UNIVERSITI PUTRA MALAYSIA

# MODELLING TSUNAMI BORE-INDUCED PRESSURES ON VARIOUS SEAWALL TYPES

ZATY AKTAR BINTI MOKHTAR

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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# DEDICATION

*This thesis is dedicated to my wonderful husband, my backbone,*
*my best friend, my soulmate, Rozaide bin Md Aziz. I love you abang.*
*Thank you for your love, patience, encouragement and for always pushing me*
*to be the best I can be whilst still reminding me to syukur and remain grounded.*

*To my dear Abah, Hj Mokhtar Abu Bakar, and*
*to my beloved Mama who taught me the meaning of courage and always*
*has confidence in me, Hjh Siti Zauyah Arifin.*
*You are my pillar of strength. Thank you for your endless support.*
*Alhamdulillah, your prayers have been answered.*
.
*This thesis and the pursuit of my goals would*
*not have been possible*
*without you all.*

~

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

**MODELLING TSUNAMI BORE-INDUCED PRESSURES ON VARIOUS SEAWALL TYPES**

By

**ZATY AKTAR BINTI MOKHTAR**

**January 2019**

**Chair : Badronnisa Yusuf, PhD**
**Faculty : Engineering**

Catastrophic failures of many tsunami seawalls along the affected coasts during the 2011 Japan Tsunami has prompted extensive investigation into improving and revising design codes for tsunami defence structures. To date, researchers and coastal engineers are investigating to understand the failure mechanisms of seawall and to find solutions so that the structures merely remain intact in the extreme event such as tsunami. With this as the background, the main objective of this study was to experimentally investigate and quantify the tsunami bore-induced pressures exerted on various seawall types. In addition, the tsunami bore impact pressures on seawall models protected by a porous breakwater was also investigated. Four different seawall models; a solid vertical wall, a porous vertical seawall that consisted of a perforated front wall and a solid rear wall and two prevalent curved front seawalls, that were installed individually downstream in a 2D wave flume. Five impounding water depths (0.55, 0.60, 0.65, 0.70 and 0.75 m) were used to produce dam-break waves with various heights and velocities, which have been shown to be analogous to tsunami-induced bore characteristics as stated in theories. Time-history of bore pressures exerted on the seawall models were recorded. In additon, the flow depth-time histories were also recorded at various locations along the length of the flume. A high-speed video cameras together with a regular camera were used to monitor the bore-structure interaction. Experimental results revealed that there were significant differences between the measured pressures exerted on each seawall model. A high impulsive pressure was measured at the lowest-located pressure sensor of solid vertical wall model with 8 kPa in this study. It is found that the impulsive pressure recorded at other seawall models were less than that recorded at the solid vertical wall. It is also noted that the maximum pressure occurred at different times in one recorded time history of bore impacts for all seawall models. In addition, a partially submerged perforated wall with 30% porosity were installed upstream from the seawall models to investigate its efficiency as tsunami mitigation measures. Experimental results indicated that the maximum

pressure exerted on the perforated seawall type can be reduced by approximately 20% to 50%. It was also revealed that the higher amount of pressure exerted on the upper section of the recurved seawall type can be reduced approximately 45% in the presence of the breakwater. The experimental measured data were also compared with those estimated from the current available formulations. The results and analysis presented in this study will be significant use to better understand the interaction between the tsunami bore and more complex seawall geometries. The findings from this study could also be used for validating any numerical models works as well as can be a guideline for future research in designing tsunami barrier structures.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PEMODELAN TSUNAMI MENIMBULKAN TEKANAN-TEKANAN PADA PELBAGAI JENIS TEMBOK LAUT**

