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TSUNAMI-INDUCED HYDRODYNAMIC AND DEBRIS FLOW FORCE ON STRUCTURAL ELEMENTS

Y. Nouri[1], I. Nistor[2], D. Palermo[3] and M. Saatcioglu[4]

ABSTRACT

The 26 December 2004 Indian Ocean tsunami has severely affected human communities along the coasts of Indonesia, India, Sri Lanka, Thailand, Maldives Islands, as well as the littoral zones of several West African countries. Generated by one of the most powerful earthquakes recorded in the history of the humankind, tsunami waves propagated over the entire area of the Indian Ocean causing the largest amount of causalities to have ever occurred due to a natural disaster and also generating huge economical losses.

The infrastructure of hundreds of cities and villages in the above mentioned countries was severally affected by the impact of tsunami waves. Unlike coastal structures such as breakwaters, jetties, groins or quay walls whose design and construction is based on the effect of wave breaking and the forces associated with it, the evaluation and impact of hydrodynamic forces on the structural elements which are an integral part of buildings used for habitation and/or economic activities received little attention by researchers and designers alike.

The present paper tries to evaluate the impact of these hydrodynamic loads on structural elements, specifically on concrete columns subject to hydraulic bores induced by tsunami waves. Moreover, the impingement of the hydrodynamic forces on structures is often accompanied by the impact of floating debris, which increases the magnitude of forces acting on structural elements. The paper will estimate in a first step the hydrodynamic and debris loads. Further, the impact of these loads on a typical reinforced concrete structure is evaluated and compared with seismic forces.

Introduction

The devastating effects of the 26 December 2004 Tsunami on many countries bordering the Indian Ocean has raised public concern and revealed existing deficiencies with the current warning and defense systems against tsunamis. One of the important elements that need significant improvement is the lateral resistance of onshore structures against tsunami-induced forces. Also, the estimation of impact forces generated by the water-born debris needs significant updating. Before the Indian Ocean Tsunami, it was assumed that there was no need for the design of structures against tsunami-induced forces. This situation was due to the assumption that tsunamis are "rare" events, with significantly large return periods (for some regions, of more than 500 years). The lessons learned from the aforementioned disaster

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[1] Graduate Student, Dept. of Civil Engineering, University of Ottawa, 161 Louis Pasteur, Room A106, Ottawa, Canada K1N 6N5.
[2,3] Assistant Professor, Dept. of Civil Engineering, University of Ottawa
[4] Professor, Dept. of Civil Engineering, University of Ottawa

revealed the fact that tsunami-induced forces should be accounted for in the design of structures built within a certain distance from shoreline in tsunami prone areas

Reinforced concrete structures have been observed to withstand tsunamis with acceptable low levels of damage (Shuto 1994). However, the results of field surveys performed in the aftermath of the 2004 Indian Ocean tsunami in Indonesia and Thailand showed that poorly detailed concrete structures experienced partial damage (Saatcioglu et al 2006 a,b). This highlighted the fact that current structural design codes do not given proper attention to tsunami-induced forces and the impact of floating debris. As shown in Fig. 1, inundation depths of more than 5 meters can induce partial damage on concrete structures.

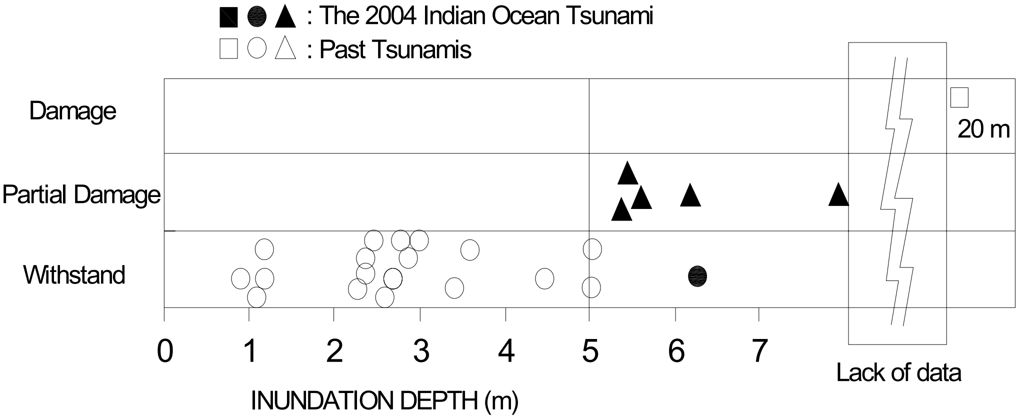

Figure 1. Relation between the inundation depth and degree of damage to reinforced concrete buildings. (Matsutomi et al. 2006)

