A review of international guidance for tsunami loading on buildings

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ABSTRACT

Tsunami loading on structures creates a potentially controlling structural demand that is less understood than other design loads. Guidance for tsunami loading scenarios is sparce, and there is a great deal of variation among design specifications worldwide in the methods used to estimate the loads on buildings. Understanding the expected loads in more detail would allow for more efficient structural design, resulting in safer and more cost-effective buildings – that is the focus of this research. The work completed to-date has focused on providing a better understanding of the structural loadings caused by tsunamis by: (1) performing a critical review of American, New Zealand, and Japanese tsunami loading standards, (2) completing a practical comparison of the differing loadings to an existing case study building, and (3) identifying topics adjacent to the existing guidance which may provide a more wholistic loading scenario. In the current phase of the research, flume tests are being designed, taking into account flexibility in the scaled structures, to experimentally evaluate the efficacy of the three loading standards in estimating tsunami forces accounting for structural deformation. The results of this work will be used to inform future tsunami design specifications in New Zealand.

1 INTRODUCTION

Tsunami design guidelines are less mature than those for other loading cases despite the vulnerability and exposure of major coastal cities to tsunami hazards, and the efforts made to improve the guidelines over the past 20 years. The devastating nature of the 2004 Sumatra and 2011 Tohoku tsunamis emphasised the threat posed to the people and infrastructure of coastal cities, but also demonstrated the capability of modern building technologies to resist tsunami loading. Post-tsunami reconnaissance following the 2011 Tohoku tsunami concluded many buildings designed to modern specifications survived the tsunami with little to no structural damage (Chock et al., 2013a).

The juxtaposition of the damage to buildings that were not able to withstand tsunami loading with buildings that sustained relatively minor damage lead to improvements of design guidance for tsunami loading in the United States, Japan, and, more recently, New Zealand. The rapid advancement of the literature and recommendations for tsunami loading subsequently lead to reviews of the standards by Cawley (2014) and

Macabuag et al. (2018) which described significant differences between the loading estimation methods utilised in various design guidelines. This paper broadens these reviews to include a discussion of the hydrostatic and hydrodynamic components of fluid loading included in various design guidelines and the literature used to inform each standard. A case study building in Wellington is presented to demonstrate the tsunami forces predicted by the various loading standards. Based off of this discussion, relevant fluid loading factors which are not currently incorporated into the tsunami guidelines are introduced to help inform changes to the specifications to better reflect the behaviour of buildings under tsunami loading.

2 PREVIOUS WORK

Cawley (2014) provides a brief review of international documents concerning tsunami loading on structures. Crawley's paper was written prior to the introduction of tsunami loading to ASCE 7-16 (2016), so it is no longer current; however, it provides an overview of tsunami loading recommendations developed prior to the introduction of the ASCE standard. The paper concludes that there is not one unanimous force estimation method used across tsunami design standards for calculating hydrodynamic loads on structures and provides a brief outline of each methodology.

In a more recent and in-depth review, Macabuag et al. (2018) examined the tsunami guidance of ASCE 7-16 (2016), the Japanese guidance MLIT 2570 (MLIT 2011), and alternative loading equations not currently used in any specifications. Detailed explanations of the lateral loading equations for each standard are provided and compared to one another; however, limited information on the foundational literature used to inform the loading requirements was discussed. This review demonstrated the differences between the American and Japanese standards, discussed topics relevant to tsunami loading which are not currently considered in either standard, and provided numerical estimations from both literature and the specifications for forces acting on a building for various inundation depths. The authors concluded there is a wide variability of the anticipated forces and that engineering guidance need be applied. It is also acknowledged that differences between the guidelines are to be expected given the varied philosophies for protecting life safety during natural disasters.

3 PROCEDURE

In this work, several tsunami loading standards and the supporting research were reviewed, and the hydrodynamic loading was applied to a case study building to allow for a direct comparison of the resulting tsunami loads. The specifications evaluated here included the New Zealand guideline (MBIE 2020), ASCE 7-16 (2016), and the Japanese guidance, MLIT 2570 (2011). The review of each guideline covered all hydrostatic and hydrodynamic loading cases, a general description of the methodology used to estimate the loading, and the literature that informed the guidance. This review did not include the estimation of tsunami inundation depth or flow velocity, as the methodologies for calculating those parameters differ based on geographical location and methodology. Thus, the inundation depths and velocities used here were assumed to be approximately equal across all standards. It is clearly noted where any standard requires amplification or reduction of the inundation depth or flow velocity. Only certain load cases are consistent across all of the standards – the different cases are explained for each standard and the hydrodynamic loads were produced for a case study building in Wellington.