Oleh

**ZATY AKTAR BINTI MOKHTAR**

**Januari 2019**

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Kegagalan besar terhadap banyak tembok laut tsunami di sepanjang pantai yang terjejas semasa Tsunami Jepun 2011 telah mendorong kepada siasatan lebih menyeluruh untuk menambah baik dan menyemak semula kod-kod reka bentuk bagi struktur pertahanan tsunami. Sehingga kini, para penyelidik dan jurutera pantai masih menyiasat untuk memahami mekanisme kegagalan tembok laut dan mencari penyelesaian supaya strukturnya tetap utuh dalam kejadian bencana ekstrem seperti tsunami. Dengan ini sebagai latar belakang, matlamat utama kajian ini adalah untuk mengkaji dan mengukur secara eksperimen tekanan-tekanan yang disebabkan oleh tsunami yang dikenakan pada pelbagai jenis tembok laut. Di samping itu, tekanan impak tsunami bor pada model-model tembok laut yang dilindungi oleh tembok pemecah ombak berliang juga turut dikaji. Empat model tembok laut berlainan iaitu; dinding menegak padat, tembok laut menegak berliang yang terdiri dari dinding depan yang berlubang dan dinding belakang padat dan dua tembok laut depan melengkung yang lazim, yang dipasang secara individu di bahagian hilir flum gelombang 2D. Lima kedalaman air (0.55, 0.60, 0.65, 0.70 dan 0.75 m) digunakan untuk menghasilkan ombak-ombak empangan pecah dengan pelbagai ketinggian dan kelajuan, yang telah dibuktikan sama dengan ciri-ciri tsunami seperti yang dinyatakan di dalam teori. Sejarah waktu tekanan bor yang dikenakan pada model-model tembok laut direkodkan. Selain itu, sejarah waktu kedalaman aliran juga direkodkan di pelbagai lokasi sepanjang flum. Kamera video berkelajuan tinggi berserta dengan kamera biasa digunakan untuk memantau interaksi di antara bor dan struktur. Keputusan eksperimen menunjukkan bahawa terdapat perbezaan yang signifikan di antara tekanan yang diukur pada setiap model tembok laut. Tekanan impulsif yang tinggi diukur pada sensor tekanan yang terletak paling rendah di model dinding menegak padat iaitu 8 kPa di dalam kajian ini. Didapati bahawa tekanan impulsif yang direkodkan pada model tembok laut yang lain adalah kurang dari yang direkodkan di dinding menegak padat. Juga diperhatikan bahawa tekanan

maksimum untuk setiap model tembok laut masing-masing berlaku pada waktu yang berlainan dalam satu sejarah waktu impak bor yang direkodkan. Selain itu, tembok berpori dengan keliangan 30% juga telah dipasang dengan terendam sebahagiannya di hulu dari model tembok laut untuk menyiasat kecekapannya sebagai langkah-langkah untuk mengurangkan tsunami. Keputusan eksperimen menunjukkan bahawa dengan adanya pemecah ombak ini, tekanan maksimum yang dikenakan pada jenis tembok laut berlubang boleh dikurangkan kira-kira 20% hingga 50%. Juga didapati bahawa jumlah tekanan yang lebih tinggi yang dikenakan pada bahagian atas jenis tembok laut melengkung dapat dikurangkan kira-kira 45% dengan kehadiran pemecah ombak ini. Data ukuran secara eksperimen ini juga dibandingkan dengan yang diperkirakan dari formulasi sedia ada pada masa ini kini. Hasil dan analisis yang dibentangkan di dalam kajian ini boleh bermanfaat secara signifikan untuk lebih memahami interaksi di antara tsunami bor dan geometri tembok laut yang lebih kompleks. Penemuan dari kajian ini juga boleh digunakan untuk mengesahkan sebarang model berangka dan dapat juga menjadi garis panduan untuk penyelidikan di masa hadapan di dalam merancang struktur penghalang tsunami.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Date:

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This is to confirm that:

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| | |
|---|---|
| $h_b$ | Bore depth or height of the bore from the ground level (m) |
| $h$ | Height of the bore from the still water (m) |
| $d_s$ | Downstream still water depth (m) |
| $h_d$ | Impoundment water depth (m) |
| $h_m$ | Maximum bore depth (m) |
| $H$ | Height of the jump (m) |
| $t$ | Time (s) |
| Fr | Froude number |
| $g$ | Acceleration due to gravity (m/s$^2$) |
| $\rho$ | Mass density of water (kg/m$^3$) |
| $u_b$ | Bore velocity (m/s) |
| $z$ | Height from the still water (m) |
| $z'$ | Height from the ground level (m) |
| $p$ | Pressure (N/m$^2$) |
| $p_{max}$ | Maximum pressure (N/m$^2$) |
| $h_s$ | Height of the seawall (m) |
| GO | Gate opening (m) |
| $R^2$ | Coefficient of determination |
| $K$ | Coefficient of wave pressure |
| $\theta$ | Wedge angle |
| $C_F$ | Coefficient that depends on the wedge angle $\theta$ |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Tsunami is a series of water waves in a wave train which caused by the vertical displacements of a water column. This deformation of the sea surface is commonly caused by an underwater earthquakes; submarine fault ruptures during seismic disturbances or due to volcano eruptions, submarine landslides and meteorites impact (Al-Faesly et al., 2012). The displacement of water column caused by an abrupt motion of sea floor will usually generate small initial amplitude of tsunami in the vicinity of a tsunami source region. The initial height of the sea surface displacement is typically only a meter or less in general.

