Performance-Based Assessment of Onshore Structures due to Initial Tsunami Impact: A Preliminary Investigation

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ABSTRACT

The Tohuku earthquake and tsunami of March 2011 illustrated a greater vulnerability of onshore structures to tsunami loads than to those experienced during the earthquake. This is unsurprising when one considers that Earthquake Engineering is a more established field than Tsunami Engineering. It is because of this disparity that this paper aims to show how the gap can be bridged between these inter-related fields of engineering. This was accomplished by measuring initial tsunami impact loads in the laboratory and using them to estimate resultant structural displacements and determine the extent of damage by standard Earthquake Engineering practices. By doing this, it is hoped that future researchers will further explore the notion of utilizing Earthquake Engineering techniques to improve Tsunami Engineering.

KEY WORDS: Tsunami; Impact force; Damage; Guidelines; Japan.

INTRODUCTION

On the 11th March 2011, Japan was struck by a massive magnitude 8.9 earthquake that triggered a devastating tsunami. This tragic event resulted in more than 15,000 deaths and widespread destruction, caused in the most part by tsunami loads. The skew towards tsunami-driven damage was partly due to Japan's vastly advanced and widely implemented Earthquake Engineering design practice. This is however juxtaposed against the less understood and infrequently implemented field of Tsunami Engineering for onshore structures; an imbalance which is a worldwide issue with many tsunami risk zones having no building codes that consider tsunami loads. This paper addresses this issue by demonstrating the ability to apply well established techniques that underpin Earthquake Engineering in a Tsunami Engineering context.

This is achieved by a combination of physical experimentation and theoretical calculation. The experimentation focuses on measuring initial impact forces from a tsunami wave on a 1:150 scale model of a structure, with the forces measured by a novel method involving pressure sensitive pads. The data are used to theoretically calculate resultant displacement of a reinforced concrete frame structure, chosen to be representative of those commonly found in tsunami risk zones. Finally, the displacement calculation results are used to determine the expected structural damage state by reference to the ATC-40 Performance Based Design code from Earthquake Engineering. By making this link between the two fields, this research aims to demonstrate how advances in Earthquake Engineering can be used to further develop and improve Tsunami Engineering.

EXISTING BUILDING CODES

Modern Tsunami Engineering began with the Dames & Moore (1980) report. This was one of the first to provide expressions for tsunami loadings on structures, and these have been integral in the City and County of Honolulu Building Code (CCH) up to its latest revision in 2000. This lack of development of building code equations over a twenty year period is compounded by the fact that there are still only five building codes at present which directly address the design of onshore structures at risk of tsunamis. Two of these are the aforementioned CCH code and the FEMA 55 Coastal Construction Manual (2005) which also uses Dames & Moore's expressions. The other three codes have been devised for designing evacuation structures rather than standard onshore structures. The first of these is the Japanese Structural Design Method of Buildings for Tsunami Resistance (SMBTR) (2005). The remaining two are closely linked with the SMBTR, namely the Guidelines for Structures that Serve as Tsunami Vertical Evacuation Sites (Yeh et al, 2005) and the Guidelines for Design of Structures for Vertical Evacuation from Tsunamis, FEMA P646 (2008). Both the latter aim to address the tsunami threat posed to the western USA by the Cascadia subduction zone.

APPRAISAL OF BUILDING CODES

In 2009, Lukkunaprasit et al identified numerous issues with both the CCH and FEMA 55 building codes. The first problem is FEMA 55's suggestion that tsunami loads could be calculated using river flood theory. This idea is flawed because maximum river flood velocity is determined with maximum water depth, whereas maximum tsunami inundation depth can correspond to minimum velocity. This is because the interaction of tsunami run-up and drawdown can cause a cancelling effect on the velocity and an increase in depth. The next issue found in both FEMA 55 and CCH is the misinterpretation of an expression from

Dames & Moore (1980) used to calculate tsunami run-up (Eq. 1).

$$V=2(gh)^{1/2} \quad (1)$$

Where V is tsunami run-up velocity and g is the acceleration due to gravity. This expression was traced to work by Keulegan (1950), where 'h' was intended to represent the thickness of the tsunami's leading surge tongue, not the inundation depth at a structure. This mistake has also been carried into the surge force expressions in both codes as shown by Eq 2.

$$F_s = 4.5\rho g B h_s^2 \quad (2)$$

Where F_s is the surge force, ρ is the density of the water and B is the width of the structure. 'h_s' in Eq. 2 has also been misinterpreted to represent inundation depth rather than leading tongue thickness. Lukkunaprasit et al. (2009a) discovered that this results in 'excessively overestimated' forces. FEMA P646 has tried to counter this error by utilizing the newer 'momentum flux' method to calculate drag surge force as shown in Eqs. 3~4.

