Observations from the EEFIT-TDMRC mission to Banda Aceh, Indonesia to investigate the recovery from the 2004 Indian Ocean Tsunami

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**Abstract**: On 26th December 2004 a subduction zone earthquake of magnitude Mw 9.3 struck off the coast of Sumatra in Indonesia. A large area of the Indian Ocean seabed was vertically displaced, and as a result a tsunami wave was generated that went on to affect many countries around the world. One of the worst hit places was the Aceh province of Sumatra where the capital city, Banda Aceh, experienced serious ground shaking and significant sea water inundation. In Indonesia at least 126,732 people were killed, a further 93,652 people were confirmed missing and 533,770 people were displaced. In 2022, nearly 20 years on from the disaster, engineers and scientists from the UK Earthquake Engineering Field Investigation Team (EEFIT) and from the Indonesian Tsunami and Disaster Mitigation Research Centre (TDMRC) conducted a joint long-term recovery mission. This paper reflects on how a society rebuilds after such a devastating loss and what lessons can be learnt as a community for future disaster risk reduction. The scope of the paper includes the rapid assessment of post-disaster housing, community infrastructure and preparedness measures.

Introduction

On 26th December 2004 at 7:58:53 AM (local time) a moment magnitude (MW) 9.3 occurred off the west coast of northern Sumatra, Indonesia. The ground shaking was followed by a tsunami that devastated many countries across the Indian Ocean, including Indonesia and Thailand (EEFIT, 2005). In Indonesia at least 126,732 people were killed, a further 93,652 people were confirmed missing and 533,770 people were displaced as a result of the disaster (UNOCHA, 2005). Banda Aceh was the most severely affected city in the region with about 75,000 out of the 230,000 residents killed (Borrero et al., 2006). (Syamsidik et al., 2023).

This paper presents some preliminary findings of the long-term recovery mission to Banda Aceh, which took place in October 2022 and was carried out by a team of engineers and scientists from the UK Earthquake Engineering Field Investigation Team (EEFIT) and from the Indonesian Tsunami and Disaster Mitigation Research Centre (TDMRC). This mission was funded by the EPSRC ‘Learning from Earthquakes’ grant (EP/P025641/1), with the aim of studying the recovery of cities affected by recent earthquake and tsunami events in the Indian Ocean. For this purpose, two more mission were conducted in parallel: one in the Phang Nga province of Thailand and one in Palu, Central Sulawesi. The latter city was severely hit by the 2018 Palu earthquake and tsunami (EEFIT, 2019). A comprehensive report for all missions is presented in EEFIT (2023).

In-field activities in Banda Aceh included visits to: (a) investigate the reconstruction of buildings after the 2004 Indian Ocean tsunami (IOT), in terms of compliance to current building codes and policies, including any build-back-better projects; (b) evacuation structures along with participation to activities with local communities to understand how disaster response training is being undertaken; (c) tsunami nature-based soft defences. Figure 1 illustrates the main areas surveyed within the city of Banda Aceh that are mentioned in this paper.

