BEHAVIOUR OF INDUSTRIALISED BUILDING SYSTEM MODEL IN FLUID-SOLID INTERACTION

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For my beloved father and mother and my husband, Parham Forouzani

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ABSTRACT

The IBS block-work building system is the invention of a Universiti Teknologi Malaysia researcher. The system is targeted towards resisting earthquakes of up to 10 points on the Richter scale. During a recent tsunami after earthquakes, many reinforced concrete buildings that were engineered to resist earthquakes damaged due to the unexpected magnitude of the tsunami’s forces. Currently, there is significant disagreement on existing empirical formulae for the calculation of tsunami-induced force components. In this research, a 1:5 scale IBS model was developed, according to the Buckingham Pi Theorem and Similitude Theory. The behaviour of the 1:5 scale IBS model, when subjected to tsunami bore of ranges from 0.3 m to 1.2 m bore height and debris impact, was investigated experimentally and through dynamic nonlinear finite element analysis. The tsunami bore was simulated in a laboratory by performing a dam break test. Interactions between simulated tsunami bores and the IBS model were investigated experimentally by measuring bore-depth variations, bore velocity, force exerted on the structural models and variations of pressure on the upstream-face of the structure. The structure was assessed based on different performance levels of Operational, Immediate Occupancy, Life Safety and Collapse Prevention, according to FEMA 356. An increase in the impounding water depth led to an increase in the maximum inundation depth downstream at the location of the IBS model, and a proportional increase in the bore front velocity. The hydrostatic pressure distribution of bore impact on the structure was observed throughout the fluid-structure interaction. The impulsive and hydrodynamic forces, obtained from the experimental data, were in agreement with the Japan Cabinet Office guideline (2005) (SMBRT) and the Coastal Construction Manual (FEMA P-55), respectively. From the experimental and numerical study, the IBS structure showed an Operational Performance during tsunami bore, ranging from 0.3 m to 0.6 m height. The scaled structure had an Immediate Occupancy performance level up to 0.9m water bore height. The Life Safety performance level for the IBS structure was 1.2m tsunami bore height (equivalent to 6 metres in the real world). During the debris impact, the IBS column performed very well when impacted by a family car size and wooden log debris. Therefore, the obtained results indicate that this type of IBS model is safe to resist the tsunami.

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ABSTRAK

Model IBS kerja-blok adalah ciptaan penyelidik Universiti Teknologi Malaysia. Sistem ini disasarkan untuk merintang gempa bumi sehingga 10 skala Richter. Semasa tsunami baru-baru ini, banyak bangunan konkrit bertetulang yang direkabentuk untuk menahan gempa bumi telah rosak kerana magnitud daya tsunami yang tidak dijangka. Pada waktu ini juga, terdapat perbezaan pendapat mengenai formula empirik untuk pengiraan komponen-komponen daya yang disebabkan oleh tsunami. Dalam kajian ini, satu sistem IBS berskala 1:5 telah dibina mengikut Teori Buckingham, Pi dan Teori Kesamaan. Kelakunan model sistem IBS berskala 1:5 yang dikenakan tsunami dengan julat ketinggian air antara 0.3 m hingga 1.2 m, dan kesan puing banjir telah diselidik secara eksperimen dan analisis dinamik unsur terhingga tak linear. Ketinggian tsunami disimulasi dalam makmal dengan melakukan ujian pecah-empangan. Interaksi antara ketinggian tsunami dan model sistem IBS di ukur melalui ukuran variasi kedalaman air, halaju air, daya yang bertindak ke struktur sistem IBS dan variasi tekanan pada permukaan binaan. Prestasi struktur kemudiannya dinilaikan berdasarkan FEMA 356 pada tahap Operasi, Penghunian Segera, Keselamatan Hayat dan Pencegahan Runtuhan. Peningkatan kedalaman air yang terbendung membawa kepada peningkatan kedalaman banjir di model sistem IBS, dan berkadar terus dengan peningkatan halaju air. Taburan tekanan hidrostatik ke atas struktur berlaku sepanjang tempuh interaksi antara struktur-cecair. Kuasa-kuasa impulsif dan hidrodinamik yang diperolehi dari data eksperimen adalah bertepatan dengan garis panduan Pejabat Kabinet Jepun, 2005 (SMBRT) dan Manual Pembinaan Persisir Pantai (FEMA P-55). Hasil kajian makmal dan berangka, menunjukkan struktur sistem IBS adalah pada tahap Prestasi Beroperasi sewaktu ketinggian tsunami dalam julat 0.3 m sehingga 0.6 m. Struktur tersebut berada pada tahap prestasi Penghunian Segera pada ketinggian air 0.9 m. Tahap prestasi Keselamatan Hayat untuk struktur IBS adalah ketinggian tsunami 1.2 m (bersamaan dengan 6 meter dalam keadaan nyata). Semasa ujian banjir dan puing, tiang sistem IBS memberi prestasi yang sangat baik ketika dihentam oleh sebuah kereta saiz keluarga dan serpihan kayu balak. Oleh itu, keputusan yang diperolehi menunjukkan bahawa model IBS ini adalah selamat dan dapat menahan tsunami.