Currently, there are no clearly established procedures to address the aforementioned forces. Moreover, significant disagreement on existing empirical formulas has fostered new research interest in an effort to properly address both tsunami-induced forces and the impact of floating debris in the design codes. Aspects related to tsunami-induced forces and the impact of floating debris are hence discussed in the present paper. Some of the shortcomings and inconsistencies of the existing codes are also highlighted.

This paper aims to provide more information on the likely effects of tsunami–induced forces and to compare with seismic forces calculated based on the new National Building Code of Canada (NBCC 2005). In this paper, a typical reinforced concrete building is considered and forces are calculated and compared for both earthquake- and tsunami-type events. At the same time, most of the existing formulations for estimating tsunami-induced forces have been gathered and compared, and a simple structural analysis was performed to determine differences between magnitudes of forces for these two events: tsunami and earthquake.

Existing Codes

The design of structures in flood-prone areas has previously been investigated, but only few existing codes specifically address the design of onshore civil structures built in tsunami-prone areas. However, tsunami-induced forces and the impact of debris are not properly accounted for in the existing codes and significant improvement is needed. Although some formulas were presented by several researchers, they are not always directly applicable. The authors identified this as one of the most significant deficiencies in the current design codes. The only two existing codes that account for tsunami impacts are (1) the Coastal Construction Manual (FEMA 55) and (2), the City and County of Honolulu Building Code (CCH).

However, two new documents have been recently published and they were specifically developed as guidelines for the design of structures that serve as tsunami vertical evacuation sites (tsunami refuge buildings). The documents were published by the Building Centre of Japan (Okada et al. 2006) and Washington Department of Natural Resources (Yeh et al. 2005).

Tsunami-Induced Forces

When a tsunami bore runs inland, the hydraulic bore will generate forces on the structures in their path. The forces associated with such tsunami-bores consist of the hydrostatic force, hydrodynamic (drag) force, buoyant force, surge force and the impact of floating debris. A brief description of each of these forces is further presented.

Hydrostatic Force

The hydrostatic force per unit width (F_{HS}) can be calculated using Eq. 1, where ρ is the sea water density, g is the gravitational acceleration, d_s is the inundation depth and u_p is the normal component of velocity against a wall. Eq. 1 is proposed by CCH and accounts for the velocity head. Alternatively, FEMA 55 does not include the velocity head in its formulation since it is assumed to be a negligible component of the hydrostatic force.

$$F_{HS} = \frac{1}{2}\rho g\left(d_S + \frac{u_p^2}{2g}\right)^2 \tag{1}$$

It should be noted that, generally, the hydrostatic force is significantly smaller than the drag and surge forces, especially for the case of a tsunami which travels inland as a hydraulic bore. On the other hand, Dames and Moore have noted that the hydrostatic force becomes important when tsunami is similar to a rapidly-rising tide. (Dames and Moore 1980)

Buoyant Force

For the calculation of the buoyancy force, the same expression (Eq. 2) is used in all existing codes and/or published research.

$$F_B = \rho g V \tag{2}$$

where V is the submerged volume of the structure.

Hydrodynamic (drag) Force

There is a lack of agreement on the calculation of the hydrodynamic force. The general expression for the hydrodynamic force is shown in Eq. 3. All existing codes use the same expression, but the difference in the results is due to the use of different drag coefficient (C_D) values as proposed by each code. For example, values of 1.0 and 1.2 are recommended for circular piles by CCH and FEMA 55, respectively.

$$F_D = \frac{\rho C_D A u^2}{2} \tag{3}$$

where
F_D = total drag force acting in the direction of flow
A = projected area of the body normal to the direction of flow
u = velocity of flow

The flow is assumed to be uniform, so the resultant force will act at the centroid of the projected area immersed in the flow.

