1. INTRODUCTION

The Boxing Day Tsunami of 2004 must go down in human history as one of our greatest ever disasters. A magnitude 9.0 earthquake, the most powerful to hit anywhere in the last 40 years, created tidal waves in the Indian Ocean that killed at least 225,000 people in 11 countries. Sri Lanka was hit quite hard, with over 32,000 dead and approx. 5 percent of the population there left homeless. In Indonesia more than 150,000 were killed and over 12,000 lost their lives in India, most in the Andaman and Nicobar Islands. In Thailand there were more than 5,000 deaths many of whom were foreign tourists. The devastation to services, property and buildings from the effects of the Tsunami was so immense that international appeals were launched for aid to the victims, of unprecedented proportions.

The disaster spawned immediate and renewed scientific interest in Tsunamis from researchers all over the world. How Tsunamis are formed, where they may strike, their likelihood of occurrence of any significance, their characteristics and ways in which their potentially devastating effects may perhaps be mitigated, are questions that many researchers are seeking answers to. Whilst Tsunamis are not an entirely new phenomena, and a significant amount of scientific literature can be found that addresses many of these questions (Bryant, 2001), it is clear that much still needs to be done to gain a better understanding of Tsunami wave-structure interaction effects on buildings and building elements – a key issue with respect to structure integrity and survival against the effects of a Tsunami.

This paper describes attempts that seek to provide guidance for wave-structure interaction effects in the coastal zone primarily due to breaking wave forces, and the limited experimental research on Tsunami-like bores and their characteristics that may be found in the literature.

Numerical modelling of bores and their interaction with walls is explored using Computational Fluid Dynamics (CFD) and comparisons made with results from the limited experimental programs found in the literature, to demonstrate their potential. The need is identified for controlled laboratory experiments to better verify CFD models of bore interaction with various structural forms.

2. APPROACHES FOR EVALUATING TSUNAMI WAVE FORCES

A number of approaches, many of which are based upon our understanding of gravity waves and their effects on coastal and offshore structures, have been adopted as a basis in modelling attempts for tsunami wave effects on land-based structures. Practically all of these approaches look at modelling force effects on continuous vertical walls.

2.1 Results from numerical studies of solitons

Fenton & Rienecker (1982) found from numerical simulations that F the force per unit length and M the moment about the base per unit length due to a solitary wave (soliton) of height H in depth of water h, impacting on a vertical wall are given by:

$$\frac{F}{\rho g h^2} = \frac{1}{2} + 2.25\left(\frac{H}{h}\right) - 0.42\left(\frac{H}{h}\right)^2 \qquad (1)$$

$$\frac{M}{\rho g h^3} = \frac{1}{6} + 1.23\left(\frac{H}{h}\right) + 0.80\left(\frac{H}{h}\right)^2 \qquad (2)$$

which apply to $H/h < 0.5$, as solitons tend to break beyond this limit. (Extrapolating Eq(1) beyond its limit to $H/h = 1$, leads to a force factor of 2.32, or less than 5 times the value of ½ , which is associated with hydrostatic pressure at depth, *h*, substantially smaller than the design recommendations for Tsunami conditions presented in §2.2).

2.2 Technical Design Guidance for Tsunami Resistance of Buildings

Historically, the Japanese islands and various coastal regions of the U.S.A., especially Alaska, have been observed to be prone to the effects of Tsunamis. Consequently, both Japan and the U.S.A. provide some guidance through technical publications on the design of coastal and land-based structures that may be subject to coastal wave effects, including Tsunamis, (Mizutani & Imamura, 2001; Okada et al, 2002; US Army Corp Engineers, 1990). A brief overview is presented here of two of these approaches.

2.2.1 Proposed Japanese design method for Tsunami resistance of buildings

The Building Technology Research Institute in Japan has produced a draft document outlining a proposed design force evaluation method for inland buildings subjected to Tsunami waves, (Okada et al, 2004). The proposal is based upon results of a number of studies by Japanese researchers, both experimental and numerical, and concentrates on the overturning and sliding stability of a structure to the hydrodynamic and buoyancy force effects of a Tsunami.

