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ESTIMATION OF TSUNAMI FORCES ON INFRASTRUCTURE: FIELD INVESTIGATIONS AND PHYSICAL AND NUMERICAL MODELING

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ABSTRACT

The paper presents the results of a comprehensive research program on tsunami-induced forces on infrastructure located in coastal areas. This research project is the result of an interdisciplinary investigation (coastal and structural engineering) which spanned over the past five years which included field data reconnaissance missions, as well as analytical, experimental and numerical modeling of extreme hydrodynamic forces on buildings and their component structural elements. The purpose of this research and engineering effort is to help elucidate the complex hydrodynamic mechanisms of impact of such extreme loadings on buildings and to properly quantify loads and further derive and propose new formulations for the design of structures located in the vicinity of the shoreline in tsunami-prone coastal areas. The research is particularly important in the Canadian context due to the significant risk of tsunami attack, particularly along the coastline of Western Canada (British Columbia).

Introduction

Though rare, tsunami waves are catastrophic events, which have the power to significantly impact communities located in coastal areas. Although not as frequent as storm-induced surges, tsunami-induced coastal flooding often leads to massive casualties and tremendous economic losses (Yeh 1991, Ghobarah et al. 2005, and Nistor et al. 2006).

The devastating effects of the 26 December 2004 Tsunami on countries bordering the Indian Ocean raised public awareness and indicated that existing design codes are not properly accounting for the tremendous forces and impacts generated by tsunamis. Prior to the 2004 Indian Ocean Tsunami, the design of structures against tsunami-induced forces was considered of minor importance when compared to the attention given to tsunami warning systems.

Reconnaissance missions of the December 2004 Indian Ocean Tsunami disaster revealed

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that tsunami-induced forces can lead to severe damage or collapse of structures (Ghobarah et al. 2005, Nistor et al. 2005, Saatcioglu et al. 2006, and Yamamoto et al. 2006). It was found that it is imperative that these forces are properly accounted for in the design of infrastructure built within a certain distance from the shoreline in tsunami-prone areas. However, at present, tsunami-induced forces and the impact of debris are not properly accounted for in existing codes and significant improvement is needed.

Tsunami Research Program at the University of Ottawa, Canada

The present work provides some results of a comprehensive interdisciplinary research project initiated at the University of Ottawa, Canada, which deals with the tsunami risk for coastal infrastructure. This interdisciplinary project has two components: (1): Identification and mapping of the areas prone to tsunami risk and development of tsunami inundation maps that would provide inundation depths and flow velocities for a given return period, and (2): Estimation of the tsunami impact on coastal infrastructure and the elaboration of design recommendations and guidelines for including tsunami loading into the National Building Code of Canada. The members of the project include coastal engineering (Dr. Ioan Nistor, Dr. Andrew Cornett), tsunami scientists (Dr. Tad Murty), as well as structural engineers (Dr. Dan Palermo and Dr. Murat Saatcioglu). The present paper presents an overview of the results obtained as part of this research program to date.

Project (1) deals with the tsunami risk for Canada, which has the longest coastline in the world. Over the past several hundreds of years, several major tsunamis occurred along the eastern and particularly the western Canadian coastline. Hence, Project (1) focused on numerical modeling of a possible tsunami generated by tectonic activity along the Cascadia Fault, offshore British Columbia. The potential for inundation of the low-lying areas around the coastline of Vancouver Island and in and around the City of Vancouver has been also evaluated. At the same time, authors collaborated with researchers from York University, Canada, and prepared the first Tsunami Atlas for the Atlantic Ocean (Nirupama et al. 2007)

The preparation of design guidelines directly addressing tsunami-induced loading is intrinsically related to the correct estimation of hydrodynamic forces exerted on structures during a tsunami event. To address this issue, Project (2) of this research program was initiated by the Department of Civil Engineering of the University of Ottawa, Canada, in cooperation with the Canadian Hydraulics Center (CHC) of the National Research Council located in Ottawa. This research project focuses on the experimental, analytical and numerical modeling of the hydrodynamic impacts on infrastructure and is coordinated by both coastal and structural engineers. The first stage of the experimental program (Nouri et al. 2010) has been finalized and some results of this work are presented herein. At present, a large-scale experimental test program and numerical modeling work (Nistor et al. 2010) are under way. The authors were also invited to contribute to the Handbook of Coastal and Ocean Engineering with the chapter on Tsunami Forces on Structures (Nistor et al. 2009).