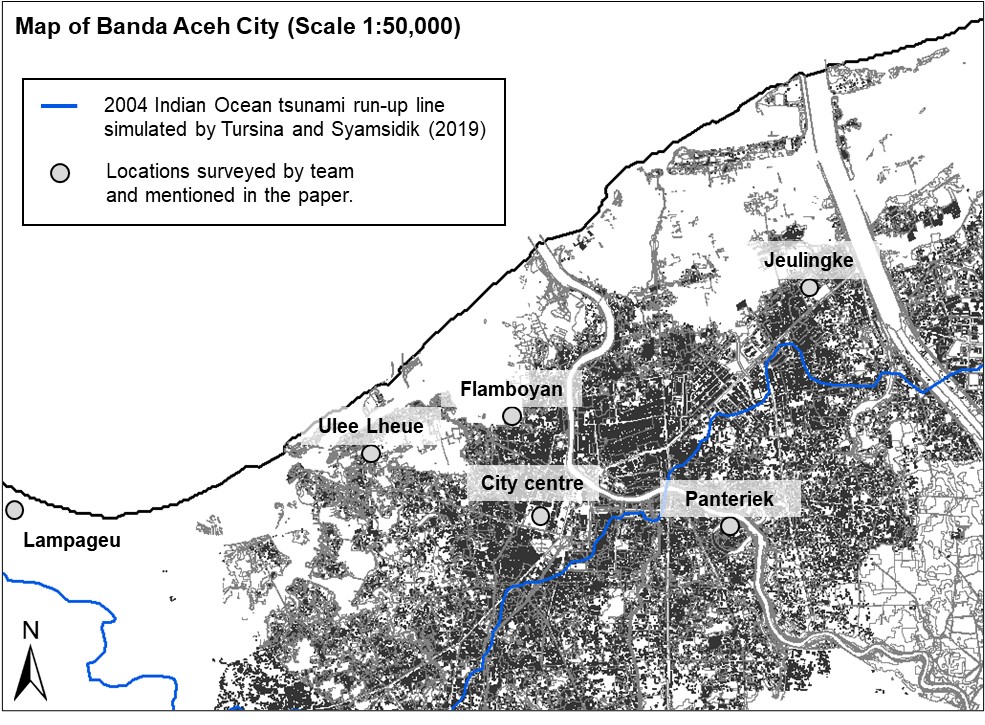


Figure 1. Main surveyed areas within Banda Aceh city.

Reconstruction of buildings

The EEFIT team visited various residential areas within the city of Banda Aceh, with the aim of capturing the nature and condition of the housing projects that were developed either in the aftermath of the tsunami or more recently. In 2004 most of the buildings within 2km from the coastline were severely damaged or washed by the tsunami. According to a recent survey, around 88% of the buildings are built with confined masonry, while the rest is mostly built with reinforced concrete (RC) and timber, respectively 11% and 1% (Syamsidik et al., 2023).

*Design codes for earthquake and tsunami loading*

In Indonesia the first seismic design code for buildings was published in 1989 as SNI 1726:1989 (BSN, 1989). Before then, the 1960s design codes included the reference to earthquake loading as live load. The seismic code was then revised in the early 2000s through the SNI 1726:2002 (BSN, 2002), which was inspired by the American Uniform Building Code 1997 (UBC, 1997). Eight years after the 2004 IOT, stricter seismic design provisions were introduced in the latest version of the design code the SNI 1726:2012 (BSN, 2012), which was made consistent with the American ASCE 7–10 (ASCE, 2010). The 2012 seismic code was initially based on a deterministic seismic hazard analysis. The National Earthquake Hazard Map was updated in 2017, following the Pidie Jaya Earthquake in 2016. The most recent seismic code is the SNI 1726:2019, which refers to ASCE 7-16 (ASCE, 2017) and includes tsunami loading. In fact, tsunami loads and effects were included in the national standard for loading SNI 1727:2013, which referred to FEMA P262. This code was updated recently and is now referred to as SNI 1727:2019. It should be noted that any improvement in the design code may not be directly reflected in the construction practice, particularly when it comes to seismic detailing of structural members.

Residential houses

A large social housing project in Flamboyan, about 2km inland, represents one of the few examples of high-rise residential structures in Banda Aceh (Figure 2a). Four RC blocks were built by a partnership between the municipality of Banda Aceh and the national government to house families that cannot afford buying a property. The multi-storey buildings present several openings at the ground level and along the height of the structure. This helps to reduce the tsunami loading acting on the building. However, roofs are double-pitched, hence these buildings may not be used as last-resort refuge for tsunami vertical evacuation.

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| (a) | (b) |
| Figure 2. Residential buildings: (a) Flamboyan; and (b) Lumpuuk. | |

Most of the reconstruction housing projects resulted in low-rise single houses, with one or two stories. A substantial difference in the quality of construction was observed, mostly dependent on the country or agency that financially supported the reconstruction. For instance the coastal town of Lampuuk, which was completely swept away by the tsunami, was reconstructed with the support of the Turkish Government. Figure 2b shows a typical single-family house made of confined masonry. By visual inspection, most of the houses were found in good conditions and with apparent little modifications, nearly 15 years after the construction.

Post-disaster construction near the coastline was allowed only for the fishing communities. One notable example is the temporary housing resettlement in Todak, near the Floodway Channel. Typical housing units, shown in Figure 3a, are made of confined masonry with asbestos roofs, and are supported on stilt-like foundations. These were deemed a suitable solution to protect houses from the effects of tsunami scour effects. Some of units are now being replaced by more permanent structures, whose design follows more traditional practice. Observation from a construction site (Figure 3b) indicate that the structural detailing of the new units is relatively deficient for earthquake resistance, e.g. still using smooth bars in relatively slender columns and beams foundations directly sitting on the ground.