Figures 1(a) and (b), extracted from this proposal, consider the Tsunami as a soliton that is “unbroken” (a), and at “break up”, (b), when evaluating the wave pressure on the building face, considered as a vertical wall.

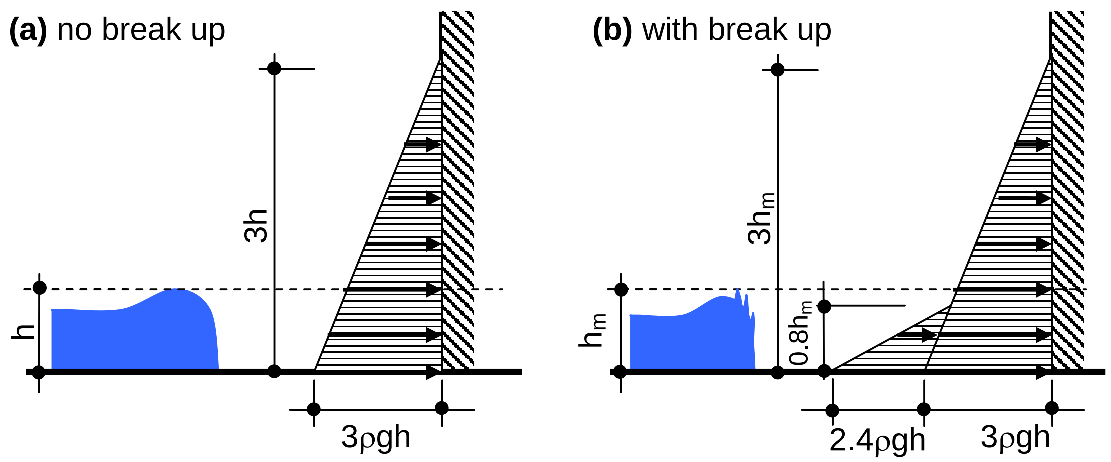

Figure 1 Tsunami wave pressure distribution with/without soliton break-up

Essentially, the depth "*h*" is taken as the Tsunami depth with surface "ripples" in the case of breaking of the soliton. The equivalent dynamic pressure resultant from the Tsunami interaction with a vertical wall is taken to be that associated with a hydrostatic distribution *3* times this height – leading to a force factor of 9 times hydrostatic. In the case of wave break-up, an enhancement to this distribution is made by considering a superimposed hydrostatic pressure starting at $0.8h$ above the ground and peaking to $2.4\rho gh$, as shown in Figure 1(b) – leading to a force factor ~11 times hydrostatic.

Sliding forces and overturning moments are evaluated based upon these distributions and the geometry of the building. Should the height of the building not exceed $3h$, it is recommended that the pressure distribution be truncated at the height of the building.

2.2.2 U.S. Army Coastal Engineering Research Centre Technical Note III-29

The U.S. Army Corps of Engineers Coastal Engineering Research Centre Technical Note III-29 (1990), considers wave forces on a wall shoreward of the still-water line, so has some relevance to Tsunamis. Figure 2, derived from this publication, presents a diagrammatic representation of a breaking wave that forms a bore of height, h_s, at the shoreline that moves up the beach, angle θ and Chezy coefficient, C_h, a horizontal distance, x_1, where the height of the bore is h, and there meets a vertical wall.

The force per unit length of wall resulting from the surge interaction is assumed to consist of hydrostatic and "dynamic" parts, the first and second terms in equation:

$$F = \frac{\rho g h^2}{2} + C_F \rho u^2 h \tag{3}$$

where C_F is a coefficient dependent upon the bore gradient at its face, and $u = 2\sqrt{gh}$.

