RECENT PROGRESS OF PHYSICAL MODELING BASED ON FIELD INVESTIGATIONS OF TSUNAMIS AND STORM SURGES

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ABSTRACT

Hydraulic laboratory experiments were conducted to ascertain various phenomena observed during recent field surveys of tsunamis and storm surges. Essentially, the nature of tsunami waves appears to be far more complex than the simple experiments that used to be carried out in previous times. Thus, in order to understand the destruction mechanism of different structures, it is necessary to clarify the physical nature of the wave at each location in order to identify whether a solitary wave, a bore wave, a dam break wave or continuous overflow should be used in the modelling. Such experiments allow not only to clarify the destruction mechanisms of tsunamis but also of bore waves, such as the ones observed during the storm surges due to cyclone Sidr in Bangladesh in 2007 and typhoon Yolanda (Haiyan) in the Philippines in 2013. The present paper will summarise the types of laboratory experiments that can be carried out according to the local geographical conditions and nature of the tsunami waves. For example, it will detail the failure of coastal dykes during the 2011 Tohoku Earthquake Tsunami due to local scour, where the continuous overflow of the tsunami wave resulted in the destruction of many dykes, and which was modelled using pump flow to produce supercritical flows running down the onshore slope of dyke. Also, laboratory experiments to reproduce the behaviour of a tsunami wave around structures to reduce inundation -such as detached breakwaters and artificial waterways constructed along the shoreline- will be detailed, amongst other experiments.

KEWORDS: TSUNAMI, STORM SURGE, HYDRAULIC LABORATORY, FIELD WORK, BORE

1 INTRODUCTION

In the last twelve years the world has been affected by a number of large coastal disasters. For case of tsunamis, major events include the Indian Ocean Tsunami in 2004 (affecting mainly Indonesia, Sri Lanka and Thailand), the Java Tsunami in 2005 (Indonesia), Samoan Tsunami in 2009, Chilean Tsunami in 2010, Mentawai Tsunami in 2010 (Indonesia) and Tohoku Tsunami in 2011 (Japan). Regarding storm surges, noteworthy events include the storms surges due to hurricane Katrina in 2005 (U.S.A.), cyclone Sidr in 2007 (Bangladesh), cyclone Nargis in 2008 (Myanmar), hurricane Sandy in 2012 (U.S.A.), typhoon Yolanda (Haiyan) in 2013 (Philippines) and the event in Nemuro in 2014 (Japan). Table 1 summarises these events, providing an estimation of the number of casualties that resulted from each, highlighting the vulnerability of coastal settlements against such disasters and how there is still much to be learnt (as highlighted for example in Shibayama (2015) and a book that details many of these disasters, Esteban et al., 2015).

Following each of these events, the authors took part in post disaster surveys and attempted to draw a number of important engineering lessons, as summarised below:

1. The nature of tsunami or storm surge wave behaviour can be classified into four different patterns, namely solitary wave type (Java Tsunami), dam break wave, continuous overflow (Tohoku Tsunami) and bore wave. Bore waves were frequently observed in previous tsunamis but have also now been observed in storm surge events, such as for example during cyclone Sidr (Shibayama et al., 2009) and typhoon Yolanda (Roebber and Bricker, 2015, Nakamura et al., 2016)

2. Coastal dykes failed due to a continuous and prolonged water overflow (for twenty minutes or more, such as during the 2011 Tohoku Tsunami or the storm surge during hurricane Katrina, see Shibayama, 2015). Essentially, these structures are typically not designed for overtopping and can catastrophically fail due to scouring of the landside toe
3. Coastal forests played an important role to increase water depth behind coastal dykes and prevent the appearance of supercritical flow over dykes (Tohoku Tsunami, Matsuba et al., 2014).

4. Inundation patterns were strongly influenced by the local topography, (Tohoku Tsunami, Indian Ocean Tsunami, storm surges due to hurricane Katrina (Shibayama et al., 2005) and the storm in Nemuro). For example, in the case of Tohoku the existence of artificial waterways constructed along the coastline somewhat influenced the movement of water over it (Watanabe et al., 2016).

5. Detached breakwaters are a common way to protect against wind waves along the shorelines in Japan, though these can offer some degree of protection against tsunamis.

