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Lessons learned from the Katrina storm surge and the development of storm surge disaster prevention in Japan

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Abstract

The present short communication will reflect on lessons that were learned by Japanese coastal engineers and disaster risk managers from Hurricane Katrina, together with those from major Japanese disasters that have taken place in recent times, such as the 1959 Ise Bay Typhoon and the 2011 Tohoku tsunami. Following a JSCE-led survey of Katrina's impact, Japanese researchers integrated their findings on the characteristics of that disaster into Japanese disaster risk management philosophy, emphasising structural upgrades, hazard mapping, and evacuation planning. While this has helped risk management in the last 20 years, rising sea levels, the potential for more intense future typhoons, and weakened westerlies could have an effect and increase future storm surge heights. Currently, Japan's two-tiered defence strategy—physical barriers designed against 100-year events and evacuation systems for 1,000-year events—guides current policy, but this may have to be reassessed to deal with the effects of future climate change. The present paper will also outline reconstruction philosophy and countermeasures employed after the 2011 Tohoku earthquake tsunami, including seawalls, elevated land, and urban retreat, which can serve as global references for disaster risk management elsewhere.

Keywords

Hurricane Katrina; storm surge; disaster risk management; Japan

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1. Introduction

Hurricane Katrina made landfall in Louisiana on 29 August 2005, causing storm surge damage to New Orleans and surrounding areas. The Japanese Society of Civil Engineers (JSCE) regarded this disaster as a lesson for Japan and dispatched a survey team of seven Japanese researchers, with the first author acting as the survey team leader. With the cooperation of the U.S. Army Engineer Research and Development Centre and the Federal Emergency Management Agency (FEMA), this survey team conducted a damage assessment of the coastal areas of New Orleans and Louisiana (Shibayama, 2015). New Orleans includes low-lying areas, even in the centre of the city, and residential areas were extensively flooded when the storm surge levees protecting them were destroyed. In Gulfport, Louisiana, the storm surge reached a height of over 10.5 *m* just 130 *m* from the shoreline, with inundation extending 470 *m* inland. What made Hurricane Katrina particularly instructive to Japanese engineers, beyond Japan's own historical typhoon and tsunami experience, was the systemic failure of urban flood protection and emergency response within a highly engineered (albeit maybe not properly maintained infrastructure) but socially complex setting. This highlighted the importance of levee robustness, redundancy in defence systems, maintenance of infrastructure, and equity considerations in evacuation and recovery—issues from which Japanese engineers gained many lessons.

The JSCE survey was conducted from 27 November to 2 December 2005. Even at that time, it was striking to see only one house in a residential area of New Orleans with lights on, using a private generator, after most residents had been evacuated. In Biloxi, one house was damaged, while a neighbouring property, situated 2.6 *m* higher in elevation, was undamaged. The extent of damage to both properties differed significantly due to this slight difference in ground level. The coastal areas of Louisiana are frequently hit by hurricanes and have systems that could serve as models for Japan, including the designation of disaster insurance premiums based on disaster probability and regulations requiring buildings in certain areas to have open ground floors with columns (pilotis) instead of walls.

The leading author has also led other post-disaster field surveys, which include the 2007 Sidr storm surge in Bangladesh, the 2008 Nargis storm surge in Myanmar, the 2012 Sandy storm surge in New York City, the 2013 Haiyan storm surge in the Philippines (Mikami et al., 2016), and others. These experiences have informed ongoing research and development in storm surge disaster mitigation in Japan, as outlined in the following sections.

2. History of storm surge protection in Japan

The construction of storm surge embankments, tsunami embankments, and coastal levees for coastal disaster preparedness in Japan was shaped by two major disasters, the *1959 Ise Bay Typhoon* and the *2011 Tohoku Earthquake and Tsunami*. The Ise Bay Typhoon generated a storm surge that severely damaged the urban area of Nagoya city, the third-largest urban and industrial centre of Japan. This disaster led to the construction of storm surge embankments, mainly in Tokyo Bay, Osaka Bay, and Ise Bay, which have largely prevented storm surges from affecting these important industrialised bays since then. Visitors to Tokyo Bay will observe substantial embankments, particularly in the inner bay, resembling high walls. Complementing these are tide gates, constructed to block water ingress into urban waterways during storm events.