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| (a) | (b) |
| Figure 3. Housing units for fishing communities in Todak. | |

Stilt houses were also built in the area of Ulee Lheue, the former seaport of Banda Aceh that was completely destroyed by the tsunami. Built by the NGO “Uplink – Urban for linkage”, those residential units were donated to fishermen families (Figure 4a). Each unit is made of a two-storey RC frame, with a bare frame at ground floor and masonry infills at the first floor, which houses a single bedroom apartment (36 m2). Corrugated steel sheets sit on a timber roof structure. Interestingly, the land on which they were built used to be a swamp and then was filled with tsunami debris. The structural typology reminds of the traditional stilt timber housing that local communities had lived for centuries. However, the original stilt layout has often been heavily modified, with extensions and new rooms at the ground level, as shown in Figure 4b. This occurred as the original space was not sufficient to meet the needs of the local families.

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| (a) | (b) |
| Figure 4. Housing in Ulee Lheue: (a) stilt housing unit; (b) extension and new apartment at the ground floor. | |

In fact, a number of housing projects is currently taking place near the coastline, i.e. within 3km inland. As pointed out in Syamsidik et al. (2023), developers tend to select such areas due to lower land prices so that houses can be sold to low-middle income homebuyers at subsidised rates. An example of this is the brand-new housing development in Jeulingke, about 3 km inland. Figure 5 shows the typical precast confined masonry houses that have been recently built. With road infrastructure now in place for this settlement, more housing is being constructed by private developers. This confirms an increase in building development in the coastal areas of the city.

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| Figure 5. Recently constructed housing development in Jeulingke. | |

Away from the coast, the team visited one-storey residential houses in the Tanjong area (to the south-west of Banda Aceh), which were seismically improved by CARE International through the installation of steel cross-braces on the building facades (Figure 6a). However, it was observed that some steel tendons were missing. Such effective but obstructive solution might have been met with little enthusiasm by some residents. In fact, some of these have been reused in a nearby construction site. Apparently, the builder had little clue about how to use them correctly, as they were installed as additional longitudinal reinforcement together with smooth rebars in relatively thin RC columns (Figure 6b). This example highlights that, despite the efforts of the NGO, there are challenges in making sure that these interventions are “absorbed” by the local community, both residents and builders.

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| (a) | (b) |
| Figure 6. Seismically-retrofitted single-family houses in Tanjong: (a) steel cross-bracings; and (b) reuse of the bracing elements within a nearby construction site. | |

Resettlement villages for tsunami survivors

Resettlement villages donated by Chinese donors are a notable example of post-disaster housing in Banda Aceh. The team visited one in Panteriek, donated by the Buddhist Tzu Chi Charity Foundation, and one in Perumahan, the so-called Jackie Chan village, named after the Hong-Kong movie star who made a donation. These villages are easily identifiable from satellite images of the city, due to their dense and regular grid of houses along narrow streets (see Figure 7a). Single-family houses were constructed using RC walls, metal roofs and asbestos for the non-structural partitions, and were given for free by the Agency for the Rehabilitation and Reconstruction of Aceh and Nias (Badan Rehabilitasi dan Rekonstruksi, BRR, in Indonesian) to former homeowners displaced by the tsunami as temporary settlements. However, due to the relatively small size of the units and cheap construction material, some settlers have modified or partly rebuilt their allocated houses (Figure 7b). Such process is likely to continue in light of the recent decision made by the government of granting ownership of the land to residents. The move is welcome by the local community as it effectively makes these settlements permanent.

On purpose both villages were built on land that was not affected by the tsunami in 2004. However, their location is far from ideal. The Jackie Chan village is located at 300 metres above the sea level, but it is quite remote from the city centre: lack of public transport infrastructure has forced many people who were rehoused there to move closer to the city. After seven years from the construction, only half of the 2,400 people were found to be living there (Vale et al., 2014). The Panteriek site is highly prone to pluvial flooding. A pumping station has been constructed to transfer flood waters during heavy rainfall from the reservoir of the oxbow to the adjacent river. The mission team participated in a training session given by TDMRC to the local community on a new web-based GIS software system that provides GIS flood prediction maps for the village.