$$F_d = \tfrac{1}{2}\, \rho\, C_d\, B(hV^2)_{max} \quad (3)$$

$$F_s=1.5F_d \quad (4)$$

Where F_d is the drag force and C_d is the drag coefficient of the structure. The '$B(hV^2)_{max}$' term in Eq. 3 represents the 'momentum flux' per unit breadth and tries to improve upon FEMA 55 and CCH by accounting for maximum velocity not occurring at the same time as maximum inundation depth. The 'max' subscript represents the maximum combination of V^2 and h, which yields the maximum combined effect of these parameters, rather than the maximum values of each separately. Lukkunaprasit et al. suggest this approach presents many advantages, because the momentum flux can be determined with fine scale numerical modelling. Furthermore, FEMA P646 also provides an equation for calculating an estimate of $(hV^2)_{max}$ if numerical modeling is not possible, although it should be noted that this relies upon tsunami inundation maps to determine the momentum flux and these are not widely available.

RECENT RESEARCH

In the aftermath of the 2004 Indian Ocean Tsunami and the 2011 Tohuku Earthquake and Tsunami in Japan, Tsunami Engineering research has placed more emphasis on the survivability of onshore structures when subjected to tsunami loads. An example of this is the Thusyanthan et al (2008) study which experimentally analysed the performance of a tsunami-resistant house, the design of which had been adopted in Sri Lanka. The method to displace water and simulate a tsunami during the experimentation was to drop a 100 kg weight into a tank, quite different to the 'dam break' predominantly used in other studies. To measure impact pressures, the widely accepted method of pressure transducers was utilized. They determined that the tsunami-resistant house was prone to smaller pressures than typical coastal houses due to its smaller frontal surface area. An issue with using pressure transducers is the need for interpolation to determine pressure values away from their locations, which means that peak values greater than those recorded by a transducers are missed. This issue is countered in this paper's use of pressure sensitive pads which are able to monitor over the entire structural face.

Another more recent study is that by Lukkunaprasit et al. (2009b) which investigated the performance of buildings with openings when subjected to tsunami loads. This research found that structural openings had little effect on peak pressure values, although they were able to reduce hydrodynamic forces by up to 30%. This study also utilized pressure transducers, with their associated drawbacks. Further studies analysing structural responses to tsunami loads include Van de Lindt et al (2009) and Kodanda Rama Rao et al (2010). Van de Lindt et al (2009) found when they compared experimental force results to predictions that tsunami loading expressions did not adequately consider nuances in structural geometry. Interestingly, they considered expressions from both the FEMA 55 and CCH codes as part of their study, which could add weight to the findings of Lukkunaprasit et al (2009a) which showed that misinterpreted parameters resulted in overestimated forces. There is a link in the work carried out by Kodanda Rama Rao et al. (2010) to others in the field as they made use of FEMA 55's expressions to numerically model hydrodynamic tsunami loads on a structure. Unfortunately, this also means that there is a clear path for error in this study due to the inaccuracy of FEMA 55's expressions for force as discussed earlier. It is clear from these studies that there is an emphasis on the loading that structures experience from tsunamis and their response to it, but there is no research at present which uses structural displacement to determine damage from tsunami impact forces.

RESEARCH METHODOLOGY

Physically Modeling a Tsunami

Fig.1 illustrates the University of Southampton wave tank setup that was used for the reduced scale tsunami experiments. The target offshore wave height H_0 for the tsunami of 0.1m is shown. The main requirement of the tsunami wave simulation was to generate a large wave that would break on the slope, without emphasizing totally accurate tsunami wave generation. This was achieved by using the wave paddle driven by a 12v motor to quickly shunt water in a forward direction, to model the principal attribute of natural tsunami waves which is a sudden jolt that causes bulk displacement of water. Control of the wave paddle was accomplished using a proprietary program that