6. The transportation of debris by flooding water can exacerbate the destruction caused to structures and houses (storm surge due to hurricane Katrina and typhoon Yolanda, Chilean tsunamis, Tohoku Tsunami, see Chock, 2015)

Essentially, these field surveys and the lessons learnt from them highlight that the nature of tsunami waves appears to be far more complex than the simple experiments that used to be carried out in previous times. Thus, in order to attempt to reproduce the findings from field experiments a number of laboratory experiments have been performed at Waseda University. These experiments make use of novel methodologies to more realistically simulate the effects of tsunami overtopping waves over a variety of structures, as outlined in the remaining sections of this paper.

<table>
<thead>
<tr>
<th>Year</th>
<th>Disasters</th>
<th>Locations</th>
<th>Number of confirmed casualties (including those still missing)</th>
<th>Special Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>Indian Ocean Tsunami</td>
<td>Indonesia/Sri Lanka/Thailand</td>
<td>220,000</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>Storm Surge by Hurricane Katrina</td>
<td>USA</td>
<td>1,250</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>Java Tsunami</td>
<td>Indonesia</td>
<td>668</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>Storm Surge by Cyclone Sidr</td>
<td>Bangladesh</td>
<td>5,100</td>
<td>Construction of Cyclone Shelters (1970: 400,000 1991: 140,000)</td>
</tr>
<tr>
<td>2008</td>
<td>Storm Surge by Cyclone Nargis</td>
<td>Myanmar</td>
<td>138,000</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Tsunami in Samoan Islands</td>
<td>Samoa</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Chile Tsunami</td>
<td>Chile</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Tsunami in Mentawai Islands</td>
<td>Indonesia</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Tohoku Tsunami</td>
<td>Japan</td>
<td>Death 15,894 Unknown 2,562</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Storm Surge by Hurricane Sandy</td>
<td>USA (New York)</td>
<td>147 (USA 72)</td>
<td>2.5-3.0m in Manhattan Around 4.0m in Staten Island</td>
</tr>
<tr>
<td>2013</td>
<td>Storm Surge by Typhoon Yolanda</td>
<td>Philippines</td>
<td>Death 6,300 Unknown 1,062</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>Storm Surge in Nemuro</td>
<td>Japan</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

2 LABORATORY EXPERIMENTS

2.1 Tsunami or Storm Surge Generation in Laboratory

In the past, tsunami waves in the laboratory were often reproduced using solitary waves or dam break flows (Esteban et al., 2015). However, it is now clear that the behaviour of tsunami and storm surge waves as they attack the coastline is far more complex than previously thought (Bricker et al., 2015). Judging from video footage of the 2011 Tohoku tsunami these events result in a complex array of failure mechanisms and inundation patterns, with one of the defining failure modes being the overtopping effect of the wave. A prolonged overflowing effect generates a very intense current, and many structures along the Tohoku coastline appeared to have failed due to scour of the landside toe of the structure (Jayaratne et al., 2015). This has led some researchers (Kato et al., 2012, Sakakibara, 2012) to state that the main failure mode is directly related to this overflowing current. As such, the use of solitary waves to simulate tsunamis during laboratory experiments might not be valid for the case of overflowing tsunamis. This in effect reduces the validity of some research carried out in the past, highlighting the need for location and structure specific laboratory experiments, and essentially meaning that none of the tsunami generation methods most commonly employed can alone successfully reproduce all possible failure mechanisms due to tsunami attack. Figure 1 shows three of the main types of tsunami generation methods that are currently being employed in Japan and other countries to reproduce the various types of tsunami destruction mechanisms, and the laboratory researcher must carefully consider which method to use in order to correctly reproduce the failure mechanism he or she wishes to investigate.

It is also worth noting that it is also now understood that storm surges can also be far more complex than previously thought. For the case of cyclone Sidr, bore waves were observed by refugees in cyclone shelters, changing the old perception of a storm surge being a simple change in water level, and highlighting how they could bring about high
momentum bore flows (Shibayama et al., 2009). This was corroborated during the storm surge due to typhoon Yolanda, where bore waves were also created, flooding over land and destroying many houses and structures (Roeber and Bricker, 2015). Thus, it is clearly necessary for those working in laboratory experiments to carefully take into account the local bathymetry and conditions due to each tsunami or storm surge in order to reproduce what is observed during post disaster field surveys. A careless approach to take into account such considerations can lead to the formulation of experiments that do not accurately represent the reality of these types of disasters, and potentially lead to flawed structures that fail to improve the resilience of coastal communities.