4 TSUNAMI LOADING STANDARDS

4.1 New Zealand Tsunami Loads and Effects on Vertical Evacuation Structures (MBIE) & ASCE 7-16

Requirements in the New Zealand guidance Tsunami Loads and Effects on Vertical Evacuation Structures (MBIE, 2020) and ASCE 7-16 (2016) are largely the same because the MBIE guideline was developed using the ASCE standard. The primary difference between the two documents is the limitation of the application of the New Zealand guidance to Vertical Evacuation Structures (VES). As a result of this distinction, a factor of 1.25 is used across the standard in place of the tsunami importance factor (I_{tsu}) used in ASCE 7-16 (2016) and a bore impact factor of 1.5 is used in all hydrodynamic loading calculations. Beyond the additional factors of safety due to the critical nature of the structures, the hydrostatic and hydrodynamic portions of the guidance are effectively identical.

Critical to understanding the NZ guidance (MBIE 2020) and ASCE 7-16 (2016) are the three load cases that account for the expectation that maximum inundation depth and maximum flow velocity will not occur simultaneously. In both standards, the following load cases are defined based on work by Ngo and Robertson (2012) that analysed video evidence from the 2011 Tohoku tsunami:

- **Load Case 1**: Depth equal to the lowest value between maximum inundation, storey height, height of first storey windows; Corresponding flow velocity from normalized time history plot
- **Load Case 2**: $\frac{2}{3}$ Maximum Inundation Depth; Maximum Flow Velocity
- **Load Case 3**: Maximum Inundation Depth; $\frac{1}{3}$ Maximum Flow Velocity

4.1.1 Hydrostatic Loads

MBIE (2020) Section 2.5 and ASCE 7-16 (2016) Section 6.9 cover buoyant forces, unbalanced lateral hydrostatic forces, and hydrostatic surcharge forces. All hydrostatic forces are calculated using their respective first principle equations with modifications to account for variability and introduce a conservative nature.

Buoyant forces are included in Section 2.5.1 of the MBIE guidance and Section 6.9.1 of ASCE 7-16 (MBIE 2020; ASCE 2016). The buoyant force acting on a structure is considered in the guidance to account for the reduction in a structure's net weight and the potential for uplift. These forces produce the potentially controlling load case where a structure might be lifted or overturned if the gravitational forces and the tensile strength of the foundation are overcome by the buoyant forces combined with the lateral fluid loading (Chock et al. 2013a, 2013b). The buoyant forces are calculated using the first principle equation based on the displaced volume of water.

Unbalanced Lateral Hydrostatic Forces are included in Section 2.5.2 of the MBIE guidance and Section 6.9.2 of ASCE 7-16 (MBIE 2020; ASCE 2016). This loading scenario occurs when the inundation cannot reach equilibrium on one side of a wall which leads to hydrostatic pressure build-up. Limitations based on wall size and orientation are included to ensure the load is applied only where inundation is present on one side of the wall and the force is calculated using the hydrostatic pressure equation.

Surcharge loading on floors and walls accounts for water which remains on upper storeys following the drawdown stage of inundation and is included in Sections 2.5.3 and 6.9.3 of the MBIE guidance and ASCE 7-16 respectively (MBIE 2020; ASCE 2016). The presence of water following the drawdown stage introduces a force equal to the weight of that water to the gravitational load resisting system. Surcharge loading on the foundation is accounted for in Section 2.5.4 of the MBIE guidance and Section 6.9.4 of ASCE 7-16 (MBIE 2020; ASCE 2016). The pressure of any water above the foundation will act on the foundation and must be considered in the design.