Most tsunamis are usually associated with a large and destructive wave. In general, tsunami typically has wave periods of 100 s – 2,000 s (1.6 min – 33 min), depending on the wavelength and water depth. Unlike ordinary wind wave, tsunami has very long wavelength which can propagate at very high speeds which may reach up to 900 km per hour in the very deep ocean which is nearly similar to the speed of a jet airplane and with their kinetic energy is evenly distributed throughout the entire water depth (Ward, 1989). Tsunamis retain their energy in which they can propagate across the entire ocean or can travel great transoceanic distance with very little energy loss.

As the tsunami approaches the shallow water and propagates towards the shoreline, the waves will experience a transformation. Their huge amounts of energy are remains nearly constant. Since the velocity of tsunami and the wavelength are depending on the water depth, both the speed of the waves and the wavelength will decrease. Whereas, the height of tsunamis will then be amplified due to shoaling effect and other factors, for instance the effects of coastal topography and bathymetry as well as harbour resonance effects. Upon reaching near the shoreline, the waves eventually break when the incident tsunami height is approximately equal to the ocean depth and thereafter forming a sequence of either strong turbulent hydraulic bores or surges advancing toward the shoreline (Yeh et al., 1989). As mentioned by Yeh (2007), the tsunami waves break in a plunging mode and when the overturning tip of the wave touches down on the sea surface, it will transform into bores. The bores run-up the shore and strike the coastal structures with considerably high velocity.

From the past tsunami events, apparently the largest wave is not necessarily the first wave to arrive the shores. Snapshots from video footage of the 2011 Japan tsunami (Figure 1.1) and the 2004 Indian Ocean Tsunami (Figure 1.2) shown that the tsunami waves broke upon reaching near the shore area and transformed into a hydraulic bore.

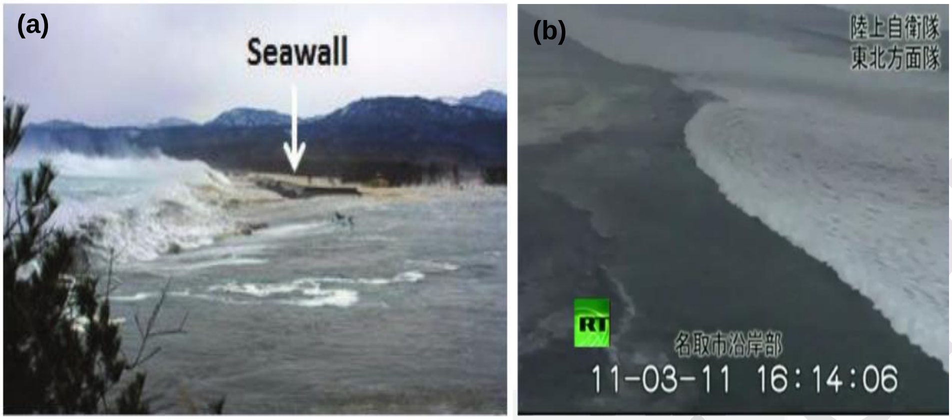


**Figure 1.1: The 2011 Japan tsunami arrived at the beach area: (a) Noda Coast** (Source: Ogasawara et al., 2012)**, (b) Japan's eastern coast**
(Source: Asian Tsunami Videos, 2011)

The propagation of bores approaching the shores was clearly seen in many video recordings and photographic records during the occurrence of these two past devastated tsunami events.

**Figure 1.2: The 2004 tsunami bore and surge fronts arrived at the Krabi beach area**
(Source: Asian Tsunami Videos, 2005)

The evidence of strong currents of tsunami flow can also be found in various documented structural failures and eyewitness accounts. As reported by many witnesses, a white foam strip visibly coming towards the shore which stretched along the distant horizon in a high speed during the 2004 Indian Ocean Tsunami waves struck a large part of Peninsular Malaysia's western coast (Komoo and Othman, 2006). As a result, the 2004 Indian Ocean tsunami disaster had caused severe damage to many coastal infrastructures and facilities in various countries in the Indian Ocean including west coast of Malaysia. The huge tsunami generated had also claimed more than 230,000 lives, in which 68 fatalities were reported in Malaysia. The similar observations were also reported during the occurrence of the 2011 Japan tsunami where the incident tsunami waves were in a form of a series of turbulent hydraulic bores, which inundating over hundred kilometres square of land and inundated some coastal regions by up to 10 meters tsunami height (Miyamoto, 2011). Mori et al. (2012) reported that the measured run-up heights were over 30 meters. The massive tsunami devastated large parts of Japan's north-eastern coastline and causing a critical failure mode to many well-engineered reinforced coastal protection structures and caused more than 15,000 deaths (Nandasena et al., 2012). Both these disastrous events have drawn the attention amongst the coastal engineers and scientists to re-investigate the impact of tsunami wave forces on coastal structures and re-evaluate the effective mitigation measures that could be considered.

