International Symposium Disaster Reduction on Coasts
Scientific-Sustainable-Holistic-Accessible
14 – 16 November 2005 Monash University, Melbourne, Australia

STRUCTURAL DESIGN LOADS FOR TSUNAMI & FLOODS

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ABSTRACT: This paper collates and presents relevant information available in the literature and proposes a simple methodology to derive loads for the design of building structures which are exposed to the forces of tsunamis and storm floods in coastal areas of the Indian Ocean. The paper is primarily directed to those generated by tsunamis due to the substantial magnitudes involved. Load path of a tsunami is traced through the phases of source, energy input to water, ocean wave and wave approaching shore, dry-land run-up, design zones and load. Part of the energy generated, for example from a tsunami earthquake, transforms into wave energy. This energy is transmitted from fast moving small amplitude deep-ocean waves to slower but taller waves approaching the shore. On shore these waves usually run as bores without breaking, generating substantial forces on the objects they come in contact with. Inundation depths and load zones are determined using generation, propagation and run-up models available in the literature. Inundation depths are converted to pressures and loads using an appropriate hydraulic model. Following examination and parametric study of some such models, a rational and simple model is proposed for hydraulic pressures on walls and piles/columns of a structure. Zoning of coasts is suggested based on the vulnerability and exposure. Scour depths of footings are also discussed here.

1. INTRODUCTION

The recent Indian Ocean tsunami and its devastating effects have raised questions as to what could be done to prevent or minimize such a level of loss in the future. Storm generated floods are also a common problem in the area. This submission forms part of an effort towards developing a 'Disaster Reduction Guide (DRG)' to achieve risk reduction due to such natural hazards.

The purpose of this paper is to collate and present relevant information available in the literature and propose a simple methodology for the design of building structures in coastal areas of the Indian Ocean. Building safety could be achieved either by policy or design. Policy covers areas of strategy, planning, warning and other related measures. These are not discussed here.

This paper focuses on the physical design of building structure to withstand loads generated by tsunamis and similar actions of nature. This is addressed in two parts: (1) Loads and (2) Structural Form & Materials. Part 1 of the paper presented in this symposium deals with the loads and their nature, and is primarily directed to those generated by tsunamis due to the substantial magnitudes involved.

Path of a load induced by a tsunami could be traced through the following phases: Source, Energy input to water, Ocean wave, Wave approaching shore, Dry-land run-up, Design zones and Loads. Each of these stages will be discussed below.

Part of the energy generated, for example from a tsunami earthquake, transforms into wave energy. This energy is transmitted from fast moving small amplitude deep-ocean waves to slower but taller waves approaching the shore. On shore these waves usually run as bores without breaking, generating substantial forces on the objects they come in contact with.

Inundation depths and load zones are determined using generation, propagation and run-up models available in the literature. Inundation depths are converted to pressures and loads using an appropriate hydraulic model. Following examination and parametric study of some such models, a rational and simple model is proposed for hydraulic pressures on walls and piles/columns of a structure.

Zoning of coasts is suggested based on the vulnerability and exposure. Scour depths of footings are also discussed in this paper.

2. SOURCE

Tsunami earthquakes are the source of majority of tsunamis (about 90%), but submarine landslides (i.e. sub-sea ground movement) and pyroclastic (volcanic) flows also have created high intensity tsunamis. This paper pays direct attention to the former since the latter phenomenon is rare and such localized very high magnitude events are addressed at a policy level (example: Krakatoa).

Tsunami generating earthquakes are identified by the moment magnitude (M_W) scale and the earthquake energy (E_S) in generating a tsunami. Tsunami is usually measured as tsunami magnitude (M_t) or tsunami intensity (I_t). Energy trapped in a tsunami close to the source (Et) is found to be dependent on the earthquake moment magnitude (M_W), amount of crustal settlement (b in cm) at source etc.

Horikawa & Shuto[1] studied extent of coastal damage and the recurrence period of disastrous tsunamis for given tsunami magnitudes and intensities for Japan and the Pacific rim area using methods proposed by Iida and Soloviev. Insufficient availability of data and lack of established study in the Indian Ocean rim makes an attempt to correlate severity of or loads generated by a given tsunami magnitude extremely difficult.