Tsunami Field Investigations

The scale of the impact and the destruction induced by the tsunami waves on infrastructure and local communities in coastal areas can only be revealed and understood in its real dimension by conducting post-tsunami disaster reconnaissance missions. The team of researchers from the University of Ottawa, in collaboration with academics from McMaster University in Canada and Yokohama National University, Japan, carried out several field investigations in the regions affected by tsunami. Field investigations were carried out first in Thailand and Indonesia immediately following the December 2004 Indian Ocean Tsunami (January 2005), and later on, to asses the reconstruction effort and investigate other damage induced by the tsunami waves to the coastal areas around the Indian Ocean. Post-disaster investigations included Thailand (2005), Sri Lanka (2006), and Tanzania (2007) and focused on reconstruction of infrastructure, hazard mitigation of inundation-prone areas, as well as on the investigation of the long term impact of tsunami waves on coastal morphodynamics.

The first field reconnaissance visit to Thailand and Indonesia was carried out in January 2005 by a team of three academics from the University of Ottawa (Drs. Saatcioglu and Nistor) and McMaster University (Dr. Ghobarah). The visit concentrated on urban areas with engineered construction, closest to the earthquake epicenter. Rawai Beach, Kata Noi Beach, Kata Beach, Patong Beach, Nai Thon Beach and Kamala Beach on the Thai island of Phuket were visited first, followed by Phi-Phi island, about 48 km south east of Phuket Island, as well as the coastal town of Khao Lak located about 100 km north of Phuket. One location was visited in Indonesia: Banda Aceh, the capital of Indonesia's Aceh Province at the northern tip of Sumatra. Banda Aceh suffered extensive tsunami damage and was, in fact, the coastal city most affected by tsunami for all around the Indian Ocean Basin. Moreover, due to its proximity to the earthquake epicenter, the Banda Aceh region suffered also extensive seismic damage.

Infrastructure damage was significant along the western coast of Thailand, as shown in Figures 1 and 2. Both engineered and non-engineering structures were seriously damaged by the force of the tsunami-induced coastal inundation.


(a) (b) (c)

Figure 1. Structural damage in Nai Thon Beach, Thailand, due to tsunami waves


(a) (b) (c)

Figure 6. Tsunami-induced damage to the Khao Lak Port, Thailand

The field reconnaissance mission continued in Banda Aceh and its surroundings. It was observed that a large number of non-engineered reinforced concrete buildings suffered structural damage. It was estimated that the city lost more than half of its population as a result of the extensive tsunami flooding. The measurements of the flooding extent indicated that the flood reached maximum values of 3 to 4 km inland. All coastal structures in the region of Banda Aceh (the fishing ports, the commercial port, the protection dikes, etc) were completely wiped out (Saatcioglu et al. 2006). Figure 3 illustrates the extent of damage observed in Banda Aceh caused by both the earthquake and the ensuing tsunami flooding.

(a) (b) (c)

Figure 3. Tsunami damage in Banda Aceh, Indonesia, 2004 Indian Ocean Tsunami

The follow-up field investigations conducted in Thailand (Fall 2005), Sri Lanka (2006), and Tanzania (2007), showed that the infrastructure reconstruction in the three visited countries outlined several common problems:

(1) Though construction zoning for tsunami-prone coastal areas has been either proposed (Thailand and Tanzania) or legislated (Sri Lanka), the development of coastal infrastructure continued chaotically and simply ignoring the new provisions;

(2) For the vast majority of the structures surveyed in the countries surveyed, the redesign and reconstruction of the coastal infrastructure was undertaken without accounting for or making any provisions for tsunami loading.

Research on Tsunami Loading on Structures

Broken tsunami waves inundate shoreline in the form of a hydraulic bore, which is a fast moving body of water with an abrupt front. However, while the impact of tsunami-induced forces on coastal protection structures, such as breakwaters, seawalls, etc, has been analyzed and, to a certain extent, clarified by researchers and engineers, the mechanisms of impingement of broken tsunami waves on structures located inland are not yet well understood. Building codes do not explicitly consider tsunami loading, as it is understood that inland infrastructure can be protected by proper construction zoning and site planning. Therefore, forces generated by tsunami are rarely accounted for in structural design practice. Recent catastrophic events (2004 Indian Ocean Tsunami; 2007, 2009 Solomon Islands Tsunamis, Chile Tsunami 2010) have, once more, stressed the importance of protecting structures located in areas with potential risk of being affected by the destructive power of tsunami-induced hydraulic bores.