Figure 1. Different types of tsunami generation in laboratory (Mikami et al., 2014).

2.2 Coastal Dyke Failure due to Overflow (Mikami et al., 2014)

(1) Velocity and Pressure Field

During the 2011 Tohoku Tsunami many coastal dykes along the Pacific coast of Tohoku were damaged, with field survey reports indicating that the landward side of structures suffered more severe damage than the seaward side (see Jayaratne et al., 2015, Mikami et al., 2012 and other papers in the 2012 CEJ special issue on the Tohoku Tsunami). The mechanisms of failure of the landward sides of damaged coastal dykes included a failure of the covering materials, washout of the inner soil, and scouring (see Jayaratne et al., 2015, for a more complete description of these mechanisms). Damage was mainly caused by the overflowing nature of the tsunami, which continued for a long time, as stated earlier.

In order to understand the hydraulic characteristics and damage mechanisms of a prolonged overflowing tsunami on a coastal dyke laboratory experiments were carried out in a wave flume (dimension: 12m long, 0.4m wide, and 0.6m high) at Waseda University, Japan. Figure 2 shows the layout of the laboratory experiments, which were carried out on a scale of 1/50. To generate a prolonged overflowing tsunami in the flume, pump flow was used (instead of a solitary wave or a dam break mechanism). By controlling the initial water depth and the flow rate generated by the pump, three different types of overflowing tsunamis on the dyke model could be generated, as shown in Figure 3. By changing the downstream boundary condition, three different overflow patterns appeared (as the downstream water depth increasing flows went from the a pattern to the c pattern). To understand the basic hydraulic characteristics of each flow type, the velocity field around the dyke model was visualized and the pressure acting on the dyke model surface was measured.

The velocity field around the dyke for each flow type was analyzed by using a visualization technique, the Particle Tracer Method (see the right part of Figure 3). By using laser beams, tracers were visualized, representing water particle movements. In types (a) and (b) a supercritical flow was generated along the landward side of the dyke model surface. However, when the downstream depth increased (type c), a supercritical flow was not generated, and the velocity near the
landward side of the dyke model surface was lower than the upper flow. These results indicate that the high velocity flow along the dyke surface observed in type (a) and (b) can cause severe scouring failure, as observed in many dykes during field surveys of the damage due to the 2011 Tohoku Tsunami (Jayaratne et al., 2015)

Pressure profiles were obtained from instruments placed at 6 points along the dyke surface model. In type (a) and (b), the on-offshore profiles of pressure distribution were similar, though differed considerably to those of (c). Essentially, for cases (a) and (b) the pressure on the top of the landward slope was lower, and on the toe of the landward slope higher. These results indicate that the non-uniform pressure profile on the landward slope in type (a) and (b) can cause instability in any existing concrete panels covering the core of the dyke (as was the case in many dykes present in the Tohoku regions, see Jayaratne et al., 2015, Mikami et al., 2012)

Figure 2. Layout of dyke overflow laboratory experiments.

Figure 3. Flow types of overflowing tsunamis around a coastal dyke.

(2) Scour Behind Coastal Dyke Induced by Overflowing Tsunami

Laboratory experiments were carried out in a newly built tsunami basin physical modelling facility (dimension: 9m
long, 4m wide, and 0.5m high) at Waseda University collaborating with University of East London (Dr. Ravindra Jayaratne). Tsunami-like waves were generated by chambers with electrically controllable valves on one side of the basin. Wave heights and waveforms were controlled by the initial water level in the chambers and the valves. The authors designed and constructed a dyke model and placed behind it a sand section to simulate the ground adjacent to a dyke protecting a beach section in Tohoku. The dyke was manufactured from stainless steel in order to observe only the scour behind a coastal dyke induced by an overflowing tsunami, as shown in Figure 4. The experiments were carried out on a scale of 1/50.

Wave heights and waveforms were changed to test the sensitivity of the scour depth and profile caused by the overflowing waves. The laboratory experiments indeed indicated how an overtopping tsunami can cause significant scour in the landside toe of a dyke, as shown on Figure 5. This failure mode is quite significant, as during field surveys it was observed how in many cases this scour probably gradually expanded and undermined the entire landside of the structure, leading to its ultimate collapse. As a result, most of the rebuilt dykes in Tohoku now have some type of landside toe protection, which was absent in many structures present before the 2011 Tohoku tsunami. This signals a clear difference in design philosophy, as the original structures had not been designed for overtopping, but present Japanese disaster management philosophy allows structures to be overtopped for the case of level 2 tsunamis (see Shibayama et al. 2014, for a summary of current Japanese philosophy regarding tsunami classification).