It appears more pragmatic and simpler to relate energy to major ($M_W = 9$) and a minor ($M_W = 7.5$) tsunami earthquakes. Such major or minor energy in turn is converted to loads using empirical relationships available in the literature.

Murty[2] lists the following relationships due to Iida and to Takahashi as:

$$M_t = (2.61 \pm 0.22)M_W - (18.44 \pm 0.52) \quad (1)$$

$$\text{Log } E_t = 10.3 + 1.5M_W \text{ and } E_t \approx E_S/10 \quad (2)$$

3. PROPOGATION AND OCEAN WAVE

Part of the energy from the source is transferred to water in its vicinity to create waves. Murty lists the works of Kranzer-Keller, Le-Mahaute, Lamb and others on wave propagation due to potential energy change and impulse excitation. Several other numerical models are available in the literature. Generation models for submarine landslides (Pelinovsky) and pyroclastic flows (Monaghan) are also available.

Outside its transfer zone and in the ocean the tsunami appears as a small amplitude oscillatory long wave rapidly traveling towards the shore. Mader[3] found the following characteristics for typical tsunamis in the ocean: amplitude = 0.5m to 1m, period = 10min to 30min & wave length = 200km to 600km

The wave in the ocean approximately satisfies linear Airy wave theory with celerity ('c' in 'm/s') and wave length ('L' in 'm') at depth ('d' in 'm') for d<<L is given by (where g = gravity = 9.81 m/s^2):

$$c = [(gL/2\pi) \tanh(2d/L)\pi]^{1/2} \approx (gd)^{1/2} \quad (3)$$

Wave energy/ wave length is (H = wave height from trough to crest in 'm' & ρ = density of water in 'kg/m^3':

$$E_t = \rho g H^2 L/8 \quad (4)$$

4. NEAR-COASTAL WAVES AND RUN-UP

As the wave approaches the coast the amplitude increases and the wave length decreases. The wave undergoes transformation due to shoaling on a sloping bed near the shore. Smaller waves called fore-runners arrive first before the tsunami. Withdrawal of water at coast may be observed if a trough reaches first.

Tsunamis also amass several magnification effects. Edge waves can form along the beach increasing the amplitude. Bays could be subject to resonance. Local effects around islands and cliffs can be also profound. These effects are not addressed in this paper in any detail.

Most researchers have observed tsunami as a solitary wave or a bore offshore and a bore/solition onshore. Relevant hydro-dynamic characteristics found in the literature relating to these phases of the tsunami are included in this section.

Substantial energy is lost as the tsunami reaches the shore refraction, shoaling, bottom friction, coriolis effect etc. Murty reports that up to 90% loss of energy could be expected for far-field tsunamis. Assuming the tsunami energy reaching the shore (E_{ts}) is dependent upon the energy received at the source 'E_t' in 'ergs' and the distance from the shore under consideration 'R' in 'km', an empirical relationship can be proposed as:

$$E_{ts} \approx \alpha E_t \tag{5}$$

where $\alpha = [E_t/(R+100)]^{1/2}/15000$

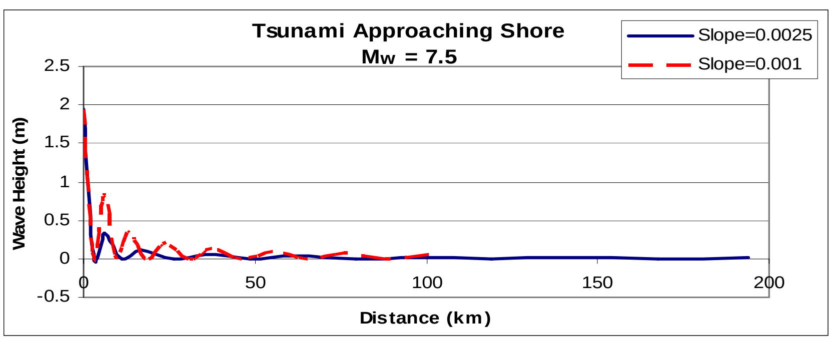
Energy per wave length in a solitary wave is given by Muir Wood[4]:

$$E_{ts} = 8\rho g(Hd/3)^{3/2} \tag{6}$$

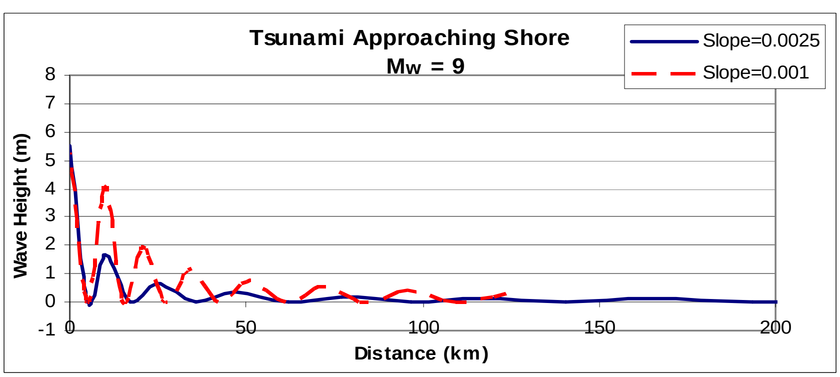
Mader gives the wave celerity of the solitary wave approaching shore as:

$$c = (gd)^{1/2}.[1+(H/2d)-0.15(H/d)^2] \tag{7}$$

With the aid of equations 2, 5 to 7 path of a tsunami approaching the coast could be traced. Tsunamis resulting from 2 different types of earthquakes on 2 bed-slopes are presented in Figure-1, which show reducing wavelengths and increasing amplitudes as the tsunami approaches the shore. Amplitudes away from shore are larger with narrower wavelength for the tsunami on shallower bed slope, but the differences tend to cease at shore. Wave height at shore (H_s) become 2m & 5.8m using R=2000km (far-field) for minor and major tsunamis respectively. These figures become 3.2m & 8.7m when R=100km (near-field) is used.



(a) Far-field Minor Tsunami



(b) Far-field Major Tsunami

Figure-1: Amplification of Tsunami approaching shore

T = 900sec used for the above evaluation, which is within the typical range suggested by Mader. 'H_s' is independent of 'T'. Equation-4 could be used if needed to track the tsunami further back into the ocean.

Garcia & Houston[5] state wave height at shore 'H_s' as (x = distance of 'H' from shore & J = Jacobian). Results obtained using this equation is not far from that predicted by Figure-1.:

$$H_s = H/J0(2(kx)^{1/2}) \text{ with } k = (2\pi/T)^2 x_0/(gH) \quad (8)$$

Togashi & Iwasaki[6] carried out several experiments and analysis based on the method of characteristics to map bore run-ups and made the following conclusions:

Classical formula of Keller & Keller/Shuto (presented below in logarithmic scales) of run-up height (H_r) to incident wave height at shore (H_s) compared well, with the empirical correction proposed by Togashi in the lower range, is shown approximately on Figure-2.
'l' & 'L' denote length of bed slope and wave length (J = Jacobian & U = 4πl/L for shallow slopes of bed).

$$H_r/H_s = [J_0^2(U) + J_1^2(U)]^{1/2} \quad (9)$$

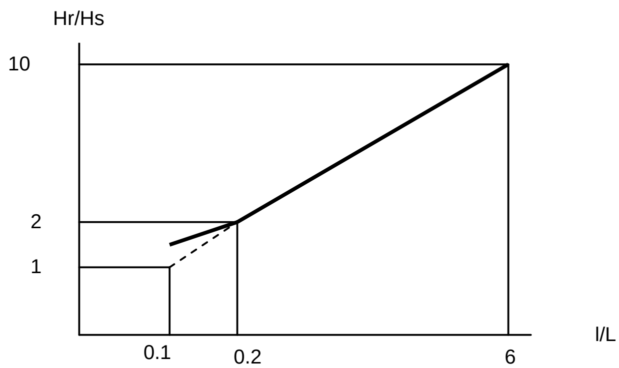


Figure-2: Relationship of Run-up/Shore Height to Bed-slope/Wave Length Ratios

Two types of run-ups were observed:
In the first type, wave breaks offshore due to shoaling transformation and runs as a disturbed progressive breaker noted in Figure-3a under the conditions of,

$$(g/d)^{1/2}.T/2 < 200 \ \& \ H/L < 0.001 \quad (10a)$$

In the second type, there is little shoaling and therefore no breaking. The front takes disturbed form of a transitory breaker or runs as undisturbed non-breaking partial claptois noted in Figure-3b under the conditions of,

$$(g/d)^{1/2}.T/2 > 200 \ \& \ H/L < 0.001 \quad (10b)$$

This mode is said to be observed by other researchers during the recent Indian Ocean tsunami. Tsunamis in Figure-1 fall in this category too. No definite quantifiable conclusion on the effect of bed slope was made.