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LIST OF ABBREVIATIONS

AC - Accelerometer
ACI - American Concrete Institute
ASCE - American Society Civil Engineers
ASTM - American Society for Testing and Materials
LC - Load Cell
LVDT - Linear variable Displacement Transducer
CCH - City County of Honolulu Building Code
CP - Collapse Prevent
FEA - Finite Element Analysis
FEMA - Federal Emergency Management Agency
FFT - Fast Fourier Transform
IBS - Industrial Building System
IO - Immediate Occupancy
LS - Life Safety
NLFEA - Nonlinear Finite Element Analysis
PC - Pressure Cell
RF - Reaction Force
SMBRT - Structural Design of Building for Tsunami Resistance

LIST OF SYMBOLS

d_s - initial standing water level

h_j - jump height

h_b - bore depth

ρ - density of water

μ - dynamic viscosity of water

σ - surface tension of water

E_b - bulk modulus of elasticity of water

g - acceleration of gravity

F_r - Froude number

E_u - Euler number

R_e - Reynolds number

W_e - Weber number

M_a - Sarrau- Mach number

E_s - Young’s modulus of elasticity

ϑ - Poisso’s ratio

f_c' - compressive strength of concrete

f_y - steel yield strength

σ_y - Yield strength

ε_y - Yield strain

σ_u - Ultimate strength

ε_u - Ultimate strain

P - Impulsive pressure

P' - Hydrodynamic pressure

F_i - Impulsive force

F_d - Hydrodynamic force

ρ_s - fluid density

C_D - drag coefficient

Q_x - tsunami horizontal force

z - height of pressure action

A_s - cross section area of bar

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CHAPTER 1

INTRODUCTION

1.1 Introduction

A tsunami is defined as an ocean wave generated when a disturbance occurs that vertically displaces a column of seawater (Kramer, 1996). There are various kinds of disturbances that can trigger a tsunami. These include eruption on a volcanic island, earthquakes, and submarine landslides. However, prior experiences are evident of the fact that the majority of the tsunamis are caused by earthquakes. These include the Chile earthquake (1960), Alaska earthquake (1964), Indonesia earthquake (2004), and Tohoku earthquake (2011). Therefore, it is essential to design coastal structures against earthquakes as well as tsunami loads. The extensive destruction caused in the last ten years owing to the Indian Ocean Tsunami of 2004 and the Japan Tsunami of 2011 has compelled policy makers, political leaders, engineers, and economists to give a serious thought to tsunami-resistant designs.

On 26 December 2004, an earthquake measured at 9.3 on the Richter scale occurred near the northwest coast of Indonesia’s Aceh region. The earthquake then triggered several huge tsunamis, killing nearly 250,000 people, including 68 in Malaysia. Since this disaster, Malaysia has keenly taken up research on certain elements of tsunamis, such as numerical simulations of tsunamis and improving the condition of structures so as to ensure minimal damage from such hazards. As far as structural damages are concerned, the Kuala Muda district in Kedah suffered the highest losses, primarily because the area which was impacted is basically a settlement area and the majority of the damaged dwellings were non-engineered structures. The height of the tsunami waves in Kuala Muda reached up to 3.8 meters and the inundation distance from the coast was said to be 100.524 meters (Koh et al., 2009). Considering the abovementioned problem, the need for shelters within the flat coastland, which are able to resist and stay stable in front of tsunami loads is inevitable.

“Safe house” is a garrisoned room set up in public or private structures in order to safeguard occupants from natural disasters and other such hazards. The basic idea behind the safe house is derived from the safe room or hurricane shelter built by Federal Emergency Management Agency (FEMA) in United States. Such safe house has adequate space to stockpile enough human supplies. It is equipped with telecommunication equipment, kept ready well before the rescue team arrives at the site of disaster.

Researchers from Universiti Teknologi Malaysia have developed a new IBS structural system tested for seismic performance. The structure has been built using reinforced concrete block work system. It can be expanded vertically up to double story. The structural system can be assembled as well as disbanded quickly prior to and after a natural disaster occurs. Its structural components can be instantaneously replaced following the disaster. This dwelling acts as an interim shelter for people while they are rebuilding their houses. The structure can be constructed internally for new buildings or set up externally for existing buildings. Given the hostile social needs, this structure can be designed to match the engineering requirements for different kinds of loads, including projectile, torsion, as well as extended flood levels which can be triggered due to certain natural disasters.

Current research investigated the utility of IBS structural system in tsunami prone area. The force exerted of tsunami bore impact and waterborne debris impact on structure were considered in this study because according to filed survey of previous tsunami, this loads caused mostly damage on structures specially reinforced concrete structure (Suppasri et al., 2013).

This research has made a significant contribution with regard to following aspects:

1) This research develop the understanding of tsunami induced force on structure using large scale of dam break flow in laboratory.

2) This research thoroughly analysed the behaviour of IBS structural system owing to tsunami loads.

1.2 Importance of Study

The infrastructure of hundreds of cities and villages in countries may severely affected by impact of tsunami waves. The devastating effects raised public concern and revealed deficiencies that exist with the current design, implementation and warning systems against tsunamis, and highlighted the need for constructing tsunami shelters.

One important element that needs significant improvement is the estimation of lateral resistance of onshore structures against tsunami-induced forces and also the quantification of impact forces generated by water borne debris. Proper attention must be paid to the detailed design of structural members exposed to the above mentioned forces.

The design of coastal structures such as breakwaters, jetties, groins, and quay walls, against waves, is typically governed by the effect of breaking waves and their associated forces, and is well established in the literature (Nouri et al., 2007). However, unlike coastal structures, the evaluation and impact of tsunami-induced hydrodynamic forces on structure, which used for habitation and/or economic activity, has received little attention by researchers and designers.

The poor performance of structures during the tsunami and shortcomings of structural design codes may indicate that designers had assumed that there was no need to design structures against tsunami-induced forces due to economy reason. Lessons learned from the previous tsunami revealed that tsunami-induced forces should be accounted in the design of structures built within a certain distance from the shoreline in tsunami prone areas.

1.3 Problem Statements

Until very recently, reinforced-concrete structure engineered to withstand seismic loads were assumed to withstand tsunamis. This assumption did not hold for the Japan. During Tohoku, 2011 event, many engineered reinforced concrete buildings failed due to the unexpected magnitude of tsunami forces (Yeh et al., 2013).