4.1.2 Overall Hydrodynamic Loads

Sections 2.6.1 and 2.6.2.1 of the MBIE guidance and Sections 6.10.1 and 6.10.2.1 of ASCE 7-16 provide simplified and detailed equations for the calculation of the hydrodynamic loads acting on a structure (MBIE 2020; ASCE 2016). These forces are considered to account for the overturning and base shear failure modes

(Chock et al. 2013b). The equations differ slightly between the two standards because the MBIE guidance is limited to VES, but in both cases the equations are based on the hydrodynamic drag equation. Both standards include both simplified and detailed equations. The detailed equations include non-standard factors to account for variation in loading including: a fluid weight density factor (γ_s), a tsunami importance factor (I_{tsu}), a closure coefficient (C_{cx}), a flow amplification factor, and a bore impact factor – these factors are discussed in more detail in the next paragraph. The simplified equations assume the coefficients of the detailed equations are the most conservative values in the expected range, and include an additional factor to account for any uncertainty, applies the pressure over an area of $1.3h_{max}$ to account for upstream flow build up, and uses a Froude number of $\sqrt{2}$ to approximate the flow velocity.

The tsunami importance factor (I_{tsu}) depends on the risk category of the building and the values were calculated and verified by Chock et al. (2016) by applying a Monte Carlo analysis to numerical models of potentially critical structural members. The closure coefficient (C_{cx}) approximates the area of the structure upon which the hydrodynamic force is applied. The range of expected closure coefficient values is limited to 0.7-1.0 based on reconnaissance investigations by Chock et al. (2013a, 2013b) following the 2011 Tohoku tsunami. The flow amplification factor accounts for the increased flow velocity due to upstream structures and is dependent on the wake clearance angle as defined by experimental work done by Thomas et al. (2015). The bore impact factor of 1.5 –applied throughout the NZ standard – was determined based on experimental and computational work by Ramsden (1993), Arnason et al. (2009), Paczkowski (2011), and Robertson et al. (2013). The bore impact factor is limited to elements three times wider than the inundation depth based on the work by Arnason et al. (2009). It should be noted that there were not significant increases found by Arnason et al. (2009) in the case of a square column rotated 45° relative to the direction of flow.

The drag coefficient (C_D) is a term found in all drag force equations, but is limited to a range of 1.25-2.0 for rectilinear structures and 1.2-2.5 for structural components. The commentary for ASCE 7-16 (2016) provides FEMA P-55, Volume 2 (2011) as the source for the drag coefficients.

4.1.2.1 Drag Force on Components

The Drag Force on Components is included in Sections 2.6.2.2-2.6.2.4 of the MBIE guidance and Sections 6.10.2.2-6.10.2.5 of ASCE 7-16 (MBIE 2020; ASCE 2016). The drag force equation is used with the inclusion of the tsunami importance factor. The values for the drag force on components are not additive with the overall drag force, but are used to assess the expected loads on individual members. The drag force on exterior structural components is amplified to account for debris build-up and may also be reduced for openings. Hydrodynamic loads are amplified for bore impact on vertical components and reduced for perforated walls and walls angled to the direction of flow.

4.1.2.2 Hydrodynamic Loads on Slabs

Section 2.6.3 of the MBIE guidance and Section 6.10.3 of ASCE 7-16 cover the hydrodynamic pressures acting on slabs (MBIE 2020; ASCE 2016). The flow stagnation pressure is applied to the walls and slabs of confined spaces in Sections 2.6.3.1 and 6.10.3.1. An uplift pressure, defined in Sections 2.6.3.2 and 6.10.3.2 and considered additive to buoyant forces, is applied to all inundated slabs. Sections 2.6.3.2.2 and 6.10.3.2.2 define an equation for the uplift force caused by flow under a sloped slab forcing the slab upwards. Sections 2.6.3.3 and 6.10.3.3 outline the uplift pressure acting on a slab from a bore forced upwards by a wall and the reductions to the pressure due to lower inundation, wall and slab openings, and tsunami breakaway walls.