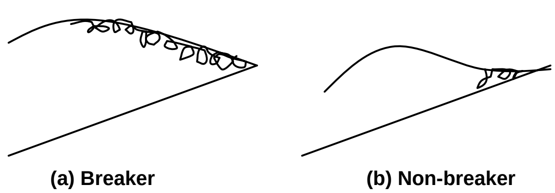


Figure-3: Typical Breaker and Non-breaker Run-ups

Chu & Abe[7] in their similar study found bores running close to shoreline with Froude Number of 2+ , confirming Togashi & Iwasaki's observations. However, their observation of 'H_r/H_s' to 'H_s/L' (similar to Figure-2) demonstrates much smaller run ups. A possible reason could be their consideration of backwash and use of smaller bore velocities.

Bryant[8] lists run-up as given by (a = 2.83 for solitary wave & 3.86 for N-wave. N-wave has a trough unlike the solitary wave):

$$H_r = a.(\cot\beta)^{1/2}.\ H_s^{1.25} \tag{11}$$

For $H_s = 0.5$m & $\tan\beta = 0.0025$, $H_r = 23.8$m. Typically theses results are higher than those given by others. Pelinovsky[9] gives a minimum value and Spielvogel[10] gives a maximum value for run-up of a tsunami at a wall. Pelinovsky also suggests that for a wave to break, the wave height needs to be large, about 3 times the inundation depth (h), and gives a range:

$$H_s < H_r < 5.4H_s \tag{12}$$

Abe[11] proposes maximum run-up at distance 'R' (km) from the epicenter of the tsunami earthquake:

$$H_r = \text{Max}(2H_{r1}, H_{r2}) \text{ where,} \tag{13.1}$$
$$\text{Log } H_{r1} = M_w - 8.8 \text{ (for far field tsunami)} \tag{13.2}$$
$$\text{Log } H_{r1} = M_w - \log R - 5.55 + C \text{ (for Japan)} \tag{13.3}$$
$$\text{Log } H_{r2} = 0.5M_w - 3.30 + C \text{ (for Japan)} \tag{13.4}$$

For $M_w = 9$ & 7.5 with R = 10km these equations give $H_r = 7.7$m & 2m and with R = 2000km, $H_r = 4.1$m & 2m respectively. C = 0.2 was assumed for all of the cases above.

5. ZONING AND INUNDATION DEPTH

From the above analysis and workings, two zones can be identified in terms of the severity of damage. Zone-A is classified as the 600m of beach-front for Indonesia/Andaman Islands and 300m for other countries of the Indian Ocean rim. Zone-B is classified as from the end of Zone-A to 1.2km from shore for Indonesia/Andaman Islands and to 800m for other countries.

'Beachfront' is defined as a hypothetical line of minimum 100m from the mean shoreline to generate a Manning's 'n' roughness of 0.03. Since the tsunami is a long wave, depending on which phase of the wave hits the shore, the transition zone is difficult to determine. Therefore the leading edge of the bore on land could be well beyond this limit.

Proximity to Source	Zone	Tsunami Size	Design Inundation Depth-h (m)	Type of Buildings Included in Design	Type of Buildings Excluded in Design
Near-field (Ex: Sumatra, Andaman Islands)	A	Major	10	Refuge Centres, Buildings of significance	Hospitals, Schools, Fire & other Emergency Services, Community Centres
		Minor	4	Residences, Tourist Resorts	-
	B	Major	4	Refuge Centres, Public Buildings, Hospitals, Schools, Fire and other Emergency Services, Community Centres.	-
		Minor	2.5	Residences (optional).	
Far-field (Ex: Sri Lanka, India)	A	Major	6.0	Refuge Centres, Public Buildings	Hospitals, Schools, Fire & other Emergency Services, Community Centres
		Minor	2.5	Residences, Tourist Resorts	-
	B	Major	2.5	Refuge Centres, Public Buildings, Hospitals, Schools, Fire and other Emergency Services, Community Centres.	-
		Minor	1.0 (optional)	-	-

Table-1: Design Inundation Depth & Use Guide

Bryant gives the maximum inland penetration ('x_i' in 'm') as:

$$x_i = (H_s)^{4/3}.n^{-2}.k \qquad (14)$$

where k = 0.06 & Manning's coefficient n = 0.015 for flat, 0.03 for building and 0.07 for tree lined landscapes. H_s = 6.6m & 10.5m, with n = 0.015 gives x_i = 825m & 1533m respectively.