## 1.2 Problem statement

It is known that the impact of tsunami is greater than any other natural disasters. Thus, tsunami protective structures for instance seawalls, breakwaters and dikes are most critical infrastructure that was crucial for protection of life and property against such an extreme wave actions like tsunamis and storm surges. Although tsunamis have been viewed as a very rare event, but it is desirable to ensure that the sea defence structures are adequately designed to provide some degree of protections to the coastal infrastructures, commercial development and coastal residential living in the tsunami hazardous areas. These tsunami barrier structures certainly would not be able to stop the incoming tsunamis onto the shore, but it could somehow minimize the tsunami inundation over the land and thus may contribute to less risk of tsunami impact. Besides, it may also indirectly play a great aspect in delaying the incoming tsunami waves, and therefore will give some ample times for the community evacuation purposes. Thereby, it is very crucial to ensure that the tsunami defences are well-designed constructed and are able to resist the forces imposed by the incoming tsunami wave energy, enable to reduce the impact of strong waves as well as to remain intact when the tsunami flows over. Therefore, in dealing with this issue, clear understanding of bore interaction with sea defence structures and characteristics of bore-induced pressure on these structures is essential requirement to a successful design.

While numerous large tsunami events have been recorded throughout history, the last decade has seen many coastal defensive structures were destroyed and failed due to tsunami impacts as reported in Camfield, (1994), Kato et al., (2012), Mase et al., (2013), Tanaka et al. (2012), Yamamoto et al., (2006), and Yeh et al. (2013). The 2011 Japan tsunami disaster have awakened the attention of many countries and it has prompted considerable rethinking amongst the coastal engineers on evaluating the existing coastal seawall's design criteria and their performance under the impact of great tsunami wave forces. Many field surveys of the 2011 Japan tsunami reported that most of the coastal protection structures particularly the seawalls and breakwaters were severely damaged and destroyed due to tsunami impact forces. Field observations showed that the failures of many coastal seawall structures were because of these structures were not actually designed to withstand high impact tsunami loads, and instead, the structures were initially designed based on storm surge and high tide conditions as well as based on their historical tsunami event conditions that have occurred. The field survey reports also revealed that the typical mechanisms of seawall failures include scouring due to strong overflowing currents and wall overturning due to the collision of the tsunami wave front into seawall (Kato et al., 2012; Takahashi et al., 2011). Interestingly, a number of studies later have attempted to demonstrate that the seawall failure mechanisms during the extreme 2011 Japan tsunami are due to the impact of tsunami wave force (Ishikawa et al., 2012; Mikami et al., 2014) and also due to the tsunami-induced local scour around seawalls (Kato et al., 2013; Jayaratne et al., 2014; Shimozono and Sato, 2016). Nevertheless, the actual mechanisms behind the failures of many coastal seawalls during this devastated tsunami occurrence are still not fully understood and explored.

Consequently, it is rather important to have an effort to further enhance the coastal protection strategies that can withstand any extreme events such as large impact forces generated by tsunami wave in the future. To date, there have been numerous studies on the interaction of tsunami wave with coastal protection structures and their impact. Several attempts have been made to investigate the tsunami wave forces and pressures exerted on seawall. Though this subject of research has been an interest among the researchers since the late 1900s (Chen et al. 2016; Fukui et al., 1963; Hamzah et al., 2001; Hsiao and Lin, 2010; Kato et al., 2013; Kihara et al., 2015; Mizutani and Imamura, 2001; Nakamura and Tsuchiya, 1973; Ramsden, 1993), but there are still rooms for improving and extending the knowledge on this subject area. However, the challenging problems remain due to the difficulties in understanding the complicated behaviour of tsunami wave near the shore when downscaled to laboratory scale for further research.

The current literature mainly shows that many experimental and numerical studies of the wave impact forces of tsunami bore on a typical type of coastal vertical seawall and sea dike. The literature survey indicates that research on the impact forces of bores on specifically curved-front seawall is scanty, which mostly pertain to forces of ordinary wind waves. This has indicated that study on the interaction between a tsunami bore and a curved-front seawall has received much less attention. The tsunami loading on this type of seawall is still unclear. Furthermore, the effect of upstream perforated breakwater on the exerted bore pressure on the seawall also has not been evaluated in the past research. The knowledge of tsunami-induced pressure acting on seawall is the most important parameter for designing the structural dimensions of seawall. Therefore, the current study is intended to fill this gap to some extent which is still fragmented.