Substituting for an empirically derived expression for C_F , one obtains $F \approx 4.5\ \rho g h^2$, for a Chezy roughness coefficients at the shoreline of $30 < C_h < 100$. Values for the dynamic term can exceed *8* times the hydrostatic term, using this approach. (This condition would yield a result similar to that from a hydrostatic pressure distribution of 3 times the bore depth, *h*, being a squared relationship on this factor, which is in line with the approach proposed by the Japanese and outlined in §2.2.1 above).

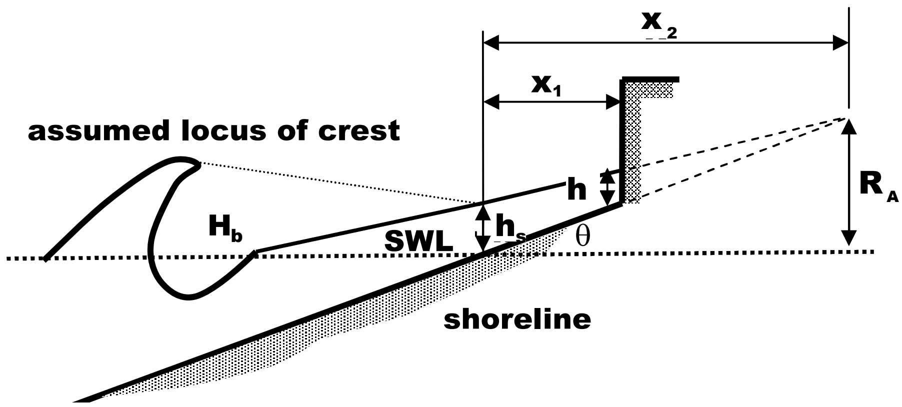

Figure 2 Wave pressures from broken waves on walls landward of the still-water line

2.3 Studies of Bore Surge Interactions with Walls

Cross (1967) was one of the earliest researchers to specifically study Tsunami surge forces (as opposed to "general" breaking wave force studies) both using a theoretical treatment and experiments conducted in a wave-tank. His results have "fed" into the document outlined in §2.2.2. Cross identified a runup effect of a column of water on the wall, from his surge experiments, that lead to a peak in the wave force coinciding with the collapse of this column back into the surge. He also suggested that turbulence/other fluctuations and "ripples" in the surge could possibly lead to local effects (increased pressures), that his instrumentation was not capable of observing well enough, and consequently there was a need for further work to be conducted in this area. Despite this recommendation, there appears to have been very little experimental (and even theoretical) work on Tsunami surge forces on walls, since this early study.

Ramsden (1996) performed experimental studies on long waves (solitons), bores and surges in a horizontal wave tank. Whilst some verification of the earlier work by Cross was afforded by his studies, results for turbulent bores indicated the presence of wave slamming effects and other instabilities due to the interaction of the incident bore and reflected water columns from the wall, that resulted in wall forces that significantly exceeded values from an assumed hydrostatic force distribution based upon maximum wave runup. To what extent a Tsunami surge can be modelled as a strong turbulent bore (parameter "waveheight to water depth ratio", H/h, and the associated "wave" celerity, c), as required to evaluate the characteristics of force and moment acting on a vertical wall, from the graphical results presented by Ramsden, is somewhat problematic.

There is therefore a strong need to perform further more detailed experimentation in the wave-tank that generates surges tailored specifically to Tsunami wave properties in order to gain a better understanding of Tsunami force effects on structures. CFD code, when calibrated to results of such fundamental experimental studies, can then be used with confidence to investigate Tsunami wave force effects on specific building geometries and building clusters, not so easily able to be treated experimentally.