Assuming the dry-land beach and adjacent area slopes are small, it could be seen that the inundation depth (h) is closely related to the run-up height (H_r), wave height at shore (H_s) and distance from shore (x). Equation-15c and Figure-4 should be referred for better demonstration of this relationship. Design inundation depth 'h' ≈ '1.2H_s' is adopted in zone-A. From the above workings and section-4, minimum inundation depths ('h' in m) with reference to the type of building use for each of the design zones are determined.

Refer Table-1 for the design guide as discussed above. The information presented is a basic guide only and should be verified before use These are minimum recommended depths and higher values should be used if available from an appropriate survey or past records from sources such as USGS[12].

Local magnification effects could be accounted by increasing the inundation depths and extents of zones given above by 50% where edge wave effects could be expected and by 100% in bays, harbors, river deltas, estuaries, lees of islands etc, in the absence of a more refined method or data.

6. LOAD MODELS

Various models predicting imposed hydraulic forces due to tsunami and similar activities are presented in this section. Their merits and suitability of use as design tools will be discussed later.

Muir Wood presents static & dynamic components of the loads offshore and onshore from the shore-line of a beach due to the impact of breaking wave. Although not directly applicable to tsunamis these expressions are included for comparison. Figure-4, which is reproduced from reference 4, demonstrates various parameters included in the formulation.

$$\text{Total pressure, } p = p_s + p_d \qquad (15a)$$

Offshore pressures at wave breaking (with $d_b = H_b$ and water particle velocity $u_b = c_b = (gd_b)^{1/2}$):

$$\text{Static pressure, } p_s = \rho g(d_b + 0.75H_b) = 1.75\rho g H_b \qquad (15b.1)$$
$$\text{Dynamic pressure, } p_d = \rho u_b^2 = \rho g d_b, = \rho g H_b \qquad (15b.2)$$

Onshore static & dynamic pressures at distance 'x' from the shore-line (at x = 0, inundation depth h = H_b and run up 'H_r' is given as '2H_b'):

$$p_s = 0.75\rho g H_b(1-x.\tan\beta/2H_b) = 0.75\rho g h \qquad (15c.1)$$
$$p_d = \rho g H_b(1- x^2.\tan^2\beta/4H_b^2) = \rho g h \qquad (15c.2)$$

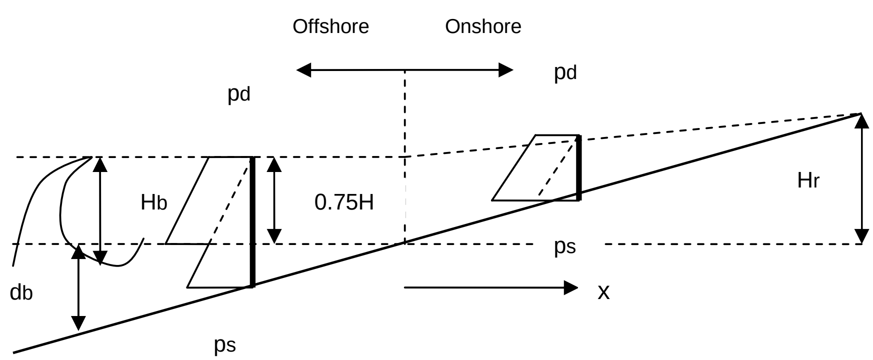


Figure-4: Offshore and Onshore Hydraulic Forces

CIRIA[13] gives coastal hydraulic pressures (uniform distribution- Morrison's Formula), which is intended for storm surges (C_d = 2 for square/straight objects; C_m = 2.5 for square,1.6 for straight & 2 for circular objects):

$$\text{Pressure due to drag, } p_d = ½.C_d\rho u^2 \quad (16.1)$$
$$\text{Pressure due to inertia, } p_m = C_m\rho(du/dt)h \quad (16.2)$$
$$\text{Total pressure, } p = p_d + p_m \quad (16.3)$$