![Figure 4. Experimental setup.](image1)

![Figure 5. Example of scour profile.](image2)

2.3 A New Disaster Prevention Function for Coastal Forests (Matsuba et al., 2014)

As shown in the previous section, if an overflowing tsunami on a coastal dyke does not generate a supercritical flow in its landward side, the coastal dyke is more likely survive the overflowing tsunami event (taking into account the characteristics of the velocity field and pressure around the landward slope). Possible solutions to prevent such supercritical flow from appearing include the placing of some obstructions or to make the landward slope milder. In fact, prior to the 2011 Tohoku Tsunami, and even at present, in some coastal areas in Tohoku (especially along the Sendai Plain coast) coastal forests were located behind coastal dykes. Hence, in order to investigate the effect of coastal forests on an overflowing tsunami around coastal dykes, laboratory experiments were carried out at the wave flume in Waseda University that was described earlier.

A coastal forest model (scale 1/50) was placed behind the coastal dyke model, with Figure 6 showing a snapshot of the
overflowing tsunami. The experimental results show how indeed a coastal forest can help to reduce the damage to coastal dykes caused by an overflowing tsunami, by increasing water depth behind the dyke and changing the flow type. Also, it appears that the length of the coastal forest is an important factor that can contribute to make the structure more resilient, and thus coastal forests of appropriate length should be considered. Essentially, it would appear that a small forest is unlikely to significantly alter the flow pattern of the water, and it should be noted that in such cases the rapid flow of water is likely to damage the trees, which can become floating debris and further contribute to structural damage in areas behind the forest. Thus, it would appear that for a forest to be considered as an appropriate mitigation measure (both to alleviate damage to the dyke and any human settlements located behind it) it should be a rather thick large forest, rather than a small area of isolated trees.

Figure 6. Laboratory experiment of an overflowing tsunami on a dyke with a coastal forest model (Matsuba et al., 2014).

2.4 Influence of Local Topography on Flooding Water (Watanabe et al., 2016)

During the 2011 Tohoku Tsunami there were eyewitness testimonies that the tsunami inundation height was reduced due to the presence of the Teizan Canal along the coast of the Sendai Plain (the canal is 25 to 45 m wide, 49 km long, and 0.3 to 2 m deep). Field data obtained after the 2011 Tohoku Tsunami confirmed eyewitness accounts, though this effect has not been studied in the past. Thus, in order to understand the detailed characteristics of an overflowing tsunami over a canal, laboratory experiments were performed in the tsunami basin and wave flume described earlier. In the tsunami basin, the amount of flow over the canal model was measured under different wave conditions and for different canal depths. In the wave flume, the fluid motion over the canal model was visualized by PIV (Particle Image Velocimetry).

Figure 7 shows the experimental layout of the experiments carried out in the tsunami basin, with Figure 8 showing a detailed view of the canal model installed at the onshore end on the basin. The offshore water depth was set to 20 cm. An overflow measurement device was placed behind the canal model, which stored the water that went over the canal model. The experiments were carried out on a scale of 1/100. The wave height, waveform, and water depth in the canal model were changed to test their influence on the amount of overflow. The wave heights at three different locations were measured using wave gauges (KENEK Co., LTD) with a sampling frequency of 50 Hz. The experiments were repeated for three different conditions, one with the canal, and the other two for two different canal depths (2cm and 4cm). Three types of waves were generated. The experiments were performed at least twice for each of the cases, and the final results were the average of the measurements taken.