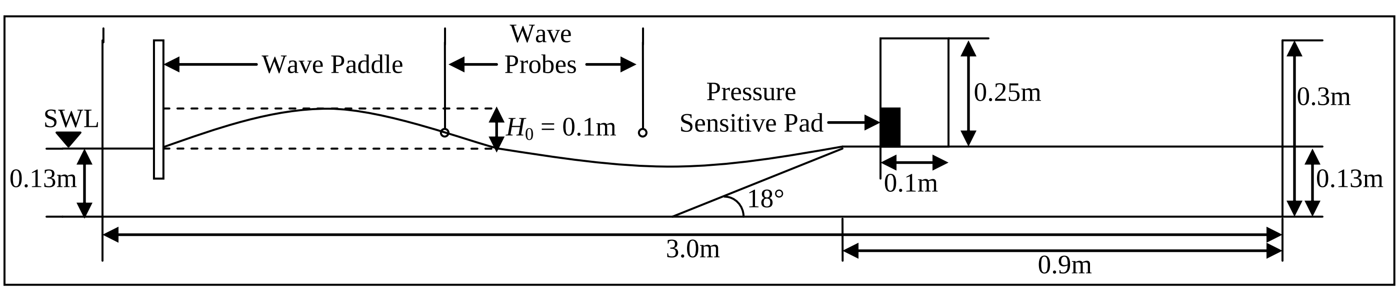

Fig. 1 Experimental setup of wave tank and tsunami wave height force

communicated with the 12v motor via a digital-analogue converter. This program derived its commands from a Microsoft Excel file that contained a digital voltage chart. A positive voltage was used to drive the paddle with the paddle stroke proportional to the voltage amplitude. To determine tsunami induced loads, the 100 mm square cross-section Perspex structure shown in Figure 2 was located on a raised plateau at the top of the beach slope where it would be impacted by the tsunami wave. A novel technique was chosen for recording the forces on the structure which involved pressure sensitive pads (Stagonas et al, 2011). These have 196 measuring points, with each point recording force over the duration of the tsunami event at a sampling rate of 4 kHz. Force values ranging from 0 to 0.87 newtons are determined from digital values between 0 and 255. To obtain the force values, it is necessary to calibrate the pads using an appropriate dynamic wave impact force scenario. This is challenging because pads of this type have previously only been used in solid-to-solid pressure applications such as in biomechanical research (*e.g*. Brimacombe et al, 2009), not high speed wave impacts. To achieve the calibration, an equal wave impact pressure was simultaneously applied to the pressure sensitive pad and an adjacent pressure transducer, by modeling a wave which broke in a plunging manner directly onto both instruments together. The data yielded from this process enabled a link to be determined between the pressure transducer and pressure pad digital output, giving a calibration that made it possible to interpret the digital output data from the experiments.

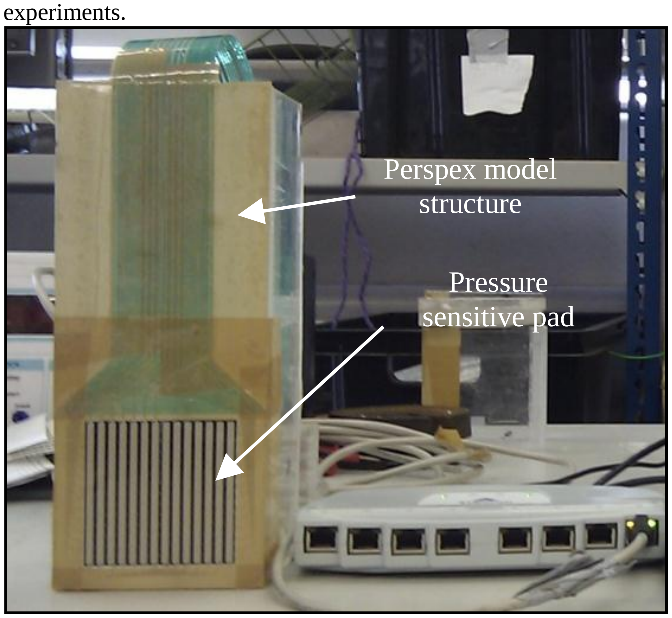

Fig. 2 Rectangular structure with pressure sensitive pad attached

Calculating displacement

Figure 3 shows the time history response of the initial impact event on the structure, presented in terms of an average force calculated as the average of the forces on the 196 measuring points that make up the pressure-sensitive pad. The impact event can be seen to be a pulse force with a sharp rise and fall, which may be idealised as a symmetrical triangle pulse shape, as shown by the dashed line in Figure 3. This enables the use of structural dynamics theories (Chopra, 2000) to determine the displacement response of a structure of known natural period as a result of this applied pulse force as shown by Eqs. 5~6.

$$(U_{st})_0 = P_0 \div k \qquad (5)$$

$$U_0 = R_d(U_{st})_0 \qquad (6)$$

In Eq.5, $(U_{st})_0$ is maximum static displacement of the structure, P_0 is the peak pulse force experienced by the structure and k is flexural stiffness of the structure. In Eq. 6, U_0 is maximum dynamic displacement of the structure, R_d is the dynamic amplification factor and $(U_{st})_0$ is the maximum static displacement result from Eq. 5.