As many of these structures are now over 50 years old (see Figure 1), they are due for renewal. However, two major concerns must be addressed during reconstruction. Firstly, it is known that as the climate warms, sea level will rise (due to thermal expansion of the oceans and glacial melt) and typhoons are likely to become more intense, mainly due to the rise in sea surface temperatures around the Japanese islands (Nakamura et al., 2020). This will cause the water level of storm surges to rise when typhoons make landfall (Hoshino et al., 2015). Nevertheless, it should be noted that some simulations show a projected reduced frequency in typhoons, and large variability in the trends of 50-year return water levels (Shimura et al., 2022). When renewing or repairing seawalls, it is necessary to predict the level of the expected future storm surges and raise the height of the seawalls to compensate (although practitioners use a variety of different projections, not only in Japan but throughout the world, Hirschfeld et al., 2023; 2024).

In addition, in order to minimise the use of land many seawalls in urban areas were constructed using a thin-walled structure called a "special dike", which can be vulnerable to earthquakes. In the event of an earthquake taking place directly under Tokyo Bay, the vertical and horizontal displacement of the ground could cause damage to dikes and embankments, with the possibility of water leaking through the gaps. Therefore, seawalls that are likely to perform well against storm surges could be vulnerable to tsunamis due to problems related to their seismic performance (Nagai et al., 2019). Hazard maps published by local governments in Japan often show inundation areas, which are calculated by considering two different scenario cases: i) when the structures are standing intact and ii) when all structures are destroyed (such as a consequence of an earthquake).

Figure 1: Storm surge embankments in Tokyo Bay

3. Future storm surge projections: changes in typhoon behaviour

When calculating storm surges in the future, it is necessary to attempt to estimate how these may change as a result of climate change.

3.1. Rising sea surface temperatures and increase in typhoon intensity

Future rises in ocean temperatures will result in an increase in mean sea level (due to the thermal expansion of the oceans and melting of glaciers and polar ice sheets). Furthermore, the higher sea surface temperatures will likely increase future typhoon intensity and strengthen wind fields due to enhanced water vapour generation, resulting in higher storm surges being generated (Nakamura et al., 2016).

In response to such fears, local authorities such as the Kanagawa Prefectural Government have conducted storm surge projection studies for Tokyo Bay. These projections assume a 0.38 *m* sea level rise by 2100 and incorporate scenarios of increased storm surges and wave heights caused by stronger winds.

3.2. Weakened Westerlies and Slow-Moving Typhoons

There is a prevailing westerly wind near the Japanese archipelago that traditionally blows strongly from west to east. In the past, typhoons approaching Japan were often swept away by these winds, quickly deflecting towards the northeast. However, in recent years the westerly winds have begun to meander, and the typhoon paths have become unstable. Increasingly, periods of weakened westerlies have led to more cases of typhoons stagnating around Japan or moving westward. In recent years, some typhoons have made landfall in the northern Tohoku region, while others have managed to approach Hokkaido while maintaining a strong intensity. In the case of Hokkaido, unprecedented high waves struck the coast, prompting the revision of breakwater design standards and increasing assumptions regarding design wave heights.

To address this, Japanese researchers have modelled various typhoon paths based on past experience and recent cases, with numerical forecasting calculations being used to predict future storm surges and high waves. When a typhoon slows down, the wind field—formed by the combined effect of the typhoon's movement and its vortex-induced wind—diminishes. As a result, the generated storm surge and wave heights may decrease. However, as the wind blows for a longer period of time, the storm surge height and the wave height due to the wind are expected to increase. As this latter effect becomes larger, storm surges and waves may become higher due to the reduction in typhoon speed (Inagaki et al., 2020).