4.2 Ministry of Land, Infrastructure, Transport, and Tourism

The Japanese Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) produced MLIT 2570 (2011) as a technical appendix to a similar design document from 2005 following the 2011 Tohoku Tsunami (Fukuyama et al. 2013). The largest difference between MLIT 2570 (2011) and the other guidelines is the use of hydrostatic pressure to approximate the tsunami wave force. The hydrostatic pressure equation uses only the inundation depth resulting in only one load case:

- **Load Case 1**: Maximum inundation depth; No approximate velocity

The inundation depth used in the hydrostatic pressure equation is amplified by a water depth coefficient (a) to account for the hydrodynamic force lost due to the hydrostatic approximation. This methodology results in a triangular pressure distribution extending to a height $ah_{inundation}$. The tsunami wave force is calculated by integrating the pressure distribution across only the pressure receiving surface which creates a trapezoidal pressure distribution. The methodology of accounting for hydrodynamic effects is attributed to experimental work by Asakura et al. (2000) studying the force of a tsunami acting on a structure. Their work is summarised as establishing the water depth coefficient should be 3.0 if there is no seawall, 2.0 if there is a seawall and the building is within 500m of the shoreline, and 1.5 if there is a seawall and the building is over 500m from the shoreline (Fukuyama et al. 2013). The tsunami wave force can be reduced due to openings by up to 70% of the total wave force. Non-pressure resisting members are not considered to add to the area acted on by the tsunami wave pressure. No specific guidance for the directionality of the tsunami wave force is included it must be considered in all directions unless an inundation analysis is performed.

Hydrostatic buoyancy forces in MLIT (2011) are calculated using the same method and equations specified in the MBIE and ASCE standards without any increase to the fluid density.

MLIT (2011) requires that any pressure resistant members are designed to have ultimate strengths in flexure and shear greater than the anticipated tsunami loads. In addition, the structural frame is designed to have ultimate strength greater than the shear forces resulting from the sum of the tsunami wave force acting above each storey.

5 CASE STUDY COMPARISON OF STANDARDS

5.1 Case Study Building Parameters

A case study building in Wellington was used to compare the tsunami forces predicted by the MBIE (2020), ASCE (2016) and MLIT (2011) standards. The case study building is a seven storey steel frame building in Wellington, New Zealand. Approximately 275m from the shoreline, this building is within the expected inundation zone according to hydrodynamic inundation modelling of the Wellington harbour (Mueller et al. 2015). The case study was chosen for its proximity to the shoreline and low site elevation.

The Energy Grade Line Analysis (EGLA) methodology outlined in ASCE 7-16 (2016) was used to calculate the flow characteristics. The maximum inundation depth is 5.52m with a maximum flow velocity of 7.94m/s at the site of the building. Note that the EGLA method is not allowed by the MBIE guidance because the guidance is only applicable to VES; however, the method is considered acceptably conservative by ASCE 7-16 for the case study building and other non-VES structures (MBIE 2020; ASCE 2016).

5.2 Case Study Results

The resulting tsunami base shears from the three standards are presented in Table 1 assuming a closure coefficient of 0.7 and a tsunami importance factor of 1.25 across all calculations. The results demonstrate the significantly conservative value of the simplified equations in the MBIE and ASCE 7-16 specifications. Note that the simplified forces calculated using the MBIE and ASCE 7-16 method only differ due to rounding in the MBIE document. The hydrostatic approximation used in MLIT 2570 (2011) falls between the values of the simplified and detailed hydrodynamic drag equations in MBIE and ASCE 7-16. This suggests the Japanese standard provides a reasonable estimation of the tsunami forces (being neither unsafe nor excessively conservative) despite being more simple to implement.

Table 1: Summary of hydrodynamic loads.

Guidance	Force Type	Tsunami Base Shear (kN)	Pressure Distribution
ASCE	Simplified Hydrodynamic	7175.19	Uniform
	Detailed Hydrodynamic	1507.71	
MBIE	Simplified Hydrodynamic	7163.71	Uniform
	Detailed Hydrodynamic	1507.71	
MLIT	Hydrodynamic - $a = 3$	5650.78	Trapezoidal

6 RECOMMENDATIONS FOR CONSIDERATION AND FUTURE WORK

Significant progress has been made in the estimation of tsunami loading, but work remains for the expansion of loading factors considered in the guidance. The work presented here was intended to provide insight into the basis for the hydraulic loading components of several international guidelines, however there are several important topics where further research is needed. This includes the effects of structure orientation on the hydrodynamic forces (which has previously been investigated, but isn't currently considered), the effects of ductility on structural performance and the reduction of flow velocity due to shadowing by upstream buildings, and the influence of the sequential seismic-tsunami impact loading scenario. The intent of this ongoing research programme is to address these shortcomings to provide practitioners with additional tools to design for the tsunami hazard.

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