Currently, there are no clearly established procedures that address tsunami-induced forces for the design of buildings located in the vicinity of the shoreline in tsunami prone areas. Moreover, significant disagreement on the existing empirical formulae for the calculation of tsunami-induced force components has fostered new research interest in an effort to properly address both tsunami-induced forces and the impact of floating debris within design code.

1.4 Aim and Objectives of Study

The aim of this research is to investigate the utility of IBS structural system due to tsunami forces. In this study a three-dimensional dam-breaking wave interacting with one to five scale of two story three-dimensional IBS structural system are simulated. The objectives of this research are:

1. To develop the experimental modelling of tsunami bore characteristics.

2. To determine the exert pressure generated by tsunami bore on structure.

3. To estimate the lateral resistance of IBS structure against tsunami by quantification of displacement of structure component, and estimate the structural failure due to bore impact.

4. To measure exerted force generated by debris on structure, and investigate the behaviour of IBS concrete building and estimate the structural failure due to debris impact.

1.5 Scope and Limitation of Study

The scope and limitation of this research consider as following:

1) This study was performed to investigate the tsunami-induced force in two parts:
    a) Hydrodynamic force on the structure due to tsunami bore.
    b) Impact load on the structure consist of waterborne debris.
2) The effect of two aforementioned loads measured on displacement and acceleration of IBS structure.
3) The assessment of IBS structure conducted to determine the building performance based on horizontal story drift and damage of 1 to 5 scale of two story block work system.

1.6 Significant of Research

The research significance towards the following issues:

1. This research investigates novel system to create dam break flow for simulating tsunami bore.

2. It improves estimation of tsunami forces on structure.

3. This study enhances the estimation of vertical distribution of tsunami force on structure.

4. This study is completely aligned with IBS system.

5. This research investigates the performance of IBS structural system during tsunami event across the world.

6. It can reduce catastrophic structural vulnerability due to tsunami event.

1.7 Thesis Organization

The components of the research contribute to the study on the behaviour of the IBS structural system due to tsunami loads. This contribution are presented in seven chapters and are briefly illustrated in Figure 1.1 and described as follows:

Chapter 1 describes the back ground of the research, problem statements and its aim and objectives. It also discussed the significance of the research, the scope of research, and ended with brief summary of the structure of the thesis.

Chapter 2 presents the findings of the literature review. It focuses on the dam break flow and analogy between dam break flow and tsunami bore. This chapter reviewed the analytical, experimental and numerical studies of dam break flow and exerted forces of tsunami bore and water born debris on structures. The behaviour of structures based on damage data from previous tsunami cases, and the experimental studies are summarized in this chapter. This chapter followed by introducing the available codes for tsunami and flooding loads on structure. Finally the summary of IBS structural systems and major differences between conventional structure and IBS structural system are presented.

Chapter 3 introduces the operational framework of research. In this chapter the characteristic of tsunami and analogy between tsunami and dam break flow are discussed. The physical modelling, laboratory facilities, the measurement devices and the experimental programs are describe in this chapter. At the end, the numerical modelling of IBS model are described.

Chapter 4 describes the construction and assembly process of three dimensional scale model according to IBS block work system and the empirical program for finding the characteristics of material. Furthermore, the experimental tests performed in a dam break tank at hydraulic laboratory are described in this chapter.

Chapter 5 presents and discusses the data obtained for four test models with varying inundation water depths. The competition between existing structural cods that address tsunami-induced forces and the experimental result of this study are presented in this chapter.

Chapter 6 presents the results of numerical IBS model analysis. In this chapter, the numerical result of modal analysis of IBS model are presented. Experimental results and modal analysis results were compared in natural frequencies. After that, the series of models with different loads of different tsunami bore height and debris impact are simulated and utilized for finding the dynamic behaviour of IBS model due to tsunami.

Chapter 7 concludes the results of the research. The recommendation for future study are presented in this chapter.

REFERENCES

AASHTO, (1998). *LRFD Bridge Design Specifications*. Second edition. American Association of State Highways and Transportation Officials, 26–27.

ABAQUS (2014). *ABAQUS manual*, Version 6.14, Pawtucket , R. I.

ACI Committee 444 (1982). *Models of Concrete Structures*. American Concrete Institute.

Agus, M. R. (1997). Urban Development and Housing Policy in Malaysia. International Journal for Housing Science and Its Application. 21(2), 97–106.

Al -Faesly, T. Q., Palermo, D., Nistor, I. and Cornett, A. (2012). Experimental Modeling of Extreme Hydrodynamic Forces on Structural Models. International Journal of Protective Structures. 3(4), 477-505

Arikawa, T. (2009). Structural behaviour under impulsive tsunami loading. Journal off Disaster Res., 4(6), 377–381.

Arnason, H. (2005). Interactions between an Incident Bore and a Free Standing Coastal Structure, Doctor of Philosophy Thesis (Civil Engineering), University of Washington, Seattle, Washington.

Asakura, R., Iwase, K. and Iketani, T. (2000). Experimental research about wave force by the tsunami which overflow the revement. Procceding of the Coastal Engineering of JSCE. 47, 911-915.

ASTM A615 (2011) Standard specification for deformed and plan billet-steel bars for concrete reinforcement.

ASTM C33/C33M-11a (2011), Standard Specification for Concrete Aggregates.

ASTM C39 / C39-11a (2011). Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,

ASTM C469.61 (2010), Standard Test Method for Static Moudulus of Elasticity and Poisson’s Ratio of Concrete in Compression.

Badir, Y. F. and Razali, A. (1998). Theory of classification: Its application and Badir Razali Building Systems Classification. *Journal of the Institute of Engineering,* Malaysia.