Murty states tsunami bore velocity & pressure at inundation depth of 'h' (as per Fukui/Mattock), with $u = 1.83(gh)^{1/2}$ & $C_d = 1.2$ and $p = p_s + p_d$ is given by:

$$p_d = ½.\rho C_d.u^2 \text{(uniform distribution)} \quad (17.1)$$
$$p_s = \rho gh \text{ (triangular distribution)} \quad (17.2)$$

Kirkoz[14] suggests up-rush bore velocity of long waves using energy conversion:

$$u = (2gh)^{1/2} \quad (18)$$

Bryant gives tsunami bore velocity at inundation depth of 'h' as:

$$u = 2(gh)^{1/2} \text{ (without significant bed slope) or,} \quad (19.1)$$
$$u = H_s^{0.7}(\tan\beta)^{1/2}/n \text{ (also refer equation-15)} \quad (19.2)$$

Togashi states bore front velocity 'u' on dry bed of slope 'S' with friction 'f' at distance 'x' from the shoreline:

$$u = (u_s - Bx)^{1/2} \quad (20)$$

where u_s = velocity at the shoreline & $B = 2(S + f/a^2)/[(1+a)(1+2a)]$ with a = 1/2.
Since u = 0 when reaching maximum run up, $x = (H_r - H_s)/S$ at this point. For S = 0.0025, f = 0.01, H_r = 12m & H_s = 3m gives $u_s = (3.4gh)^{1/2}$ and for S = 0.001, f = 0.03, H_r = 6m & H_s = 2m gives $u_s = (16.4gh)^{1/2}$. At x = 10m from shore these velocities reduce to $(0.34gh)^{1/2}$ and $(0.88gh)^{1/2}$ respectively.

Nakamura[15] found shock (impulsive) pressure against a wall ($C_t \approx 3.0$ & 1.8 for incident wave angle wedges of 45degree & 22.5degree respectively) as:

$$p_t = ½.C_t\rho u^2 \quad (21)$$

Federal Emergency and Management Agency or FEMA[16] developed guidance on the design and construction of buildings in the coasts of USA that is potentially exposed to tsunamis and floods. The document provides good information on the types of loads, bore velocity, load combinations etc. Pressure distributions are generally as shown in Figure-4. The various parameters are outlined as following:

$$\text{Velocity, } u = h/t \text{ (lower limit), } (gh)^{1/2} \text{ (upper limit) \& } 2(gh)^{1/2} \text{ (extreme- tsunami)} \quad (22a)$$

$$\text{Static pressure, } p_s = \rho gh \quad (22b.1)$$
$$\text{Dynamic (drag) pressure, } p_d = ½.C_d.\rho.u^2 \quad (22b.2)$$

(triangular/uniform distribution for u < or > 3m/s respectively; C_d = 2 for rectangular & 1.2 for circular section)

$$\text{Pressure due to wave breaking, } p_b = C_b\rho gh \text{ for pile \& } p_b = (1.1C_p+i)\rho gh \text{ for walls} \quad (22b.3)$$

(uniform pressure distribution; C_b= 2.25 for rectangular and 1.75 for circular sections; i = 2.41 & 1.91 for water on one-side & both-sides; C_p = 2.8 for residences and 3.2 for critical facilities)

$$\text{Force due to impact of a floating object, } F_i = m_a.u_a/t \quad (22b.4)$$

(m_a = mass (450kg) & u_a = velocity of the object and t = 1, 0.5 & 0.1 sec for wood, steel & concrete objects)

Load combination to establish appropriate design actions are;

For piles: (1) p_b on all + F_i on a critical pile, or (2) p_b on front row + p_d on others + F_i on a critical pile (22c.1)
For walls: (1) $p_b + p_d$, for coastal buildings, and (2) $p_s + p_d$, for inland buildings (22c.2)

Structural Design Method of Buildings for Tsunami Resistance or SDMBTR[17] developed in Japan presents simple expressions to determine loads. Pressure distribution due to tsunami is based on the model proposed by Asakura for the case of solition without break-up. The proposed distribution consists of various hydraulic components stated in the FEMA document and elsewhere above.