For example, Typhoon No. 12 in 2018 (Jongdari) was a rare typhoon that moved westwards along the Pacific coast. Normally, waves increase progressively from the west, but in this case high waves suddenly swept into Odawara and Manazuru (in western Kanagawa Prefecture) without warning, resulting in road closures and damaged vehicles being swept away. Nowadays, engineers need to prepare for unforeseen disasters by utilising numerical forecasts, which should include future consequences of global warming and the application of imaginative judgment to anticipate conditions beyond past experiences or what is written in disaster manuals.

4. Two different levels of defence: 100 years (structures) and 1000 years (evacuation plans)

The establishment of two categories of return periods for the design of tsunami countermeasures was originally in response to the tsunami damage and lessons learned from the 2011 Tohoku tsunami, which represented a significant change to risk management philosophy in terms of how to protect populated areas against these events. This led to the establishment of two different levels of protection (see Shibayama et al., 2013 for more details).

This concept has also been applied to storm surges, and storm surge levels are being established throughout Japan. The 'storm surge protection level' (Level 1) is a storm surge level that shall be prevented by structures such as seawalls or coastal embankments. This level targets storm surges with a recurrence probability of once every few decades to once every hundred years and aims to protect coastal assets and aid evacuation behaviour by reducing the amount of seawater inundating the land. Regarding this protection level, the height of the embankment required to protect the land against a given storm surge is compared with the height of the embankment required for tsunamis, and the structure is to be designed to whichever of the two is higher.

The 'storm surge mitigation level' (Level 2) is above this. It involves formulating the most comprehensive measures necessary to protect human lives against storm surges, and focuses on evacuation planning. These types of countermeasures are typically designed against the flood levels expected for the worst possible storm surges, which are considered to have a return period of 1 in 1000 years.

5. Revised definition of the robustness of coastal embankments: preventing failure from overtopping

During the 2011 Tohoku tsunami, seawater overtopped many coastal barriers, causing significant local scouring on the immediate shoreside of the structures, which in many cases led to their collapse. In order to prevent collapse in the event of overtopping, levees and other structures are now covered with a protective layer not only on the surface of the seaward front (seaward) slope and the crown (shoulder), but also on the back (lee), with the aim of creating a resilient structure (see Figure 2).

Figure 2: View of a coastal embankment in Iwanuma City. Coastal defence structures are expected to survive after overtopping, reduce the overtopping rate, and delay water intrusion time over land.

6. Publication of hazard maps and their use in evacuation planning

To help residents evacuate, hazard maps are published by local governments for coastal disasters such as tsunamis and storm surges, showing the extent and height of the waves on a map. It is the role of local governments at the prefectural level to predict the potential height and extent of tsunamis and storm surges. It is the role of municipal-level authorities to plan the evacuation of residents based on such estimates. For this reason, both of these administrative levels are supposed to publish forecast maps, and those by municipal-level authorities include the location of shelters and evacuation routes.

Hazard maps are prepared using numerical prediction models. The first author chairs the Tsunami and Storm Surge Study Groups of the Kanagawa Prefectural Government and has assisted in calculating predictions for the Tokyo Bay and Sagami Bay sides of Kanagawa Prefecture, respectively. The disaster simulations shown in the tsunami and storm surge hazard maps are calculated using the seabed and land topography according to conditions selected from historical events and assumptions of numerical simulations. Therefore, depending on how the conditions are set and the precision and resolution of the topography used, the actual image of a tsunami or storm surge may differ slightly in scale and location. When using hazard maps, it is necessary to take into account these shifts and fluctuations in the calculations and consider the level of uncertainty in them, and hence the possibility of larger waves hitting a slightly wider area than what the results provided by the simulation.