3. CFD APPLICATIONS TO FLUID-STRUCTURE INTERACTION

LS-DYNA has been utilised in this research to study Tsunami wave propagation and wave structure interaction. LS-DYNA is an explicit numerical analysis code, sometimes referred to as "hydrocode", where the equations of mass, momentum and energy conservation coupled with materials descriptions are solved in the time domain. In LS-DYNA, the Lagrange technique, in which the grid distorts with the material, is typically used for modelling solid continua and structures. This technique has the advantage of being computationally efficient and gives good definition of material interfaces. The Euler technique, also available in this package, instead, uses a fixed grid through which material flows. It is computationally more expensive but is often better suited to modelling larger deformations and fluid flow such as water wave propagation.

In addition, LS-DYNA includes an ALE (Arbitrary Lagrange Euler) technique. In this technique, there are two separate grids, one is the background grid which can move arbitrarily in space and the other grid, which is attached to the material, can distort with the material, (see Figure 3). The principal difference between the ALT technique and the Euler technique is the moving background grid. This ALE technique allows the interaction between the Lagrangian grid and the moving background grid which can be used to model fluid-structure interaction.

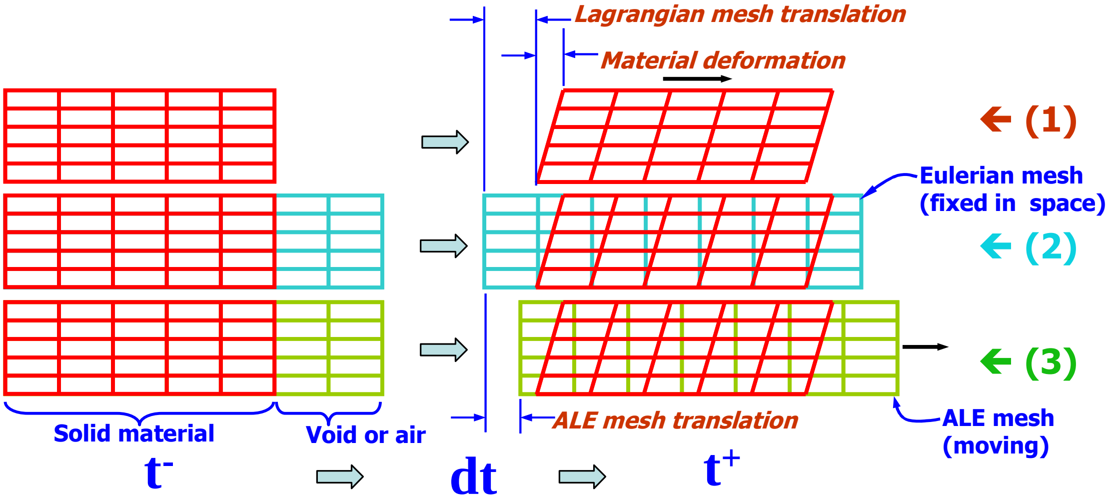

Figure 3 Description of Arbitrary Lagrange Euler (ALE) technique used in LS-DYNA

3.1 Tsunami Wave Modelling

LS-DYNA is capable of modelling water wave propagation and wave-structure interaction. The water bore and air are modelled separately using ALE multi-material options and an Eulerian mesh which enables water to expand into the surrounding environment (air or soil) without causing a distortion of the finite element meshes.

4. CFD STUDIES OF WALL FORCES DUE TO A BORE

4.1 Tsunami Runup Model

A Tsunami wave runup model consisting of bore flow of 40m/s over a sloped soil (see Figure 4) was adopted in this study. This problem is treated as a 2-Dimensional plane strain field, with the fluid region modelled as one layer (totalling 60,000) of solid elements through the depth. Water is modelled using properties as follows; density = 1 tonne/m^3, cut-off pressure = -1.0 x 1020 MPa, viscosity = 1.0 x 10-9 Nmm/s and bulk modulus = 2,300 MPa. The model allowed study of the movement and stability characteristics of a Tsunami wave as it progressed up slopes of different angles.