Tsunami-bore Velocity

Some of the significant differences in estimating forces exerted on a structure by a tsunami bore, as well as the impact of debris, are due to the difference in the estimation of the bore velocity. Since hydrodynamic force is proportional to the square value of bore velocity, uncertainties in estimating the velocity induce large differences in the calculated value of the hydrodynamic force, which is a large portion of the total force acting on the structure. Tsunami-bore velocities can vary from close to zero to large values during a major tsunami. As such, current estimates of velocity are crude: a conservatively high flow velocity impacting the structure at a normal angle is usually assumed. Also, the effects of run-up, backwash and direction of velocity are not addressed in current design codes.

Although there is certain consensus in the general form of equation for the hydrodynamic force, different researchers have derived different empirical coefficients which they included in their formulation. The general form of the equation is expressed in Eq. 4.

$$u = C\sqrt{gd_s} \tag{4}$$

where
u = the bore-velocity
d_s = inundation depth
and *C* is a constant coefficient.

Several formulations proposed by FEMA 55, CCH, Iziuka (2000), Kirkoz (1983), Murty (1977) and Bryant 1, 2 (2001) for estimating the velocity of a tsunami bore in terms of the inundation depth are shown in Fig. 2. It can be observed that the largest difference in the calculated velocities is between the formula recommend by CCH and FEMA 55, the only two existing codes which include tsunami forces in the design of structures.

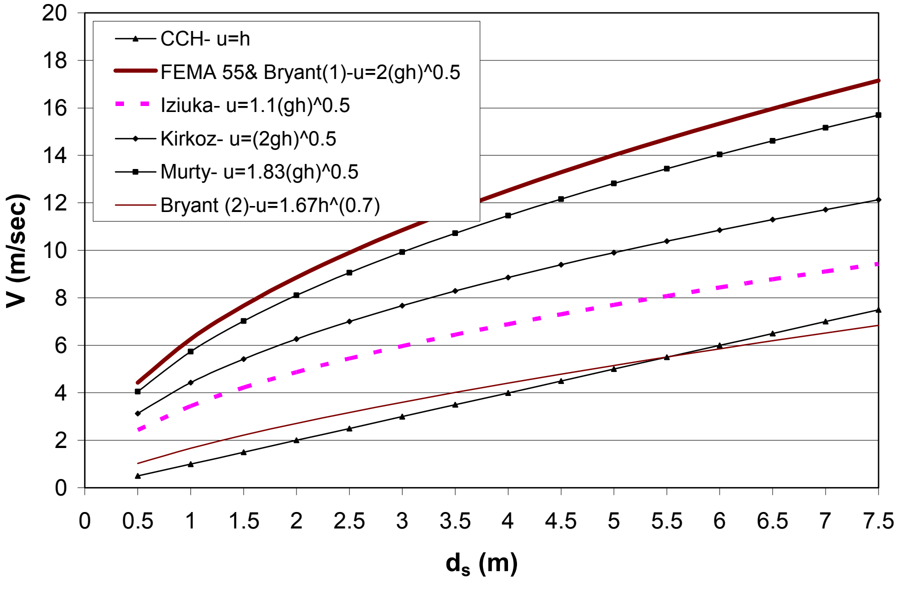

Figure 2. Tsunami-bore velocity, proposed formulas by different researches.

Surge Force

Due to a lack of detailed experiments specifically applicable to tsunami bores running up the shoreline, calculation of the surge force exerted on a structure by tsunami-bore front is subject to substantial uncertainty. Accurate estimation of the impact force in laboratory experiments is a challenging and difficult task. Consequently, in the absence of accurate studies, formulations expressed in the current design codes are used. CCH recommends the use of Eq. 5. (Dames and Moore 1980)

$$F_S = 4.5\rho g h^2 \qquad (5)$$

where F_s is the total surge force per unit width of wall and h is the surge height. This equation is applicable for walls with heights equal to or greater than $3h$. Walls whose heights are less than $3h$ require surge forces to be calculated using an appropriate combination of hydrostatic and drag force equations for each specific situation.