Having idealized the pulse loading at the reduced experimental scale, Froude similarity scaling laws were used to determine preliminary values for force and force duration. These would be used in turn to calculate displacement response of a real building of known stiffness and natural period of vibration due to initial impact of a tsunami wave. The example building used was the seismically designed, reinforced concrete framed Holiday Inn hotel in Northridge, California as described in the ATC-40 Performance Based Design guidelines (Applied Technology Council, 1996), where it was used as a case study on the damage it suffered during the magnitude 6.7 Northridge earthquake of 1994. This example structure is ideal because it is representative of similar hotels that line popular tourist destinations with tsunami risk. Note that this original structure was reduced to four equal height storeys to simplify displacement calculations and consequently it was assumed to be approximately 10.6 m tall, 46 m wide and 19 m deep.

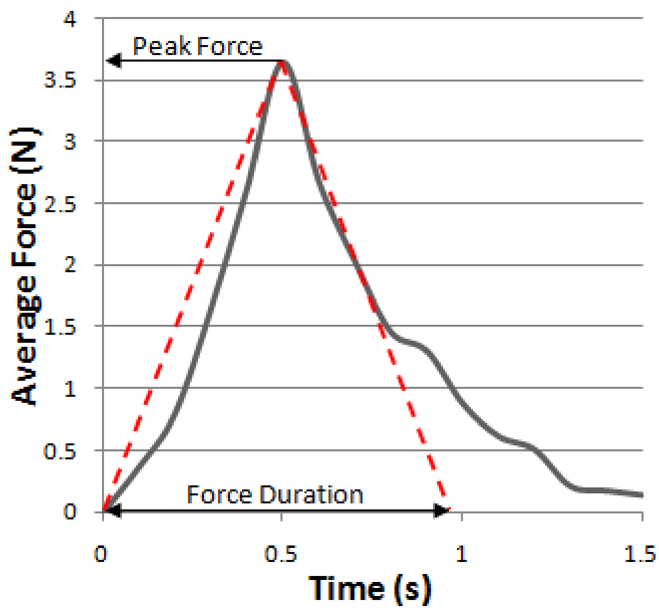

Fig. 3 Average time history from pressure sensitive pad

Hand calculations are then carried out on a shear frame idealization of the example structure to determine its natural period and flexural stiffness, taking just the fundamental mode or first natural mode of vibration. The shear frame idealization assumes that mass is concentrated at infinitely rigid floor beams with the stiffness concentrated at columns with no mass. Note that gross dimensions for the concrete cross-sections were used to determine flexural stiffness and the concrete was assumed to be linear elastic with a Young's modulus of 28 x 10^9 N/m^2. Furthermore, mass per storey was calculated by assuming a combination of both dead and imposed loads. These calculations were carried out for the East-West and North-South structural orientations separately. The peak tsunami force and force duration from the pulse force idealization in Figure 3 are then input into the calculations to obtain the maximum structural displacement, assuming that the building cladding remains integral so that the tsunami pressure is applied over its whole surface. This enables the determination of expected damage for the structure using Table 1, taken from ATC-40, in which the Roof Drift parameter represents displacement relative to a structure's height and is used to determine the damage level.

Table 1 ATC-40 damage states

Roof Drift Angle (%)	Structural Damage
< 0.2	Negligible
0.2 - 0.5	Light
0.5 – 1.5	Moderate
1.5 – 2.5	Severe
> 2.5	Collapse

RESULTS

Tsunami wave test results

The main requirement for tsunami wave simulation was to generate a consistent and repeatable wave. This objective was met by using the same wave paddle control commands throughout, resulting in an average offshore wave height of approximately 0.1 m, and a similar inundation depth at the structure in each test of approximately 0.04 m. In terms of wave breaking behavior, the intention was to produce a plunging breaker on the beach slope. This approach was taken to produce a turbulent mass of water that would travel inland where it would collide with an onshore structure as illustrated in Figure 4.

A total of thirty tests were conducted and analysis of the results showed that more than 90% of the initial impact force was applied to an area from the base of the structure to the height of maximum inundation. An average force at each time interval for each test was calculated using data from the sensors that covered this area. The force functions with time from each test were then averaged to derive an 'average pulse' force. The 'average pulse' was finally idealized using the method illustrated in Figure 3 to enable calculation of structural displacement.