Bandara, K.M.K., Dias, W.P.S. (2012). Tsunami wave loading on buildings: a simplified approach . Journal of the National Science Foundation Sri Lanka. 40(3), 211-219.

Barr, D. I. H. and Das, M. M. (1980). Numerical simulation of dam-burst and reflections, with verification against laboratory data. Procceding Institution Civil Engineers. 69(2), 359-373.

Bell, S.W., Elliot, R.C. and Chaudhry, M.H. (1992). Experimental results of two dimensional dam-break flows. Jornal of Hydraulic Research, 30(2), 225-252.

Bretschneider, C. L. (1974). Development of Structural Standards in Flood and Tsunami Areas for the Island of Hawaii. Honolulu: Final Report. *Ocean Engineering Consultants, Inctitude. 4. 132*

Briechle, S. and Kotenger, J. (2002). Experimental data for dike-break waves. Procceding of River Flow, 467-473.

Bryant, E. (2001). *Tsunami: the underrated hazard*. Second Edition, Praxis publishing Ltd Chichester, UK.

Bukingham, E. (1915). On Physically Similar Systems; Illustrations of the Use of Dimensional Equations. *Physical Review*. 4(4), 345-376.

CCH, (2000). *Regulations within flood hazard districts and developments adjacent to drainage facilities in the revised ordinances of Honolulu,* , City and Country of Honolulu Building Code, Department of Planning and Permitting of Honolulu Hawaii. Chapter 16 Article 11.

Chan, E. S. (1994). Mechanics of Deep Water Plunging Wave Impacts on Vertical Structures. *Coastal Engineering Journal.* 22, 115-133.

Chanson, H. (2004). *Environmental Hydraulics of Open Channel Flows*. Elsevier Butterworth-Heinemann.

Chanson, H. (2005a). *Applications of the Saint-Venant equations and method of characteristics to the dam-brak wave problem*. Report No. CH55/05, Department of civil Engineering, The University of Queensland, Brisbane, Australia, Chanson, H. (2005b). Analytical Solution of Dam Break Wave with Flow Resistance. Application to Tsunami Surges, *Procceding. 31st Biennial IAHR Congress*, Seoul, Korea, 0137, 3341–3353.

Chanson, H. (2006). Tsunami surges on dry coastal plains: Application of dam break wave equations. *Coastal Engineering Journal*, 48(4), 355-370.

CIDB (2003). *Industrialised Building System (IBS) Roadmap 2003-2010.* In CIDB. Malaysia (Ed.). Kuala Lumpur: CIDB.

CNN (2007).http://www.cnn.com/interactive/world/0502/gallery.tsunami.photos/ ude.html.

Como, A., Mahmoud, H (2013). Numerical evaluation of tsunami debris impact loading on wooden structural walls. *Journal of Engineering Structures* 56. 1249–1261

Consolazio GR, Cowan DR. (2003). Nonlinear analysis of barge crush behavior and its relationship to impact resistant bridge design. *Jornal of Comput Struct*;81(8-11), 547-57.

Consolazio GR, Cowan DR. (2005). Numerically efficient dynamic analysis of barge collisions with bridge piers. *ASCE Jornal of Structure Engineering* 131(8), 1256-66.

Consolazio, G. R., Cook, R. A., McVay, M. C., Cowan, D., Biggs, A. and Bui, L. (2006). *Barge impact testing of the St. George Island causeway bridge*, Final Report, University of Florida.

Consolazio, G. R., Cowan, D. R., (2005). Numerically efficient dynamic analysis of barge collisions with bridge piers. *Journal of Structural Engineering*, 131(8), 1256- 1266.

Consolazio, G. R., Getter, D. J., and Davidson, M. T., (2009). *A static analysis method for barge-impact design of bridges with consideration of dynamic amplification*. Final Repot, University of Florida, Department of Civil and Coastal Engineering.

Cox, D. C. and Mink, J.F. (1963). The tsunami of 23 May 1960 in the Hawaiian Islands. *Bulletin of the Seismological Society of America* . 53, 1191-1209.

Cross, R. H. (1967). Tsunami Surge Forces. *Journal of the Waterways and Harbor Division, ASCE,* 93(4), 201-231.

Cumberbatch, E. (1960). The impact of a water wedge on a wall. *Jornal of Fluid Mechanics* 7, 353-374.

Dames and Moore. (1980). *Design and construction standards for residential construction in tsunami prone areas in Hawaii*. Prepared for the Federal Emergency Management Agency.

Davletshin, V. KH., and Lappo, D.D. (1986). Mechanical Action of Tsunami on Vertical Cylindrical Obstacles, Izv. VNII Gidrotekhniki 170, 89.

Dias, P., Dissanayake, R., and Chandratilake, R. (2006). Lessons learned from tsunami damage in Sri Lanka. *Proceedings of Institution of Civil Engineers (ICE)* 159(2), 74-81.

Dias, W.P.S., Bandara, K.M.K. (2012),Tsunami Wave Loading on Buildings: A Simplified Approach, Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka,

Dressler, R. F. (1954). Comparison of theories and experiments for the hydraulic dam-break wave. *Procceding International Association Scientific Hydrology,* Rome, Italy. 38, 319-328.

Durmisevic, E. (2006). *Transformable Building Structures: Design for Disassembly as a Way to Introduce Sustainable Engineering to Building Design & Construction.* Netherlands: Cedris M&CC.

Federal Emergency Management Agency (1995). *Engineering principles and practices for retrofitting flood prone residential buildings*.

FEMA (2011). *Coastal Construction Manual*. Federal Emergency Management.

FEMA (2000). *Determining site-specific loads*, Federal Emergency Management Agency chapter 11.

FEMA 356 (2000). *Prestandard and Commentary for the Seis- mic Rehabilitation of Buildings.* Federal Emergency Management Agency, Washington DC.