Using Eq. 5 will generate a value for the surge force equal to nine times the value of the hydrostatic force for the same flow depth. However, a number of experiments measuring forces of long waves, bores, and dry-bed surges on a vertical wall performed by Ramsden (1996) and Arnason (2005), did not capture such significant differences of magnitude.

Yeh et al. (2005) commented on the validity of Eq. 5 and indicated that, based on the results of the aforementioned experiments, this equation gives “excessively overestimated values” and that calculated values are “contradictory to the laboratory results by Ramsden (1993) and Arnason (2005)”. However, the proposed tsunami wave pressure for the evaluation of the design force (Okada et al. 2006) which is based on results of a number of studies conducted by Japanese researchers indicated that both experimental and numerical results are in agreement with the results of Eq. 5.

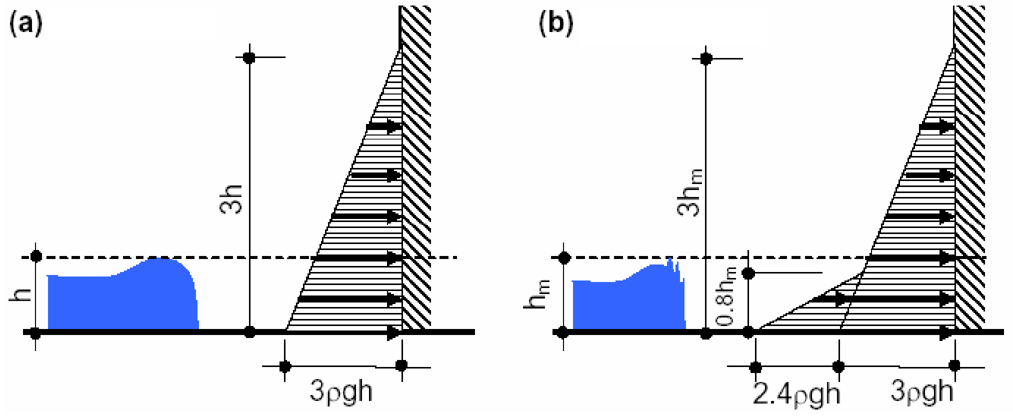

Figure 3. Tsunami wave pressure distribution, a) without soliton break-up b) with soliton break-up. (Okada et al. 2006)

It is shown in Fig. 3 that tsunami is considered as a soliton that is “unbroken” or is at the “break-up” instant (Okada et al. 2006). The equivalent dynamic pressure resulting from the tsunami interaction is taken to be associated with a hydrostatic distribution which is equal to three times the tsunami height, this leading to a force factor of nine times the hydrostatic one. In the case of wave break-up, an enhancement to this distribution is added by considering a superimposed hydrostatic pressure starting at $0.8h$ above the ground and peaking to 2.4 ρgh, leading to a force factor approximately 11 times hydrostatic. It should be noted that some researchers such as Okada et al. (2006) did not provide separate formulations for different components of tsunami-induced force and assumed that their proposed formulation contains all of the components.

In addition, recent published results by Haritos et al. (2005) which used a numerical model - shown in Fig. 4 - captured a maximum run-up height three times larger than the tsunami depth and an overshoot of approximately ten times the hydrostatic force. This is in acceptable agreement with the values calculated using Eq. 5 and the pressure distribution proposed by Okada et al. (2006).