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| (a) | (b) |
| Figure 7. Panteriek village: (a) satellite view [satellite.pro] and (b) modified housing units. | |

Schools

International efforts in the aftermath of the disaster focused on providing new school buildings on the same land where the original structures had been damaged or even destroyed. Moving such important community facilities further inland would have proved challenging and counterproductive for the city’s recovery. First, residents of the affected neighbourhoods asked for schools to be available locally. Then, finding public land for constructing new facilities was challenging for the public authorities. The vast majority of the school buildings in Banda Aceh were rebuilt using RC frames with infills, most of which are two-story high (Gentile et al. (2019). Approximately, two thirds of the schools were completed between 2005 and 2011, in accordance with the national building code SNI 1762:2002 (BSN, 2002). A smaller share was of more recent construction, hence nominally designed to the latest seismic code SNI 1762:2012 (BSN, 2012).

The team visited the Muhammadiyah 1 primary school in the city centre that was rebuilt with the support of international NGOs. It is representative of a typical school compound in Banda Aceh (Figure 8a): rectangular in shape, two-storey high, about ten bays in the longitudinal direction and two in the transverse direction. A similar plan can be observed in the main building of the primary school in Mon Singet in Kajhu. Some issues were observed by visual inspection: spalling of the concrete cover in some corner columns, damage in the ceiling across the building (see Figure 7a), and lack of connection between the gable and the tie beam (Figure 8b). The latter is a recurrent failure mode that was observed in the 2018 Palu earthquake.

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| (a) | (b) |
| Figure 8. Primary schools: (a) Muhammadiyah 1; and (b) Mon Singet. | |

The team also visited the primary school in Lampageu, which was built by USAID, i.e. the aid government agency funded by the USA government. The new school building can be seen as an outlier in terms of design and layout. It features two stories, one above the ground floor that is left open, and the second for the classrooms, clearly indicating that tsunami effects were taken in consideration in the design of the school building (Figure 9). The permeable frame at the ground floor aims to reduce the tsunami loading on the structure. There is also a higher portion of the building with three stories, of which the top one appears to be designated as the evacuation area. However, there are some concerns that the building height may not be sufficient to provide a safe refuge if tsunami inundation reaches the second floor (about 6-7m). This scenario cannot be excluded as the school site is highly exposed to future tsunami inundation.

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| Figure 9. Primary school in Lampageu. | |

Evacuation structures

Banda Aceh lies on a coastal plain and no natural escape options are available to most of the city residents. Following the 2004 IOT, a total of eight tsunami vertical evacuation (TVE) buildings were constructed. Most of them are located in the northern sector of the city, where the largest tsunami inundation depths were recorded in 2004 in the range of 10-12 m. TVEs include reinforced concrete structures built with the support of the Japanese government. Others include the Aceh Tsunami Museum, the TVE built by the Local Disaster Management Agency, and a three-storey steel building at the local firefighter department.

One of the Japanese TVE structures is located in Ulee Lheue, the area of the former seaport of Banda Aceh. As shown in Figure 10a, the building is a massive reinforced concrete structure, 13m tall, rectangular in plan, with a dense grid of large square columns (75x75 cm in section at the ground floor) and a refuge roof easily accessible via a system of gentle ramps. The building is strategically oriented to have the short side to resist the tsunami wave impact. To reduce this further, the front of the building was designed as the bow of a ship. In the surroundings, new evacuation signage is present and there are still remains of reinforced concrete hospital buildings destroyed by the tsunami in 2004. The rest of the Japanese TVE buildings, as well as the TVE structure built by the local authority in Lamjamee (Figure 10b), are massive bare RC frames, built in the middle of low-rise residential areas. The conditions of these structures are still fairly good, but some signs of deterioration were visible since they are exposed to the elements.

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| (a) | (b) |
| Figure 10. Tsunami vertical evacuation structures: (a) Ulee Lheue; and (b) Lamjamee. | |

The team found that single-purpose TVEs have not been “absorbed” by the local community in which they sit, despite efforts by the government. In the 2012 earthquake, local residents around TVEs completely ignored the TVEs and evacuated using cars and bikes. The Tsunami Museum (Figure 11a) is good example of multi-purpose TVE in the central area of the city. Local mosques are also seen as a safe place to evacuate to, as local communities are culturally inclined to evacuate to what they perceive as a safe place. However, in 2004 several mosques, including the one in Lambuuk, did not collapse, probably thanks to their large openings, but they were severely damaged (Figure 11b). Syamsidik et al. (2023) have recently conducted a survey of the religious buildings in Banda Aceh and found that the overall capacity for vertical evacuation would increase four times than the actual one, were some of these designed to be evacuation centres.