FEMA 55, (2005). *Coastal Construction Manual*. Report, Edition 3, Federal Emergency Management Agency, Washington, D.C.

FEMA P646, (2008). *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis.* Federal Emergency Management Agency.

FEMA P646, (2012). *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis,* Federal Emergency Management Agency. Washington, D.C., USA.

Ferrer B, Ivorra S, Segovia E, Irles R. (2010). Tridimensional modelization of the impact of a vehicle against a metallic parking column at a low speed. *Jornal of Engineering structure* 32(8), 1986-92.

Foytong, P. and Ruangrassamee, A (2007). Fragility curves of reinforced concrete building damaged by a tsunami for tsunami risk analysis. Proc. Twentieth KKCNN Symp. Civil Engineering, 4-5 October 2007, Jeju, Korea.

Foytonga . P, Ruangrassameeb. A, Lukkunaprasitb, P and Thanasisathitc. N (2015). Behaviours of reinforced-concrete building under tsunami loading. *The IES Journal Part A: Civil & Structural Engineering.* 8(2). 101-110.

Fraccarollo, L., and Capart, H. (2002). Riemann wave description of erosional dam-break flows. *Journal of Fluid Mechanics*, 461, 183–228.

Franco, A. B. (1996). Modelacao computacional e experimental de escoamentos provocadospela rotura de barragens. PhD thesis, Instituto Superior Tecnico, Lisbon, Portugal.

Fujima, K., Achmad, F., Shigihara, Y. and Mizutani, N. (2009). A Study on Estimation of Tsunami Force Acting on Structures. *Journal of Japan Society of Civil Engineers, Ser. B2 (Coastal Engineering)*, 65(1), 321–325.

Fukui, Y., Nakamura, M., Shiraishi, H., and Sasaki, Y. (1963). Hydraulic study on tsunami. *Journal of Coastal Engineering.* 6, 67-82.

Garcia, R., Hajirasouliha, I., Guadagnini, M., Helal, Y., Jemaa, Y., Pilakoutas, K. et al. (2014) Full-scale shaking table tests on a substandard RC building repaired and strengthened with Post- Tensioned Metal Straps. *Journal Earthquake Engineering*, 18(2), 187-213.

Ghobarah, A., Saatcioglu, M. and Nistor, I. (2006). The impact of the 26 December 2004 earthquake and tsunami on structures and infrastructure. *Jornul of Engineering Structure*. 28, 312–326.

Gomez-Gesteira, M., and Dalrymple. R.A., (2004). Using a 3D SPH Method for Wave Impact on a Tall Structure, *Jornal of Waterways, Port, Coastal, Ocean Engineering, ASCE*, 130(2), 63-69.

Haehnel, Robert B. and Daly, Steven F. (2004). Maximum Impact Force of Woody Debris on Floodplain Structures. *Journal of Hydraulic Engineering,* 130(2), 112-120.

Haehnel, Robert. B. and Daly, Steven. F. (2002). *Maximum impact force of woody debris on floodplain structures*. US Army Corp of Engineers, Engineer Research and Development Center.

Harris, H. G. and Sabnis, G. (1999). *Structural Modling and Expeimental Techniques*. 2nd . NewYork. CRC Press.

Hattori, M. Arami A. and Yui, T. (1994). Wave Impact Pres- sures on Vertical Walls under Breaking Waves of Various Types. *Coastal Engineering Journal*,. 22(1-2) 79-114.

Hibberd, S., and Peregrine, D. H. (1979). Surf and run-up on a beach: A uniform bore. *Jornal of Fluid Mechanic*, 95, 323 -345.

Hiraishi, T., Haruo, K. and Saitoh, E. (2010). Experimental study on impulsive force of drift body due to tsunami. *Jornal of. Earthquake Tsunami* 4(2), 127–133.

HoBoware User's Guide (2010). Onset copmutr corporation, Boune, USA

Iizuka H. and Matsutomi H. (2000). Damage estimation due to tsunami inundation flow. *Proceedings of Coastal Engineering* (47) 381 – 385.

Ikeno, M., Mori, N., and Tanak, H. (2001). Experimental research about wave force of a bore and a breaking wave, and the action and impulsive force of drifting timber. *Proceeding . of the coastal Engineering of JSCE*, 48, 846-850.

International Building Code (IBC). (2003). International Code Council, Inc., Country Club Hills, Illinois.

Jiffry H, Pilakoutas K, Garica R. (2015). Structural Assessment of Low- rise Reinforced Concrete Frames under Tsunami Loads. *International Journal of Civil, Structural, Construction and Architectural Engineering.* 9 (2). 171-176.

Keulengan G. H. (1950). *Wave Motion (In :Engineering Hydraulics, H. Rouse Ed.).* John Wiley &Son, Inc. New York, 711-768.

Keyvani, A., and Keyvani, L. (2013). Progressive Collapse of RC Frames Due to Heavy Impact Loads of Tsunami. Open Journal of Civil Engineering, 3, 166–172.

Kirkgöz, M. S. (1990) An Experimental Investigation of a Vertical Wall Response to Breaking Wave Impact, *Ocean Engineering Journal*, 17(4), 379-391.

Kirkgöz, M. S. (1992). Influence of Water Depth on the Breaking Wave Impact on Vertical and Sloping Wall. *Coastal Engineering Journal*, 18(34) 297- 314.

Kirkgöz, M. S. (1995). Breaking Wave Impact on Vertical and Sloping Coastal Structures, *Ocean Engineering Journal*, 22(1), 35-48.

Knill,J.,and Knill, J., (2004). http://www.cnn.com/SPECIALS/2004/tsunami.disaster/ , Cable News Network.