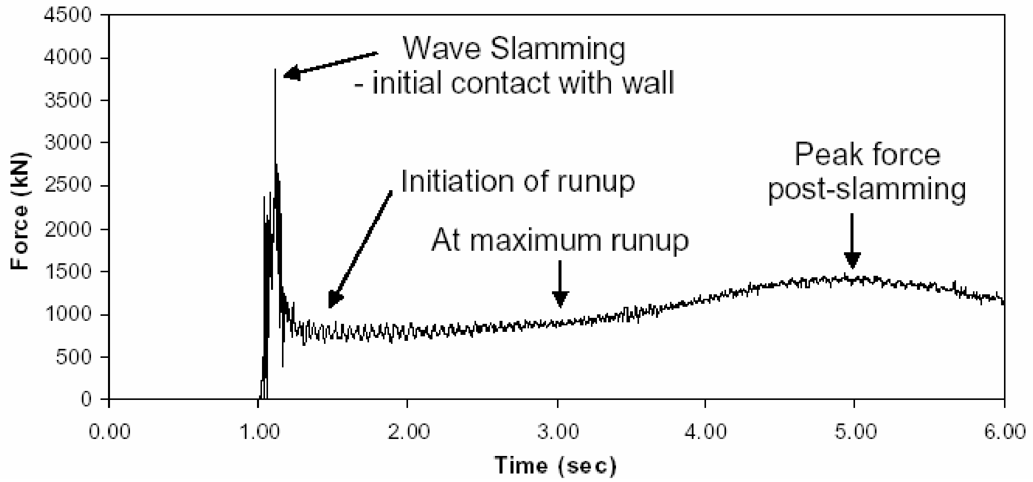

Figure 4. Tsunami force on a rigid vertical wall. (Haritos et al. 2005)

Debris Impact Force

As high-intensity tsunamis travel onshore, they carry debris such as floating automobiles, parts of buildings, drift wood, lumber, etc. The impact of floating debris to structural elements can induce significant forces on a existing building, leading to structural damage or even the collapse of the structure. (Saatcioglu et al. 2006)

Both FEMA 55 and CCH regulations account for the debris impact force in a consistent way using the same approach. Eq. 6 is used in both codes and the only difference between the two codes is in the recommended values for the duration of impact. This has a noticeable effect on the magnitude of the impact force. For example, the CCH code recommends the use of an impact time of 0.1 seconds for concrete structures, while FEMA 55 has provided different figures for walls and piles of a concrete structure, that varies between 0.2 to 0.4 and 0.3 to 0.6 seconds, respectively.

$$F_i = m\frac{du_b}{dt} = m\frac{u_l}{\Delta t} \tag{6}$$

where
F_i = impact force
m = mass of the body impacting the structure
u_b = velocity of the impacting body, assumed equal to the flow velocity
u_l = approach velocity of the impacting body, assumed equal to the flow velocity
Δt = impact duration that is equal to the time between initial contact of the body with the building and the maximum impact force.

This single concentrated load acts horizontally at the flow surface or at any point below it. This load is equal to the impact force produced by a 455 kg (1000-pound) weight of debris traveling at the velocity of the bore and acting on a 0.092 m^2 (1 ft^2) surface of the structural element where impact is postulated to occur. The impact force is to be applied to the structural element at the most critical or vulnerable location, as determined by the structural designer. It is assumed that the velocity of the floating body goes from u_b to zero over some small finite time interval (Δt). Finding the most critical or vulnerable location of impact is a trial and error - and rather difficult - procedure that depends to a large extent on the experience and intuition of the engineer.

Breaking Wave Force

A significant shortcoming of the FEMA 55 design code is the fact that it does not include the surge force and uses the same breaking wave force formulation for both river floods and tsunami bores. Tsunami waves tend to break offshore and approach shoreline as a broken hydraulic bore or a soliton, depending on their height and on the bathymetry. Consequently, the use of classic breaking wave force formulations is not directly applicable to the case of tsunami bores.

Loading Combinations for Tsunami-Induced Forces

Loading schemes can significantly influence the results of the structural design and represent an important element in the design sequence. The literature review conducted by the authors revealed that these loading schemes must be significantly improved and incorporated in the new design codes. Unlike the case of tsunamis, loading schemes for flood-induced surges are well-established and already included in the design codes. Tsunami-induced loads are very different from the flood-induced forces and using the same load combinations as the case of flood surges is not directly applicable to the case of tsunamis.

a) FEMA has considered three types of combinations for columns, solid walls facing the shoreline and vertical forces on structures respectively as follows:

Type 1: F_{brkp} (on column) + F_i (on column), or F_d (on column) + F_i (on column)
Type 2: F_{brkw} (on walls facing shoreline) + F_i (on one corner) or
F_s (on walls facing shoreline) + F_i (on one corner).
Type 3: F_b (for basements, swimming pools, empty above-ground and below ground tanks).