Structural displacement results

Table 2 contains two columns of results, for tsunami impacts on the structural frame of the Holiday Inn structure from the East-West and North-South directions for which there are slight differences in the flexural stiffnesses of the frame and the structural surface area in contact with the tsunami wave.

It is clear from the last row of Table 2 that the Holiday Inn structure suffers Moderate damage in both impact scenarios; this is determined by referencing the Roof Drift value with the ATC-40 damage categories in Table 1.

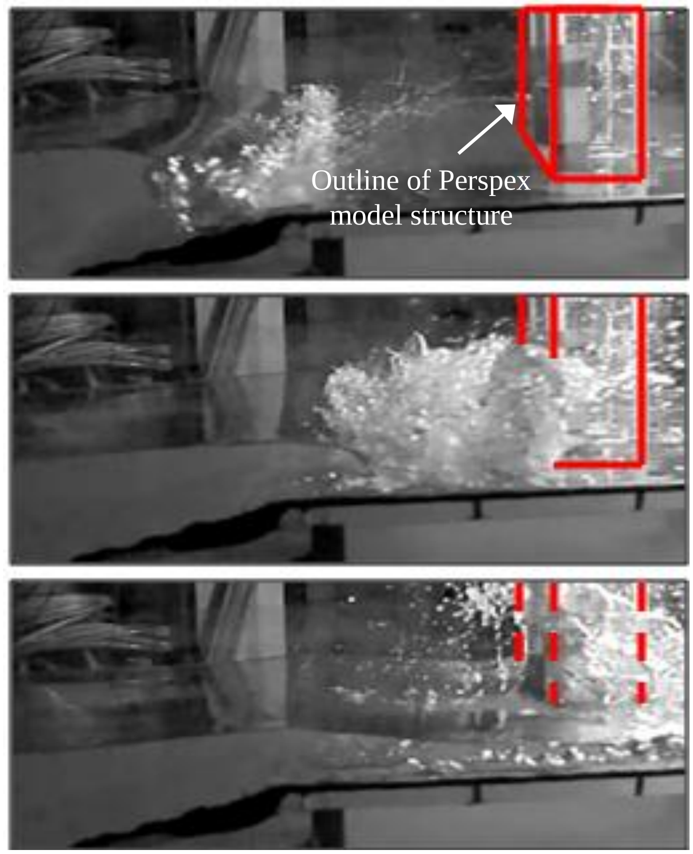

Fig. 4 Still images of tsunami wave breaking on beach slope

Table 2 Structural displacement and damage results for Holiday Inn

	East-West Impact	North-South Impact
Flexural Stiffness	1005.7 $x10^6$ N/m	1477.9 $x10^6$ N/m
Surface Area	101.23 m^2	242.32 m^2
Force	$47x10^6$ N	113 $x10^6$ N
Duration	5.14 s	5.14 s
Displacement	0.047 m	0.078 m
Roof Drift	0.88 %	1.47 %
ATC-40 Damage	Moderate	Moderate

In descriptive terms, this means that the structure would experience a combination of light to moderate structural damage with moderate to severe non-structural damage. Most importantly, this damage state would not result in structural collapse. The North-South impact scenario is the more damaging one, and approaches the lower limit for the 'severe' damage category in Table 1, while still avoiding collapse. It is important to note that the damage levels identified in Table 2 only represent the effect of an initial tsunami impact. There is a distinct possibility that impacts from following tsunami waves could result in collapse of the already damaged building. The analysis does assume however that the initial tsunami impact is applied across the full frontal area of the structure.

CONCLUSIONS

The main aim of this research is to analyze structural damage caused by tsunamis using the Earthquake Engineering approach of performance-based assessment by structural displacement. This was made possible through the measurement and idealization of the initial tsunami impact as a symmetrical triangular pulse force, followed by the use of structural dynamics theories to calculate the maximum dynamic response of a full-scale example framed structure modeled as a shear frame. It was then a natural progression to use the ATC-40 guidelines to determine damage performance of the structure from the displacement calculation results. By fulfilling this main research objective, it is hoped that future research will further develop this link between Tsunami Engineering and Earthquake Engineering by the sharing of commonly applicable methodologies, in particular focusing on relating Tsunami Engineering to the performance-based design branch of Earthquake Engineering.

One of the original features of this research was the use of pressure pads to estimate the impact force at over the whole face of the model building and not just at single points. Whilst this is a novel approach, issues related to the scaling-up of model forces / pressures, the similarity between model and prototype, and the performance of the instrument for such small pressure ranges still exist. Nonetheless, the preliminary results presented here encourage further investigation on the combined use and bridging of Earthquake and Tsunami Engineering techniques.

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