For those areas of the city without TVEs, the only option is to evacuate to a designated evacuation centre further inland. Due to the topography of the city, horizontal evacuation may require people covering a substantial distance in the region of 2-3km by car or motorbike. For instance, the village where the primary school Mon Singet is located, is in a flat area at high risk of tsunami inundation. The only way for the local community to escape the next tsunami is via a designated evacuation route to an area near the Masjid Babul Ukhwah mosque in Tanjung Deah, 3km inland. As there are some concerns that people are not familiar with the planned route, the local community has partnered with TDMRC to run a series of initiatives to raise awareness. The team observed one activity targeted at primary school students, who played a serious game (SG EvaNami) to learn how to evacuate from a tsunami on time.

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| (a) | (b) |
| Figure 11. Tsunami evacuation buildings: (a) Tsunami Museum; (b) tsunami damage still in display at Lambuuk mosque. | |

Coastal defences

Hard defences

Coastal structures were built to protect the city along some stretches of coastline. Hard defences are in the form of rubble mound or concrete seawalls. The purpose of constructing the hard defences is primarily to protect the inland area from coastal flooding during spring tides, to protect the revitalised aquaculture and to prevent sand deposition over the shoreface and coastal roads. At the Ulee Lheue peninsula, rubble mound seawalls were constructed. Most of the structure is situated in the water, emerging 2 m above the water (Figure 12). However, in terms of tsunami protection, this has very limited effect but it may protect the coastal road from tides.

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| (a) | (b) |
| Figure 12. Coastal hard defences: (a) post-tsunami; and (b) today. | |

Soft defences

Significant post-tsunami plantation of mangroves along the coastline was vastly promoted by the international and national agenda during the tsunami disaster recovery. In many cases, the mangroves that were planted after the 2004 event are used for aquaculture. The team visited a mangrove conservation area near the Lampageu Elementary School. Mangroves are relatively young and were planted mainly for purposes of aquaculture and ecological conservation. The area characteristically consists of clumps of trees in areas of 10 x 10 m, in between there are mud flats and submerged rectangular areas used previously for aquaculture (Figure 13a). Like several other coastal areas, the saltwater ingress from the tsunami has rendered land previously used for aquaculture as no longer suitable for that use.

The mangroves that were surveyed during the mission are not suitable for tsunami mitigation due to their low density and would have limited mitigation effect on such an occurrence. The width of the planting is generally around 300 m and covers only approximately one fourth of the protected bay. The majority of the planting is in the north east part of the city. These are relatively young mangroves and between 5–10 m in height. In addition to mangroves, some planting of coastal pines was observed and surveyed. In the location of Gampoeng Birek, southeast of Banda Aceh, replanting of coastal pines destroyed by the tsunami was surveyed (Figure 13b).

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| (a) | (b) |
| Figure 13. Tsunami soft defences: (a) mangroves; and (b) coastal pines. | |

Concluding remarks

This paper presented some evidence from the EEFIT return mission to Banda Aceh in October 2022. This took place nearly 20 years after the Indian Ocean Tsunami that severely hit the city. A more comprehensive report can be found in EEFIT (2023). By reflecting on how the city of Banda has rebuilt after such a devastating loss and what lessons can be learnt for future disaster risk reduction, the following remarks are drawn:

* Reconstruction of residential buildings was mostly based on standard construction practice, with little regard in practice to seismic design considerations and despite improvements in code provisions following the 2004 IOT. Some evidence of build-back-better was observed, e.g. stilt houses and seismic retrofitting, but these solutions appeared often to create living spaces that are not suitable for the needs of the local communities.
* The construction of resettlement villages presented some challenges for the survivors due to their non-ideal location, either remote or exposed to flooding hazards.
* Schools have been reconstructed using reinforced concrete structures, rather than masonry walls as done in the past. Some of these are not well maintained and just one was designed for tsunami vertical evacuation.
* Single purpose tsunami evacuation structures have not been “absorbed” by local communities, which rather evacuate to areas or buildings that are perceived as safe ones, such as the local mosques.
* Mangrove replantation along the Banda Aceh coast was not successful. It has been driven by the aquaculture sector, hence the density of trees is very low. In addition, it has been hindered by the ingress of saltwater due to changes in coastal morphology following the tsunami.

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