Where F_{brkp}, F_i, F_d, F_{brkw}, F_s and F_b refer to breaking force on columns, impact force, drag force, breaking force on walls, surge force and buoyancy force.

b) Dias et al (2006) proposed two load combinations based on the (1) instant that tsunami-bore impacts the structure (2) after the whole structure is inundated.

c) Authors use two new load combinations similar to those proposed by Dias et al. (2006). The difference is that the debris impact force is accounted for in both combinations and that the hydrostatic and hydrodynamic forces are replaced with the surge force in the 'point-of-impact' condition, as shown in Fig. 5.

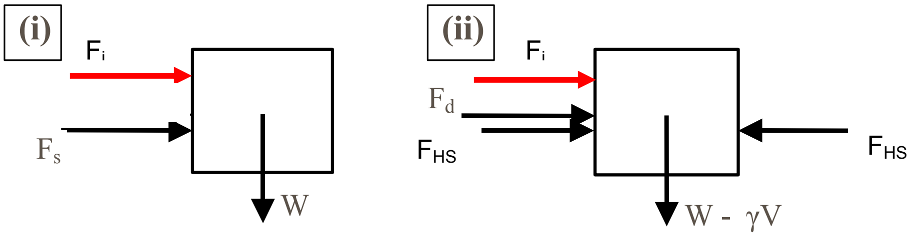

Figure 5. Proposed loading conditions (i) – point of impact / not submerged; and (ii) post-submergence / submerged.

where W, γ and V are the weight of the structure, sea water unit weight and the volume of submerged section of the structure, respectively.

Typical Reinforced Concrete Structure Subjected to Earthquake and Tsunami

In order to demonstrate the difference in magnitude of forces induced by earthquakes with tsunami generated forces, a typical reinforced concrete building in Vancouver area (Canada) is considered. The plan of the building is shown in Fig. 6. Calculation of forces has been performed for the case of up to ten-story structures. The structure is designed using ductile moment resisting frames. The interior columns have a cross section of 500 x 500 mm while the dimension of the exterior columns is 450 x 450 mm. The slab floor system consists of a 125 mm thick slab spanning between beams that are 300 mm wide x 450 mm deep. (Fig. 6) Floor height is equal to 3.65 m.

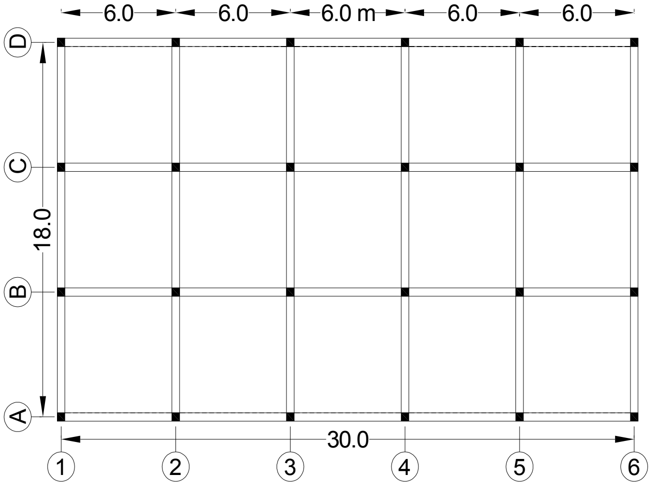

Figure 6. Typical plan of building.

Seismic-Induced Forces

Seismic-induced base shear force for structures up to ten stories is calculated based on the 2005 NBCC (National Building Code of Canada), as shown in Table 1. It is assumed that the building is to be built on very dense soil and soft rock, i.e., site class C, according to NBCC 2005. The structure is assumed to be in the *normal* importance category. It should be noted that the ductility-related force modification factor, R_d=4 and the overstrength-related force modification factor, R_o=1.7 are accounted for in order to reduce the elastic base shear.

Table 1. Calculation of base shear based on NBCC 2005.