In order to investigate the fluid motion of flow in a canal, a different series of laboratory experiments was performed in the wave flume at Waseda University, using a 1/50 scale. Figure 9 shows the experimental layout. A pump was installed to produce an overflow over the canal model, where the flow rate could be changed by controlling a handle attached to the pump. The inflow fluid motion was analyzed using PIV. A tracer (Diaion HP20SS, Mitsubishi Chemical Corp.) was used so that a laser light (PIV Laser, KATOKOKEN CO., LTD) could visualize the water flowing over the focus area. The visualized flow image was captured by using a high speed camera (High Speed Camera K4, KATOKOKEN CO., LTD).
with high magnification zoom lens (Nikkor lens 50mm f/1.2, Nikon Corp.). Finally, the images that were taken were analyzed by using fluid analysis software (FlowExpert2D2C, KATOKOKEN CO., LTD) and the velocity field was obtained. The experiments were performed for 3 cases of volume flow rate (Q = 0.0109 m³/s, 0.0139 m³/s, and 0.0170 m³/s) in 500 fps of shutter speed.

The laboratory experiments in the tsunami basin showed that the canal reduced the amount of overflow, and that the amount of overflow became larger as the water depth in the canal gradually increased. The amount of overflow depended not only on the height of the wave, but also on the waveform. The experiments in the canal showed that the inflow characteristics are actually more complicated than initially expected, and more experiments are needed to clarify how a tsunami wave interacts with a canal.

Figure 7. Experimental layout in a tsunami basin (Watanabe et al., 2016).

Figure 8. Canal model and overflow measurement equipment (Watanabe et al., 2016).
2.5 Effect of Detached Breakwater (Mikami et al., 2015)

Field surveys after the 2011 Tohoku Tsunami indicated that the presence of discontinuous detached breakwaters in front of coastal dykes greatly affected damage patterns (Mikami et al., 2014). Laboratory experiments were thus carried out in the tsunami basin detailed earlier (scale 1/50) to clarify such damage patterns, as shown in Figure 10. The field data obtained from the 2011 Tohoku Tsunami showed that tsunami flow along the coastal dykes was not uniform, due mainly to the specific arrangement of the discontinuous detached breakwaters in front of the dyke (see Figure 10 to understand a typical layout). The results from the laboratory experiments showed that the presence of a detached breakwater had a mitigation effect on the shoreline right behind the main body of each of the sections of the detached breakwater if a given parameter (namely the distance from the shoreline/length of the opening) was small. On the other hand, the shoreline areas directly behind the gaps in the detached breakwater suffered the full brunt of the tsunami, as the breakwaters did not mitigate the impact of the wave. The results obtained from the laboratory experiments agreed well with the field data obtained after the 2011 Tohoku Tsunami. PIV measurements were also carried out, as shown in Figure 11, though it is clear that there is still much to learn about the behaviour of the tsunami wave for the case of complex interactions between two sets of structures, and this should be further investigated in future laboratory experiments.
2.6 Debris Movement due to Flooded Water (Nistor et al., 2016)

In many tsunami events, such as the 2010 Chilean Tsunami (see Mikami, 2011) and the 2011 Tohoku Tsunami, many port containers were transported by the tsunami and crashed onto structures, clearly highlighting the need for a better analysis of debris movements under tsunami and storm surges. Figure 12 shows an experimental set-up for container movements under tsunami overflow in the tsunami basin, which in this case was used to model a port apron. The green boxes at the front of the photograph represent model containers, whereas the wooden blocks behind them are buildings in the port area. The experiments were carried out on a scale of 1/40. The experiments tracked the movement of the containers using a radar system, which were analysed to reveal the fluid motion. The experiments showed that when bore waves broke at the edge of apron they hit the “containers” and started to move. Also, it was clear that the interaction amongst the container units were important.

3 CONCLUSIONS

During the last 12 years intensive field investigations have been performed after each major flooding coastal disasters, whether it was a tsunami or storm surge. Based on the results of the field surveys it has become clear that there is a need for far more complex and detailed laboratory experiments that the rather simple approaches used in the past, and to adapt the type of experimental apparatus employed to the damage mechanism under study. There are different ways of modelling a tsunami wave or storm surge, including the use of solitary waves, dam break mechanisms, and flows over structures. Each of these setups can help to reproduce a certain aspect of a tsunami or storm surge, and when designing laboratory
experiments special care must be given to employ the right methodology to understand the problem being tacked. Success in doing so can lead to correct designs, which can decrease the risk of failure of disaster management strategies, leading to an increase in the safety of coastal settlements and a decrease in the human losses suffered during major events.

It is also clear that much is still not well understood about the nature and characteristics of coastal disasters, and that there is still a need to perform further laboratory experiments of increased precision to improve the understanding of how these phenomena affect coastal infrastructure.

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