence structures is a complex one. Whilst protection for a vulnerable community might be possible with very large concrete/steel structures, the economic and environmental cost of the ones constructed in Japan means that they are impossible, or perhaps even undesirable, for communities in Indonesia and Thailand. Furthermore, basic maintenance and good planning of more generic coastal and hydraulic defence structures should not be ignored.

8. Conclusions and recommendations

This paper has presented aspects of recovery from devastating tsunamis in four different locations: Banda Aceh, Sumatra (2004); Palu Bay, Central Sulawesi (2018); Southern Thailand (2004) and the Sanriku coastline of Japan [90]. Snapshots of the recoveries were obtained from short-duration visits to the first three locations, with local partners, and insight from Japan came from a local academic. Different periods of time have elapsed between locations, but preliminary comparisons of recovery have been made.

Indonesia suffers from a wide variety of natural hazards which occur on a reasonably regular timescale. The original preparedness of Palu seems to have been informed by the IOT (which was not without its problems), but its subsequent recovery shows some influence from Japan with the planned multi-layered defences. The economic situation of Indonesia is likely to impose serious restrictions on implementing any significant engineering solutions, e.g. dedicated defence or evacuation structures, in addition to the maintenance of those already constructed. However, non-structural, i.e. behavioural, changes could be implemented without great economic cost. If these are home-grown, there is a much greater chance of them being sustainable in the long term. In Southern Thailand, whose recovery can be compared most directly to Banda Aceh, the region shows signs of considerable development for the tourist industry despite the loss of life amongst that very population. Japan is known to be amongst the world's best prepared countries for natural hazards and has largely taken the route of heavily engineering defences. This has been complemented by significant training of communities at risk.

Focusing on the key criteria considered, there are several recommendations arising from this study. Pressures to build on land in previous tsunami inundation zones are very real and seem to come from income-generation drivers. However, authorities need to balance the requirement for economic activity with the need to keep their populations safe, reminding communities of their vulnerability. Tsunami resistant building code developments in the US have informed codes in Indonesia and Thailand, but very little of the respective comprehensive Japanese codes seem to have been adopted internationally. Barriers to more widespread use of the Japanese codes need to be overcome so that the international community can benefit from the work done. We have highlighted whether Thailand's tsunami codes may need refining in the light of code revisions including ASCE 7–16 and the Japanese codes. However, given the rather low frequency of tsunamis in Thailand, there may be insufficient motivation to do so. Warning sirens are ubiquitous in the regions surveyed, but more need to be installed in Indonesia, and they need to remain operational when the mains power supply is interrupted, as this often happens when strong earthquake shaking occurs. Tsunamis from all generation mechanisms must be considered in the different scenarios, including submarine landslide generation, which can result in a very fast tsunami arrival. Whilst there are disaster-preparedness programmes in all locations, more consideration needs to be given to visitors. Also, authorities in Indonesia, particularly in Banda Aceh given the elapsed time since the IOT, need to make sure that new residents are aware of the risks. Sufficient and culturally acceptable evacuation structures are essential as part of the response to the tsunami threat. They should preferably be within walking distance, considering the time available before the tsunami's arrival in each location and the time evacuees might have to spend in the structures following a tsunami. Planned multi-layer defences need to become a reality. Consideration needs to be given to the health of beaches in areas susceptible to tsunami risk, with appropriate coastal engineering schemes being deployed. These may include beach renourishment in some locations, but the long-term sustainability may be too expensive. There needs to be some conversation about the role of very large concrete defences where they can be afforded, particularly in the era of commitments to net zero carbon emissions. The use of more green and economically viable approaches, such as more extensive mangroves and evacuation hills, could possibly be considered in Banda Aceh, Palu and Khao Lak where there is available land.

CRediT authorship contribution statement

Alison Raby: Writing – original draft, Visualization, Investigation, Conceptualization. **Antonios Pomonis:** Writing – original draft, Methodology, Investigation, Conceptualization. **Anawat Suppasri:** Writing – original draft, Investigation. **Keith Adams:** Writing – original draft, Investigation. **Nurullah Açikgőz:** Writing – original draft, Investigation. **Marco Baiguera:** Writing – review & editing, Writing – original draft, Software, Investigation. **Yunita Idris:** Writing – original draft, Investigation. **Panon Latcharote:** Writing – original draft, Software, Investigation. **Francesca Marafini:** Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation. **David McGovern:** Writing – original draft, Investigation. **Ella Meilianda:** Writing – original draft, Project administration, Investigation, Conceptualization. **Harsh Mistry:** Writing – original draft, Visualization, Investigation. **Sukiman Nurdin:** Writing – review & editing, Investigation. **Eyitayo Opabola:** Writing – original draft, Investigation. **Teraphan Ornthammarath:** Writing – original draft, Investigation. **Nattapon Trumikaborworn:** Writing – review & editing, Software, Investigation. **Tiziana Rossetto:** Conceptualization, Funding acquisition, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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