It is important to assess in advance the likelihood of a disaster striking residents while at home, at work, at school, and along commuting routes, as well as how to evacuate (Han et al., 2023; Mikami et al., 2020; Takabatake et al., 2018). There is a difference between evacuation centres suitable for earthquakes and fires and those suitable for tsunamis, storm surges and river floods. In the case of coastal disasters, it is advantageous to be at a higher elevation, so it is also important to check the elevation of each location. In Japan, the ground elevation is nowadays often indicated on power and telephone poles, or rail and metro stations (it is also possible to use a variety of map applications on a smartphone to check the approximate ground elevation). In the case of the commuting route of the first author of this paper, his house sits at an altitude of 19 *m*, and then passes through lowlands of about 6 *m* on the way to his destination, which is 28 *m* high. The route follows the Kanda River, which means there is a possibility of river flooding during heavy rainfall in this section of the route.

7. Evacuation from storm surges

The location and time of an earthquake that may trigger a tsunami cannot be predicted in advance. In contrast, typhoons that can generate storm surges can be predicted in advance by weather forecasts. However, the location and magnitude of the storm surge will depend on the path of a given typhoon. Given the limitations of current weather forecasts and the sensitivity of storm surges to the path of typhoons, it is not practically possible to accurately specify the location and magnitude of storm surges until approximately half a day in advance. At this point in time, the rapidly intensifying wind and rain make long-distance evacuation to safer locations difficult (Takagi et al., 2015). Instead, evacuation to the third or fourth floor or higher of a solid reinforced concrete building often becomes the only practical option. However, in this case, the evacuee may be isolated inside the affected area until the floodwaters recede (which might last up to one week for the case of Tokyo downtown). As the height of the storm surge and the duration of the resulting flood are difficult to predict, people are encouraged to prepare well in advance for how to respond to a disaster, such as by evacuating in advance or stockpiling daily necessities so that they may survive even inside an isolated building.

For the case of resident evacuation, methods for analysing detailed behavioural choices, interactions between local residents and travellers (San Carlos Arce et al., 2017), and interactions between pedestrians and vehicles have been developed based on an agent model that can consider the decision-making behaviour and interactions of agents (Takabatake, Fujisawa et al., 2020). Such models allow for designing the rational behaviour of an evacuee, which in turn offers effective tools for real-world disaster planning and response (Uno et al., 2015; Wang and Jia, 2021; Takabatake, Esteban et al., 2020; Mostafizi et al., 2018). They can be used for a variety of local conditions, for example by considering evacuation by car and on foot at the same time.

In many coastal areas, including Kamakura City in Kanagawa Prefecture, tsunamis threaten not only local residents who know the area well but also tourists who visit there temporarily, so it is important to consider both when preparing evacuation plans. An agent-based tsunami evacuation model has been proposed (Takabatake et al., 2017) that considers the different behaviours of local residents and visitors and can estimate evacuation times, the number of people reaching each evacuation point, the location of bottlenecks and the number of victims. In a case study of Yuigahama Beach at Kamakura City, results showed that the number and behaviour of tourists significantly affected evacuation outcomes—especially congestion levels and victim counts. Furthermore, as congestion occurs during evacuation in places with many visitors, the reduction in travel speed due to congestion can be dangerous, and thus evacuation simulations must also account for reduced travel speeds caused by this congestion. Widening evacuation routes and directing evacuees to less crowded paths are important strategies for minimising casualties in coastal disasters.

8. Disaster reconstruction patterns

In the aftermath of the 2011 Tohoku tsunami, the Japanese taxpayers agreed to use a reconstruction budget of 32 trillion yen (220 billion US dollars) to recover from the disaster, with the reconstruction process being carried out through a process of consensus building in each region. Different choices were made in various places, based on their respective disaster experience, the community's history, and social structure. Some of the most representative examples are listed below. These patterns are also applicable to storm surge cases, and can inform how communities elsewhere can learn from the Japanese experience, just as the Japanese learned lessons from Hurricane Katrina.

8.1. Rebuild communities by building stronger breakwaters to prepare for the next tsunami attack.

In the Taro area (within Miyako City in Iwate Prefecture), a new 14.7 *m* seawall was constructed closer to the shore to replace the previous 10.0 *m* embankment that was overtopped during the Tohoku tsunami, see Figure 3.