Ko, H; Cox, D. T; Riggs, H. R. and Naito, C. J. (2015). Hydraulic Experiments on Impact Forces from Tsunami-Driven Debris. *Journal of Waterway, Port, Coastal, Ocean Engineering. 141(3).*

Kobayashi, M. H., Genest, R., Riggs, H. R., and Paczkowski, K. (2012). Simple hydroelastic impact models for water-borne debris. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment.* 226(2), 170-179.

Koh, H. L., Teh, S. Y., Liu, P. L. F., Ismail, A. I. M., and Lee, H. L. (2009). Simulation of Andaman 2004 tsunami for assessing impact on Malaysia. *Journal of Asian Earth Sciences*, 36(1), 74–83.

Kramer, S. L. (1996). *Geotechnical Earthquake Engineering*, Prentice Hall, Upper Saddle River, New Jersey, 254-280.

Kumagai, K., Oda, K., and Fujii, N. (2006). Applicability of simulation model for drift behavior of containers due to tsunami, *Procceding. Techno-Ocean /19th JASNAOE Ocean Engineering Symposium.*

Lauber, G., and Hager, W. H. (1998). Experiments to dambreak wave: Horizontal channel. *Journal of Hydraulic Research*, 36(3), 291–307.

Leal, J. G. A. B., Ferreira, R. M. L., and Cardoso, A. H. (2002). Dam-break waves on movable bed. *Procceding. River Flow,* 2, 981-990.

Leal, J. G. A. B., Ferreria, R. M. L., and Cardoso, A. H. (2006). Dam-break wave-front celerity. *Jornal of Hydraulic Engineering*, 132, 69-76.

Lekkas, E., Andreadakis, E., Alexoudi, V., Kapourani, E., and Kostaki, I. (2011). The Mw=9.0 Tohoku Japan Earthquake (March 11, 2011) Tsunami Impact on Structures and Infrastructure. *Environmental Geosciences and Engineering Survey for Territory Protection and Population Safety, (EngeoPro) International conference, Moscow*, 97-103.

Linton D, Gupta R, Cox D, Lindt J, Oshnack M. E and Clauson M. (2013). Evaluation of Tsunami Loads on Wood-Frame Walls at Full Scale. *Journal of Structure Engineering*. 139: 1318-1325.

LS-DYNA (2007) Keyword User's Manual, Livermore Software Technology Corporation, California.

Lukkunaprasit, P. and Ruangrassamee, A. (2008), Building damage in Thailand in the 2004 Indian Ocean tsunami and clues for tsunami-resistant design, *The IES Journal Part A: Civil and Structural Engineering*, 1 (1), 17 - 30.

Lukkunaprasit, P., Ruangrassame, A., Stitmannaithum, B., Chintanapakdee, C. and Thanasisathit, N (2010). Calibration of tsunami loading on a damaged building. *Journal Earthquake Tsunami* 4(2), 105-114.

Lukkunaprasit, P., Ruangrassamee, A., Thanasisathit, N. (2009). Tsunami loading on buildings with openings. *Science of Tsunami Hazards Journal* 28, 303-310

Lytton, L. (2008). Deep Impact: Why Post-Tsunami Wells Need a Measured Approach. *Proceedings of ICE, Civil Engineering*, 161(1), 42-48.

Madurapperuma MAKM. (2011). *Performance of columns in gravity-load-designed reinforced concrete buildings impacted by water-borne massive objects*. PhD dissertation, Department of Civil and Environmental Engineering, Tokyo Institute of Technology, Tokyo, Japan;.

Madurapperuma, M. A. and Wijeyewickrema, A. C. (2012), Inelastic dynamic analysis of an RC building impacted by a tsunami water-borne shipping container, *Journal of Earthquake and Tsunami*, 6 (01).

Madurapperuma, M. A. K. M. and Wijeyewickrema, A. C. (2013). Performance of reinforced concrete columns impacted by water-borne shipping containers. *Jornal of Advances in Structural Engineering.*

Mander, J.B., Priestly, M. J. N. and Park, R. (1984). Theoretical Stress-Strain Model for Confind Concrete. *Journal of Structural Engineering*. ASCE. 114(3). 1804-1826.

Marwan, T. S., Wael, W. E. and Robert, G. D. (2010). Seismic performance parameters for reinforced concrete-block shear wall construction. *Journal of Performance of Constructed Facilities*, 24 (1), 4-18

Matsutomi, H (1999). A practical formula for estimating impulsive force due to driftwoods and variation features of the impulsive force. *Journal. Hydraulic, Coastal and Environmental Engineering,* JSCE, Japan, 621/II-47, 111-127.

Matsutomi, H. and Harda, K. (2010). Tsunami-trace distribution around building and its particle use. Proc. 3rd Int. Tsunami Field Symp., 10-11 April 2010, Tohoku University, Sendai, Japan, 117-118.

Matsutomi, H., (2009). Method for estimating collision force of driftwood accompanying tsunami inundation flow. *Journal of Disaster Research*, 4(6), 435-440.

Midorikawa, M., and Okazaki, T. (2012). Earthquake and Tsunami Damage to Steel Structures. *Structures Congress* 1045–1056.

Miller, S., and Chaudhry, M. H. (1989). Dam-break flows in curved channel. *Jornal of Hydraulic Engineering, ASCE*, 115(11), 1465-1478.

Mizutani, N., Takagi, Y., Shiraishi, K., Miyajima, S., and Tomita, T. (2005). Study on wave force on a container on apron due to tsunamis and collision force of drifted container," *Annual Journal of Coastal Engineering*, 52, 741-745.

Mizutani, N., Takagi, Y., Shiraishi, K., Miyajima, S., and Tomita, T. (2006). Forces on a container due to tsunami and collision force by drifted container. *Procceding Second International Workshop on Coastal Disaster Prevention*, 6371.