The preparation of design guidelines directly addressing tsunami-induced loading is intrinsically related to the correct estimation of hydrodynamic forces exerted on structures during a tsunami event. Five design documents specifically account for tsunami-induced forces, namely: the Federal Emergency Management Agency Coastal Construction Manual, FEMA 55 (FEMA, 2003); the City and County of Honolulu Building Code (CCH, 2000); the Structural Design Method of Buildings for Tsunami Resistance (SMBTR) proposed by the Building Center of Japan (Okada et al., 2005); Guidelines for Structures that Serve as Tsunami Vertical Evacuation Sites, prepared by Yeh et al. (2005) for the Washington State Department of Natural Resources to estimate tsunami-induced forces on structures. Recently, the Federal Emergency Management Agency published Guidelines for Design of Structures for Vertical Evacuation from Tsunamis, FEMA P646, (FEMA, 2008). However, there are significant differences in the provisions of these design codes. Moreover, some of them (FEMA 55) do not really account for tsunami loading or, certain parameters, such as the bore velocity, debris impact characteristics, are quite differently estimated from code to code and hence need to be properly investigated.

This interdisciplinary research program focuses on the experimental, analytical and numerical modeling of the hydrodynamic impacts on infrastructure and is coordinated by both hydraulic and structural engineers.

Experimental Modelling of the Tsunami Loading on Structures

The present experimental work was carried out in a High Discharge Flume at the Canadian Hydraulics Centre (CHC) in Ottawa, Canada (Palermo et al. 2009, Nouri et al. 2010). A high-discharge flume (10.0 m in length, 2.7 m in width, and 1.4 m in depth) was equipped with a rapidly opening stainless-steel hinged gate which impounded a significant volume of water that could be released through rapid (0.25 to 0.30 seconds) opening of the gate. The experimental setup is shown in Fig. 4. The removable gate was constructed of a stainless steel frame covered with plywood sheets. The gate was located such that a relatively large reservoir (5.6 m long, 2.7 m wide and 1.2 m depth) was provided upstream of the gate in order to hold a sufficiently large volume of water (21.20 m^3) behind the gate.

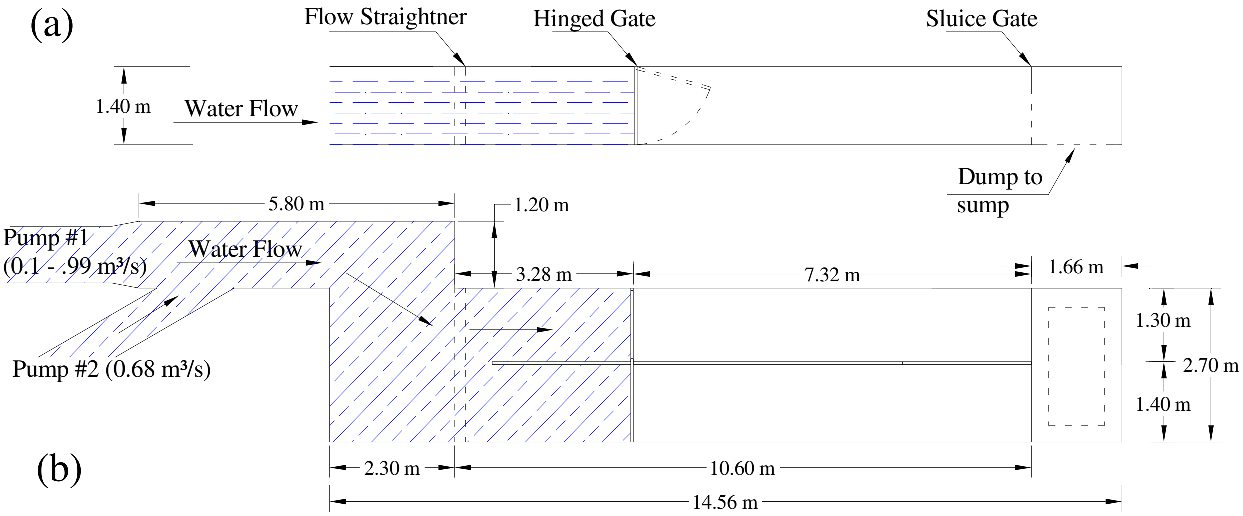

Fig. 4: Side (a) and plan view (b) of the experimental setup

Two structures with circular and square cross sections were used in the experiment (Fig. 5). The structures are herein referred to as circular and square. In addition, the square structure was used in two configurations: (1) its side parallel to the flume; and (2) rotated at 45 degrees.