This is similar to what happened in the case of New Orleans after the Katrina storm surge, where the U.S. Army Corps of Engineers constructed new defence structures such as strong levees, floodwalls, gates and pumping stations under the project of Hurricane and Storm Damage Risk Reduction System (HSDRRS). The HSDRRS can defend against a 100-year level of storm surge. (U.S. Army Corps of Engineers, 2018)

Figure 3: Construction of a new seawall in the Taro area.

8.2. Development of Artificial Elevated Land

In Rikuzentakata City (Iwate Prefecture), the urban area of the town was raised by 10–12 *m*. This was achieved by cutting surrounding hills (45 hectares) and filling the old town area (91 hectares) to create an elevated ground on which the town was then rebuilt (see Figure 4 and Valenzuela et al., 2019). Interestingly, as far as the authors know, such type of reconstruction was not attempted in the case of the USA after Hurricane Katrina, maybe due to the massive costs involved in raising the ground several metres above its original level. Instead, in New Orleans green infrastructure is being promoted to mitigate ground subsidence and flood risks, and to retain and infiltrate rainwater. Nevertheless, for the case of Japan such interventions have resulted in a far more resilient town, through the clear establishment of a fully functional multi-level defence strategy (Esteban, Takagi & Shibayama, 2015).

Figure 4: Artificial ground with embankments in Rikuzentakata City.

8.3. Low-lying old town areas inundated by the tsunami have become open spaces without any housing

In Onagawa, the old town centre is now used as a station and shopping area, while new residential areas are built on natural hills, to which residents have relocated (see Figure 5), a pattern which has been replicated along much of the Tohoku area in northern Japan (Esteban, Onuki et al., 2015). The permanent conversion of low-lying urban areas into open, non-residential spaces exemplifies a form of managed retreat (Esteban, Takagi & Shibayama, 2015), which openly contrasts with the post-Katrina emphasis on large structural defences. When thinking about the regions affected by Hurricane Katrina, retreating from highly vulnerable areas would have reduced reconstruction costs by removing assets from the most flood-prone locations, while creating multifunctional buffer zones (such as parks or areas designated for open field sports).

Figure 5: Conversion of old town areas into open space in Onagawa

8.4. Abandonment and withdrawal from residential areas

The Arahama area of Sendai City was developed as a bedroom community for the city of Sendai before the tsunami hit the area. However, following the severe damage that took place due to the tsunami (see Figure 6), all residents were relocated and left the area.

The withdrawal of residents from a large residential area is not something that is easy to do, and in the context of Katrina, it would have required careful advance planning, equitable buyout and compensation schemes, and strong community engagement to overcome legal, social and political barriers tied to property rights and place attachment. Given that, following a disaster, communities and political leaders have no other way than to rebuild, it can be useful to conduct pre-disaster recovery workshops, which can prepare plans on how an area would be rebuilt following a major event (Florentin et al., 2021).

Figure 6: Abandonment of the Arahama area

9. Concluding remarks

As described above, Japanese coastal engineering researchers and engineers studied the characteristics and aftermath of Hurricane Katrina and other storm surge events around the world, and derived a number of lessons that informed current disaster risk management in Japan. These included an emphasis on the development of numerical simulations to forecast typhoons, the storm surges that these may generate, and how these inundate nearby land. The challenges posed by global warming have also increased the awareness and urgency to strengthen storm surge embankments, develop hazard maps for residents and propose evacuation plans. In the same manner in which Japanese researchers learned from Hurricane Katrina, recent experience in tsunamis and storm surges in Japan can also help to inform disaster risk management and reconstruction elsewhere in the world.

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Data access statement

No datasets were used in the present research. Any information or data available to the authors will be provided upon reasonable request.

Contributor Statement (CRediT)

T.S.: Conceptualization, Writing – original draft, Writing – review & editing; M.E.: Conceptualization, Writing – original draft, Writing – review & editing.

Use of AI

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Conflict of interest (COI)

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