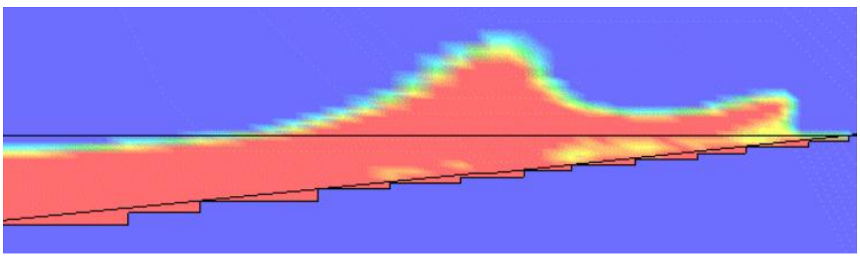

Figure 4 Tsunami wave runup on a shore line

4.2 Tsunami Runup on a Rigid Wall and Tsunami Force

Here we model a Tsunami as a bore of 5m depth moving with an initial velocity of 10m/s on horizontal ground and striking up against a rigid wall (see Figure 5). It is clear that the maximum runup approaches 3 times the Tsunami depth, (the "design" value recommended for wave surges in § 2.2 at t ~ 3s).

Figure 6 shows the resultant force trace (per meter width) acting on the wall from this Tsunami. Notice the sequence of leading "spikes" which are indicative of a "slamming" effect when the bore makes initial contact on the wall (t ~1.1 s) leading to short duration peak forces ~3 times those at the peak in the post-slamming region. The "tail" portion describes runup effects post-slamming, peaking at t ~5 s and a value of ~1.45MN/m or ~12 times hydrostatic, which value is marginally higher than for the peak force (~11 times hydrostatic) recommended in design of walls for turbulent bores in § 2.2.1.