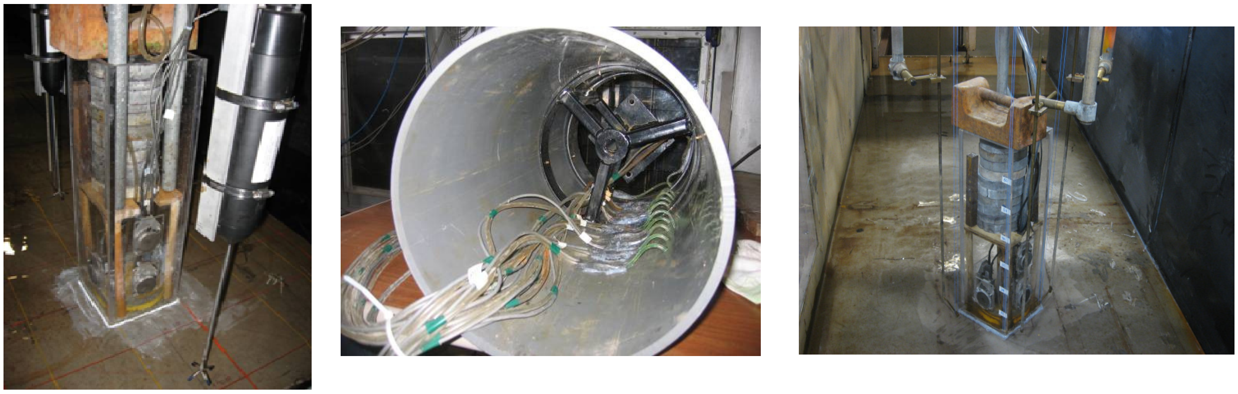

Fig. 5: Square and circular structure and instrumentation

The circular structure was a polyvinyl chloride (PVC) tube, with an outer diameter of 0.32 m, thickness of 9 mm and height of 0.7 m. The circular structure was connected to the upper surface of a six-axis dynamometer which was used to determine the base forces and the moments generated by the impacting hydraulic bore. In addition, nine pressure transducers were placed flush with the surface on the circular structure along a vertical line, directly facing the incoming bore. This ensured the recording of the time-history pressure profiles of the loading. The square/diamond structure, also shown in Figure 5, was instrumented with five pressure cells (two on the side facing the bore, and one each for the lateral sides and the back of the column), which recorded local forces. Several wave gages were used to record the time-history of the water level around the structure while three ADVs were used to measure the flow velocities. The effect of constrictions on the flow velocity around the structures and on the hydrodynamic forces exerted on them was also investigated. At the same time, the impact of floating debris was also investigated using a wooden log with a 1.48 kg mass which impacted the circular structure.

The authors analyzed the effects of several parameters on the characteristics of the bore-structure interaction: (a) the cross-section of the structure and its orientation; (b) the bore height; (c) the effects of constrictions to the flow pressure and velocity field. The experimental runs were performed using five different hydraulic bore heights (water depth ranging from 0.5 to 1.2 m.). The time-history of the total global force induced by hydraulic bores on the circular column generated through a reservoir impoundment depth, h0, of 1.00 m, is shown in Fig. 6a, while Fig. 6b provides the time-history of the pressure variation for the circular section, recorded by the pressure transducers located along its vertical face, facing the incoming bore (measurements correspond to an impoundment water depth of 1.0 m).

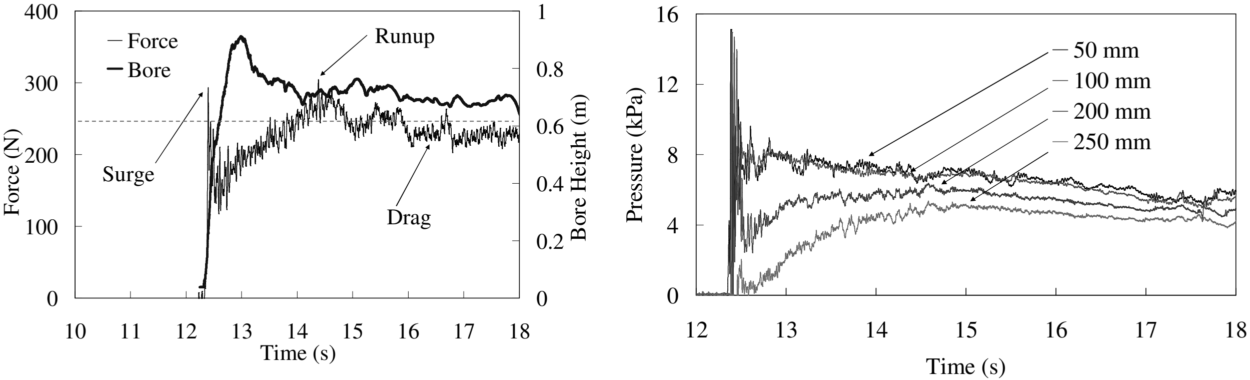

Fig. 6: (a) Time-history of forces and (b) time-history of pressures on the circular column