NAASRA, (1990). *Highway Bridge Design Specification.* National Association of Australian State Road Authorities.

Nakamura, S and Tsuchiya, Y. (1973). On the shock pressure of surge on a wall. *Bulletin of the Disaster Prevention Research Institute, Kyoto University,* 23(3-4), 47-58.

Nayak. S., Reddy. M. H. O., Madhavi. R., (2014). Assessing tsunami vulnerability of structures designed, *International Journal of Disaster Risk Reduction*, 7, 28-38.

Nistor, I., Murty, T., Nirupama, N., and Jinsong, X. (2006). Some physical oceanographic processes in the behavior of the 26th December 2004 tsunami. *15th Congress of the Asia-Pacific Division of IAHR and International Symposium on Maritime Hydraulics, IAHR*, 81-90.

Novak, P., Guinot, V., Jeffrey, A., and Reeve, D. E (2010). *Hydraulic Modelling- An Introduction.* Spon Press, London, UK.

Ohmori, M., Fuji, N., and Kyotani, O., (2000). The numerical computation of the water level, the flow velocity and the wave force of the tsunami which overflow the perpendicular revetments. *Procceding of the Coastal Engineering of JSCE*, 47, 3766-380.

Okada, T., Sugano, T., Ishikawa, T., Ohgi, T., Takai, S., and Hamabe, C. (2005). *Structural design methods of buildings for tsunami resistance. (SMBTR)*, The Building Centre of Japan

Okada, T., Sugano, T., Ishikawa, T., Takai, S., and Tateno, T. (2006). *Tsunami loads and structural design of tsunami refuge buildings*. The Building Centre of Japan.

OpenSees, (2009). *Open system for earthquake engineering simulation*, Pacific Earthquake Engineering Research Center, Berkeley, CA.

Packwood, A. R., and Peregrine, D. H. (1981). *Surf and run-up on beaches: models of viscous effects*. Report No. AM-81-07, School of Mathematics, University of Bristol, Bristol, U.K.

Paczkowski, K., Riggs, H. R., Naito, C. J., and Lehmann, A.,(2012). A one-dimensional model for impact forces resulting from high mass, low velocity debris. *Journal of Structural Engineering and Structural Mechanics,* 42(6), 831-847.

Paulay, T. and Priestley, M. J. N. (1992). *Seismic design of reinforced concrete and masonry building*. A Wiley Interscience Publication: John Wiley and Sons, INC.

Piran Aghl, P., Naito, C. J., and Riggs, H. R. (2014a). Effect of non-structural mass on debris impact demands: Experimental and simulations studies. *Journal of Eng. Struct.,* in press.

Piran Aghl, P., Naito, C. J., and Riggs, H. R. (2014b). “Full-scale experimental study of impact demands resulting from high mass, low velocity debris.” J. Struct. Eng., 10.1061/(ASCE)ST.1943-541X.0000948, 04014006.

Ramsden, J.D. (1996). Forces on a vertical wall due to long waves, bores, and dry-bed surges. *Jornal of Waterways, Port Coasts and Ocean Engineering*., 122(3), 134-141.

Ramsden, J.D. (1993). *Tsunamis: Forces on a vertical wall caused by long waves, bores, and surges on a dry bed*. Report No. KH-R-54, W.M. Keck Laboratory, California Institute of Technology, Pasadena, California., 251.

Ramsden, J.D., and Raichlen, F. (1990). Forces on vertical wall caused by incident bores. *Jornal of Waterway, Port, Coastal, and Ocean Engineering,* 116, 592-613.

Ramsden, J. D.; Raichlen, F.(1990). Forces on Vertical Wall caused by Incident Bores. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 116 (5). 592-613.

Riggs, H. R, Kobayashi, M, Cox, D., and Naito, C. (2010). A program to determine impact forces from tsunami-driven debris. *Quake Summit, NEES and PEER Annual Meeting,* San Francisco, CA.

Riggs, H. R., Cox, D. T., Naito, C. J., Kobayashi, M. H., Pairan Aghl, P., Ko, H.T. S., and Khowitar, E. (2013). Water-driven debris impact forces on structures: Experimental and theoretical program." *Proceedings of the ASME International Conference on Ocean, Offshore and Arctic Engineering*, 1-10

Ritter, A. (1892). The progration of waterwave. *Verene Deutscher Ingenieure Zeitschr*, 36(2), 947-954

Robertson, I. N., Carden, L., Riggs, H. R., Yim, S., Young, Y. L., Paczkowski, K. and Witt, D. (2010a). *Reconnaissance following the September 29, 2009 tsunami in Samoa.* Research report UHM/CEE/10-01, Department of Civil and Envi- ronmental Engineering, University of Hawaii at Manoa, Honolulu, Hawaii,

Robertson, I. N., Paczkowaski, K., Riggs, H. R. (2013). Experimental investigation of tsunami bore forces on vertical walls. *Journal of Offshore Mechanics and Arctic Engineering.* 135(2).

Robertson, I., Chock, G. and Morla, J. (2010b). *Tsunami effects of the February 27, 2010 Chile earthquake*, EERI preliminary reports, Earthquake Engineering Research Institute, Oakland, CA.

Ruangrassamee. A and Foytong. P (2012). CORRELATION ANALYSIS OF A REINFORCED-CONCRETE BUILDING UNDER TSUNAMI LOADS AND EFFECT OF MASONRY INFILL WALLS IN TSUNAMI RESISTANCE. Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan.

Sha Y, Hao H. (2012). Nonlinear finite element analysis of barge collision whith a single bridge pier. Engineering Structure 41. 63-76.