## 1.3 Objectives of the study

The main objective of this research is to investigate experimentally the interaction of tsunami-induced bores with a different configurations of seawall models. The specific objectives of this study are:

i) To investigate the characteristics of the simulated tsunami bore in terms of bore depth and bore front velocity

ii) To determine experimentally the distribution of pressure exerted on vertical and curved-front seawalls under tsunami-induced bores impact
iii) To investigate the effect of upstream perforated breakwater on the distribution of tsunami pressure exerted on seawall models
iv) To evaluate the existing equations for predicting maximum tsunami pressure on seawall and to propose estimation equations to predict maximum bore pressure on seawalls based on the experimental results.

## 1.4 Scope and limitations of the study

To achieve the objectives of this study, a series of experimental works were conducted in the moderately smooth concrete large wave flume. In this experiment, a dam-break mechanism (the sudden release of water from an upstream reservoir) is employed to generate simulated tsunami bores to investigate their characteristics and the bore-seawall interaction. In this research study, four different seawall configurations and one perforated breakwater were utilised. Five different impounding water depths were used in this study to investigate the relation between bore depth and bore velocity with bore-induced pressures exerted on each seawall. The experimental data obtained from this study is also compared with the theoretical formulations to determine how well these theories describe different characteristics of a tsunami-like bore generated in this study.

Limitations of this study are outlined below:

i. Due to imperfections of the experimental facility such as the imperfect sealing mechanism of the sluice gate employed in the flume, experimental program was performed under wet flume bed condition.
ii. Flow conditions in the form of rapid surge, which occur when the bathymetry of the beach is very steep, was not considered in this study.
iii. Only four different configurations of existing seawall models were investigated.
iv. Only one type of breakwater model was investigated: effect of different breakwater types, locations and heights were not considered in this study.
v. For many of the experiments, the incident bore depths were measured along with the pressures exerted on the front face of seawalls at vertical and transverse directions.
vi. The scale selection in this study was based on the capabilities of the wave generation method and experimental facilities
vii. Due to limited number of pressure sensors employed in this study, only six pressure measurement points on the front face of seawalls were investigated.
viii. The duration of the sustained flow was limited when compared to actual tsunami-induced bores. However, the duration of sustained flow attained in this study was sufficient to adequately quantify the characteristics of the bore pressure profiles.
ix. The effect of debris (mud, sand, gravel, ruin of any objects, trees trunk, etc.) and the damming of debris on seawalls are beyond the scope of the present study.

x. Stability of seawalls under effect of tsunami bore is beyond the scope of the present study.
xi. The effects of geological features were not considered in this study.

## 1.5 Novelty of the research

The novelty of the present study resides in the experimental investigation of tsunami-induced bores interaction with different configurations of vertical and curved front seawall structures, with respect to measuring the pressures exerted on the walls. Despite of a number of seawall impact studies under tsunami waves have been previously investigated, however, the tsunami forces and pressures acting specifically on curved-front wall has received little attention. The impact study of tsunami bore on curved-front seawall is still scanty and more knowledge could be explored. There is still questionable area relating to the interactive aspects between tsunami bores and the seawall's characteristics (i.e. more complex seawall geometries). Thus, the present study is intended to enhance the understanding of the interaction between tsunami bore and more complex seawall geometries as well as the bore loads imposed on these seawalls. There are some features of the laboratory works conducted in this research are unique with respect to past tsunami impact studies in which for the first time in such an experimental program, two curved-front seawalls and a vertical perforated-front seawall types were used which have not been previously investigated either experimentally or numerically.

To design a well-structured seawall, it is important to investigate the wave pressure distribution at various points along the seawall and the magnitude of maximum tsunami impact pressure acting on the structures. Therefore, the findings of this investigation are important for coastal engineers and the model equations proposed were found to be applicable in improving future sea defence designs in tsunami hazardous areas. A quantitative assessment on pressure reduction due to the presence of the perforated breakwater before the seawall will at least help for assessment of structural life extension in the presence of breakwater. In addition to that, the experimental results could be also used for the validation of any numerical models in future works.

## 1.6 Layout of the thesis

The thesis has been divided into five chapters. **Chapter 2** includes review of previous experimental and numerical studies with respect to tsunami acting on vertical wall and other several types of seawall configurations. A review of failure mechanism of seawall due to tsunamis is also presented in **Chapter 2**. The methodology and procedures used in the experimental study is described in **Chapter 3**. The experimental findings are presented and discussed in **Chapter 4**. Finally, the conclusions are stated in **Chapter 5** along with the suggested recommendations for future research. A list of references and appendices are attached in the final part of the thesis.

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