Numerical Modelling of Tsunami Impact on Structures

The authors have further modified the SPHysics model of Gersteira et al. (2009), which is based on the Smooth Particle Hydrodynamics method, to numerically model their own experimental runs. Several modifications were performed in order to account for the different geometry (round shapes), boundary conditions, etc. For the results shown herein (impact on the circular column), the computational domain included 319,000 particles and the time step used was t = 0.001 s. The total computational time for a duration of simulation of 1.98 seconds was approximately 48 hours (using a 2 GHz Intel Xeon E5405 processor). Figure 7 presents some results of the flow velocity field around the circular structure for an initial upstream impoundment depth of 0.7 meter.

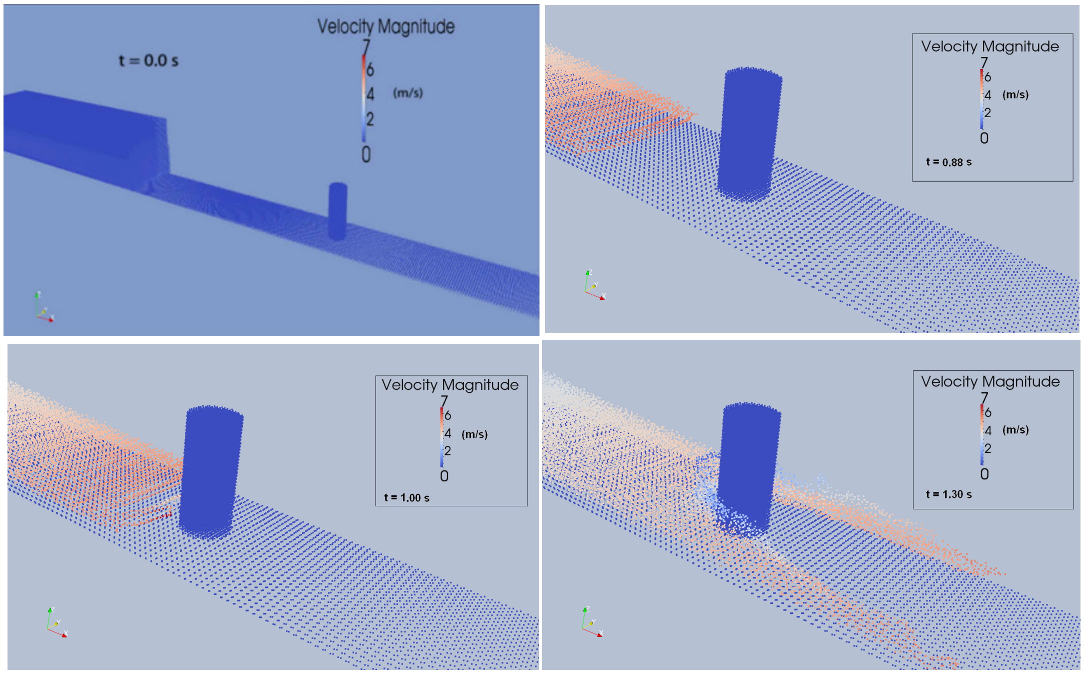

Fig. 7: Flow velocity field around the circular column at t = 0.00, 0.88, 1.00, and 1.33 seconds after gate opening.

Conclusions

An experimental, analytical, and numerical modeling research program, which is still in progress, has been undertaken with the purpose of providing a better understanding of the physical mechanisms of the interaction between the tsunami-induced hydrodynamic forces and structures located in tsunami risk areas. The paper attempts to provide a quantitative and qualitative estimation of the time-history pressures, the flow field velocities, and the distribution of hydrodynamic forces on structures exerted by a rapidly advancing hydraulic bore, similar to the tsunami-induced coastal flooding. The results of this comprehensive research program which includes field investigations as well as experimental, analytical and numerical models will be used to develop design guidelines which would directly address tsunami loading for structure which are constructed in tsunami-prone areas.

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