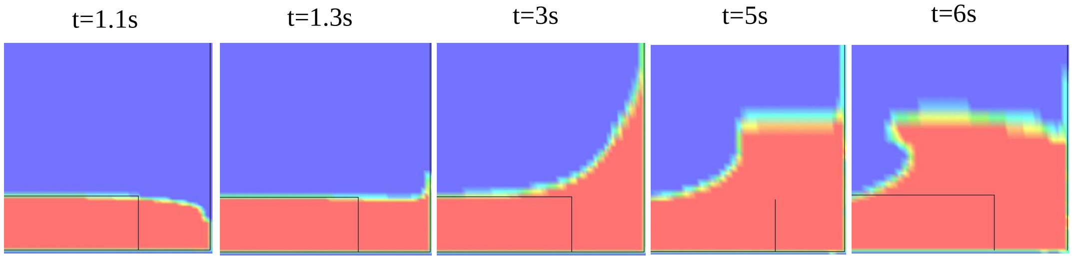

Figure 5 Tsunami wave runup on a rigid wall

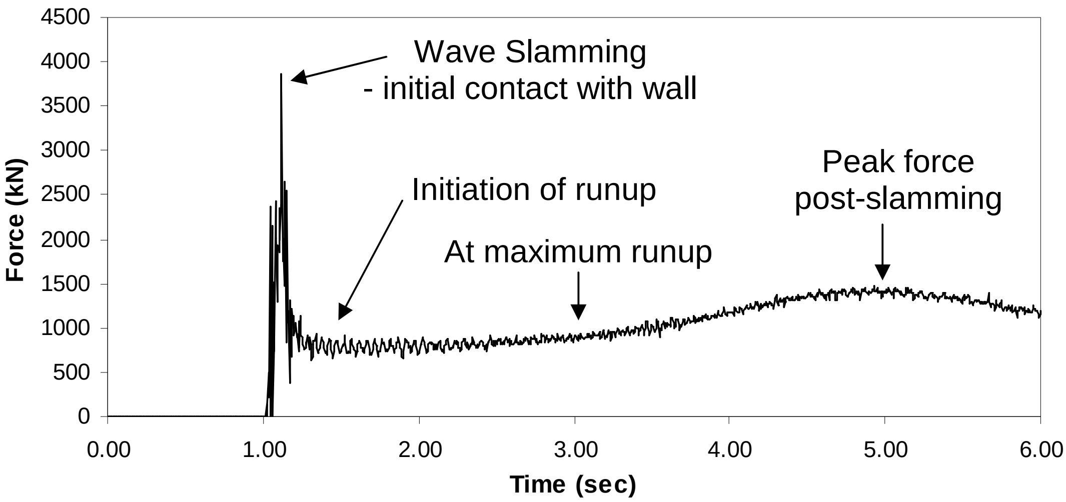

Figure 6 Tsunami force on a rigid wall

4.3 Tsunami Wave-Structure Interaction

Here we consider a Tsunami impacting on the 3 storey concrete frame shown in Figure 7. The number of solid elements in the fluid region is 80,000. Water properties are as described in § 4.1. The height of the water bore is 6m and has an initial velocity of 12m/s. The figure shows that we are able to follow the fracture of the leading ground-storey column and the ingress of the Tsunami into the frame space, post this fracture, using LS-DYNA modelling – indicative of the power of this modelling approach.

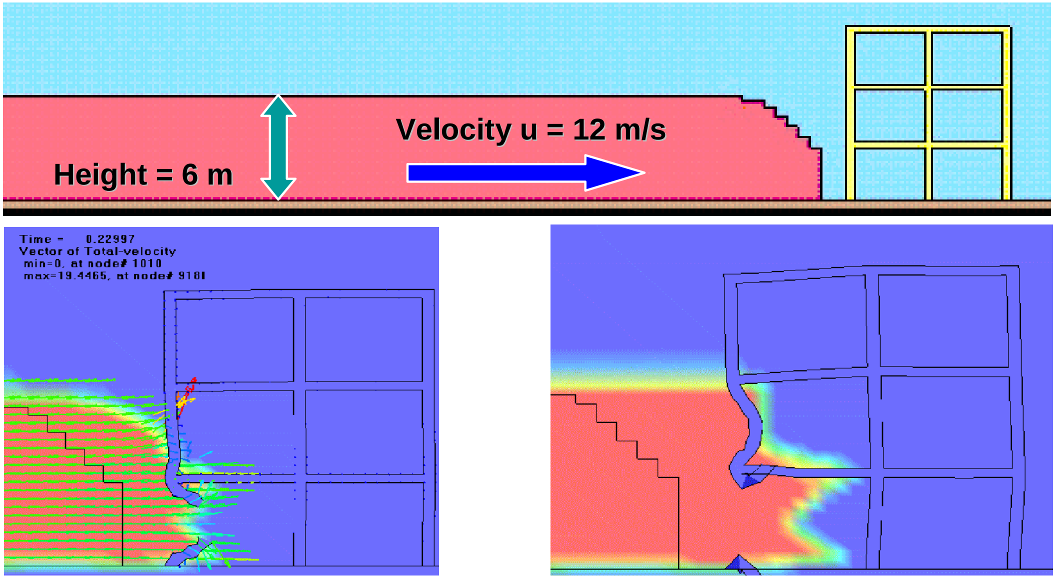

Figure 7 Structural damage due to a Tsunami wave

5. CONCLUDING REMARKS

An overview has been presented of current design approaches for coastal wave interaction with walls, concentrating on Tsunami bores. Recommendations by the Building Research Institute of Japan, and separately by the U.S. Army Corps of Engineers, suggest wave runup from such bores to reach 3 times the bore depth and the design wave force to be of the order 9 – 11 times the hydrostatic pressure force at bore depth, depending upon turbulence conditions of the surge. Preliminary studies using CFD modeling via LS-DYNA have demonstrated the power of these modelling approaches to deal with a variety of aspects of study of Tsunami bore surges and their effects on structures. Studies on Tsunami bores on walls largely confirm the design approach values, but also highlight the presence of a short duration wave slamming force much higher than peak runup values. The need for performing additional studies with verification from physical experiments is seen to be obvious from this work.

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