Shafiei. S. R, Melville. B.W., Beskhyroun. S. and Shamseldin. A.Y. (2014). Preliminary Investigation of the Tsunami-Borne Debris Impact on Structures: A new method for impact force measurement. 5th International Symposium on Hydraulic Structures

Shahrul, N. (2003). *Survey on the Usage of Industrialised Building System (IBS) in Malaysian Construction Industry*. Malaysia.

Sharma H, Hurlebaus S, Gardoni P. (2012) Performance-based response evalution of reinforced concrete columns subject to vehicle impact. *International Jornal Impact Engineering*, 43, 52-62.

Shuto, N., (1991). Numerical Simulation of Tsunamis. *Tsunami Hazard, Kluwer Academic Publishers,* Dordrecht, Netherlands, 171-191.

Stansby, P.K., Chegini, A., and Barnes, T.C.D. (1998). Initial stages of dam- break flow. *Jornal of Fluid Mechanic,* 370, 203-220.

Stoker, J. (1957). *Water waves: The mathematical theory with applications*. Wiley- Interscience, New York.

Suppasri, A., Imamura, F. and Koshimura, S. (2012a). Probabilistic tsunami hazard analysis and risk to coastal populations in Thailand. *Journal of Earthquake Tsunami* 6, 00124.

Suppasri, A., Imamura, F. and Koshimura, S. (2012b). Tsunami hazard and casualty estimation in a coastal area that neighbors the Indian Ocean and South China Sea. *Journal of Earthquake Tsunami* **6**, 00126.

Suppasri, A., Imamura, F. and Koshimura, S. (2013a) .Tsunami hazard and building damage assessment in Thailand using numerical model and fragility curves. *Journal Earthquake Tsunami* **7**(5), 1–16.

Suppasri, A., Mas, E., Charvet, I., Gunasekera, R., Imai, K., Fukutani, Y., Abe, Y. and Imamura, F. (2013b). Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami. Journal of *Natural. Hazards* **66**(2), 319–341.

Suppasri, A., Koshimura, S., Imamura, F., Ruangrassamee, A., and Foytong, P. (2013c). A Review of Tsunami Damage Assessment Methods and Building Performance in Thailand. *Journal of Earthquake and Tsunami,* 07(05), 1-21.

Tanimoto, K., Takashi, S., Kaneko, T., and Shioto, K. (1986). Impulsive breaking wave forces on an inclined pile exerted by random waves, *Proceedings of 20th International Conference on Coastal Engineering, ASCE,* 2288-2302.

U.S. Army Corps of Engineers, (1995). *Flood-proofing regulations*. Engineering Pamphlet 1165-2-314, Washington, D.C. : US Army Corps of Engineer, 1995

Uniform Building Code (UBC). (1997). Uniform Building Code. California.

US Army Corps of Engineers. (1960). *floods resulting from suddenly breached dams* Miscellaneous Paper 2(374), Report 1. US Army Engineer Waterways Experiment Station, Crops of Engineers: Vicksburg, Mississippi.

US Army Corps of Engineers. (1961). *Floods resulting from suddenly breached dams-Conditions of high resistance*. Miscellaneous Paper 2(374), Report 2.

US Army Engineer Waterways Experiment Station, Corps of Engineers: Vicksburg, Mississippi.

Whitham, G.B. (1955). The Effects of Hydraulic Resistance in the Dam-Break Problem. *Procedingc. Royal. Society. of London.* 227, 399-407.

Wijetunge, J. J. (2006). Tsunami on 26 December 2004: Spatial distribution of tsunami height and the extent of inundation in Sri Lanka, *Jornal of Science of Tsunami Hazards*, 24(3), 225–239.

Wilson, J. S., Gupta, R., van de Lindt, J. W., Clauson, M., and Garcia, R. (2009). Behavior of a One-Sixth Scale Wood-Framed Residential Structure under Wave Loading. *Journal of Performance of Constructed Facilities*, 23(5), 336–345.

Yeh, H., and Mok, K. M. (1990). On turbulence in bores. *Physical of Fluids* 2(5), 821-828

Yeh, H. (1991). Tsunami Bore Runup. *Natural Hazard Journal*, 4, 209-220.

Yeh, H. (2006). Tsunami loading. *International workshop on fundamentals of coastal effects of tsunamis*, Hilo, Hawaii.

Yeh, H. (2007). Design Tsunami Forces for Onshore Structures. *Journal of Disaster Research*, 2(6), 531-536.

Yeh, H., Ghazali, A., and Marton, I. (1989). Experimental study of bore runup. *Jornal of Fluid Mechanics*. 206, 563-578.

Yeh, H., Robertson, I., and Preuss, J., (2005). Development of Design Guidelines for Structures that Serve as Tsunami Vertical Evacuation Sites, *Washington State Department of Natural Resources.* Report No.2005-4.

Yeom, G. S., Nakamura, T., and Mizutani, N., (2009). Collision analysis of container drifted by runup tsunami using drift collision coupled model. *Journal of Disaster Research*, 4(6), 441-449.

Yi, W. J., He Q. F., Xiao, Y., and Kunnath, S., (2008). Experimental Study on Progressive Collapse-Resistant Behavior of Reinforced Concrete Frame Structures, *American Concrete Institude Structural Journal*, 105(4), 433-439.

Yoshihara, H., Kubojima, Y., Nagaoka, K., and Ohta, M., (1998). Meaurement of the shear modulus of wood by static bending tests. *Journal of Wood Science*, 44, 15-20.

Zainal Abidin, A. R. (2007). Simulation of Industrialised Building System Formation For Housing Construction. Master of Science, Universiti Teknologi Malaysia, Johor, Malaysia.

Zhu, Y. J., Li, L., and Yang, W. H. (2011). Study on shear bearing capacity of composite reinforced concrete block masonry. *Journal of Applied Mechanics and Materials*, 94(96), 1141-1145.