No. of Stories	**h(m)**	**Ta(s)**	**S(Ta)**	**V/W (elastic)**	**V/W (inelastic)**	**W(kN)**	**$V_{inelastic}$ (kN)**
1	3.65	0.198	0.950	0.950	0.093*	3906	363
2	7.3	0.333	0.817	0.817	0.093*	7812	727
3	10.95	0.451	0.699	0.699	0.093*	11718	1090
4	14.6	0.560	0.613	0.613	0.090	15624	1408
5	18.25	0.662	0.550	0.550	0.081	19530	1578
6	21.9	0.759	0.489	0.489	0.072	23436	1687
7	25.55	0.852	0.432	0.432	0.063	27342	1736
8	29.2	0.942	0.376	0.376	0.055	31248	1728
9	32.85	1.029	0.335	0.335	0.049	35154	1732
10	36.5	1.114	0.321	0.321	0.047	38906	1834

*Controlled by maximum required earthquake base shear.

In Table 1,
h = total height if the structure
T_a = fundamental lateral period of vibration of the building, in the direction under consideration
$S(T)$ = design spectral response acceleration, expressed as a ratio to gravitational acceleration, for a period of T
V = lateral earthquake design force at the base of the structure

W = weight of the structure
In calculating the weight of the structure, roof loading is assumed equal to 2.35 kPa (due to snow loading). Also, floor loading is assumed equal to 7.25 kPa, which includes **self**-weight of the structure, partition, ceiling, mechanical and electrical loading.

Tsunami-Induced Forces

Inundation depths of one, two, three and four meters are considered and subsequently, tsunami-induced base shear forces on the structure are calculated based on the CCH method, as shown in Table 2. Shear force values for different components are calculated. It is assumed that tsunami impacts the short side of the structure. If the structure is to be built with its long side facing the shoreline, significantly higher forces will occur. It should be noted that break-away walls were assumed up to the second floor; consequently, forces shown are directly applied to the columns.

Table 2. Calculation of tsunami-induced base shear.

Inundation Depth (m)	Tsunami-bore Velocity (m/s)	Drag Force (kN)	Surge Force (kN)	Debris Impact Force (kN)	Load Combination #1 (kN)	Load Combination #2 (kN)
1	3.45	73	81	16	97	89
2	4.87	292	324	22	346	314
3	5.97	658	729	27	756	685
4	6.89	1170	1296	31	1327	1201

Comparison of Seismic Forces with Tsunami-Induced Forces

It is shown that as inundation depth increases, total base shear force exerted on the structure increases significantly. The comparison of total shear force induced on the structure due to tsunami and earthquake loads, can be made from results of Tables 1 and 2. As shown, the tsunami-induced force with inundation depth equal or less than two meters is smaller than that of the earthquake-induced load. However, for inundation depth equal to three and four meters, the tsunami-induced base shear is the governing criteria to be used in the design of up to two and three-story buildings, respectively. This conclusion is case dependent and may not be generally true, since the magnitude of the tsunami-induced forces depend on the exposed breadth of the building. This highlights the fact that proper attention should be given to developing new codes that would account for the tsunami-induced loads on structures located in tsunami-prone areas. It is observed that tsunami-induced loads can be larger than reduced elastic earthquake-induced loads in particular cases. However, tsunamis are rare events where damage can be accepted, but collapsed avoided. Therefore, tsunami-induced forces should be reduced to reflect the ductility of the structure. Further research is required to establish ductility-related factors for tsunami-induced loading.

Conclusions

A number of conclusions can be drawn from the current study and they are presented below.
1) The tsunami-induced forces were considered and several formulations and their associated uncertainties and weaknesses were compared and discussed based on a comprehensive survey of the state-of-the-art technical literature.
2) Comparisons of tsunami-generated forces were conducted in order to highlight the difference between existing formulations and currently used loading schemes.
3) The authors evaluated the design forces for a typical reinforced concrete structure with break-away walls subjected to a tsunami bore and to a design earthquake. The comparison of the base shear due to the tsunami and earthquake loads has provided a quantitative understanding of differences in the design loads for the structure indicating that the tsunami-induced forces can be the critical load case.

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