

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.

## 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 variasi kedalaman air, halaju air, daya yang bertindak ke struktur sistem IBS dan variasi tekanan pada permukaan binaan. Prestasi struktur kemudiannya dinilai berdasarkan FEMA 356 pada tahap Operasi, Penghunan Segera, Keselamatan Hayat dan Pencegahan Runtuhan. Peningkatan kedalaman air yang terbandung membawa kepada peningkatan kedalaman banjir di model sistem IBS, dan berkadar terus dengan peningkatan halaju air. Taburan tekanan hidrostatik ke atas struktur berlaku sepanjang tempoh 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 Penghunan 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
$\rho$	-	density of water
$\mu$	-	dynamic viscosity of water
$\sigma$	-	surface tension of water
$E_b$	-	bulk modulus of elasticity of water
$g$	-	acceleration of gravity
$F_r$	-	Froude number
$E_u$	-	Euler number
$Re$	-	Reynolds number
$We$	-	Weber number
$Ma$	-	Sarrau- Mach number
$E_s$	-	Young's modulus of elasticity
$\vartheta$	-	Poisso's ratio
$f'_c$	-	compressive strength of concrete
$f_y$	-	steel yield strength
$\sigma_y$	-	Yield strength
$\varepsilon_y$	-	Yield strain
$\sigma_u$	-	Ultimate strength
$\varepsilon_u$	-	Ultimate strain
$P$	-	Impulsive pressure
$P'$	-	Hydrodynamic pressure
$F_i$	-	Impulsive force
$F_d$	-	Hydrodynamic force
$\rho_s$	-	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 be 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.

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