Base pressure against a wall as in Figure-5a with triangular distribution is given by (where pressure on the front & rear walls are 'p' and sides are '0.5p'):

$$p = 3\rho gh \qquad (23a.1)$$

Base pressure at an elevated wall as in Figure-5b is,

$$p = 3\rho g(hh')^{1/2} \qquad (23a.2)$$

Other supplementary models are also included in this guide as below:
Base pressure distribution due to solition break-up as per Asakura is shown in Figure-6,

$$p = 3\rho gh + 2.4\rho gh \qquad (23b)$$

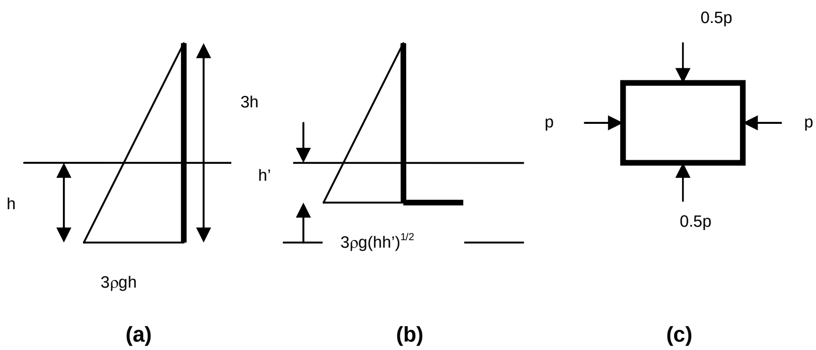


Figure-5: SMBTR Pressure Distribution

Total pressure made up of various components (similar to CIRIA) listed by Ohmori (quoted in SMBTR) is given as (uniformly distributed and ignoring effect of hydraulic gradient):

Pressure due to drag, $p_d = \frac{1}{2}.C_d\rho u^2$; $C_d = 2.05$ (23c.1)

Pressure due to inertia, $p_m = C_m\rho(du/dt)h$; $C_m = 2.19$ (23c.2)

Pressure due to impulse (shock), $p_t = \frac{1}{2}.C_t\rho u^2$; $C_t = 3.6.\tan\beta$, where β = incident angle (23c.3)

Total pressure, $p = p_d + p_m + p_t$ (23c.4)

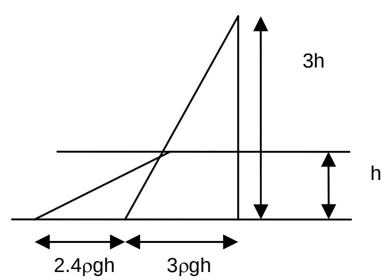


Figure-6: Asakura's Model showing Solition break-up

Scour depths of soil (d_s) near footings at inundation depth (h) are given in the FEMA document. 'w' is the pile/footing dimension:

Scour depth $d_s = 2w$ for piles (24.1)

$d_s = h\{2.2(w/h)^{0.65}[u/(gh)^{1/2}]^{0.43}\}K$ for strip footings

$= (4wh^{1/2})^{0.65}$ for $K = 2.2$ & $u = (gh)^{1/2}$ (24.2)

Lastly, uplift effects on the buildings are to be considered. Ignoring hydrodynamic uplift, this could be assumed to be primarily due to buoyancy (ρ = density of tsunami water & V = volume of submerged structure):

$$\text{Uplift } U = 1.2\rho gV \qquad (25)$$

7. CONCLUDING REMARKS

Coastal zoning and respective inundation depths were demonstrated and elaborated in section-5. These are the basic inputs to deriving loads from the methods discussed in the last section.

As seen from section-6 above, there is not much agreement between the various methods listed above as to the hydraulic pressure components, design velocity or pressure coefficients adopted. Also a breaking or non-breaking wave could make further difference.

Figure-7 shows bore velocity distribution with inundation depth for the various types nominated in the previous section. Limited field data available suggests a value close to $(2gh)^{1/2}$ could be expected within an acceptable level of confidence in zone-A. Equation 20 and other publications indicate a rapid decay of the peak velocity. Velocity is not likely to exceed $(gh)^{1/2}$ in zone-B.

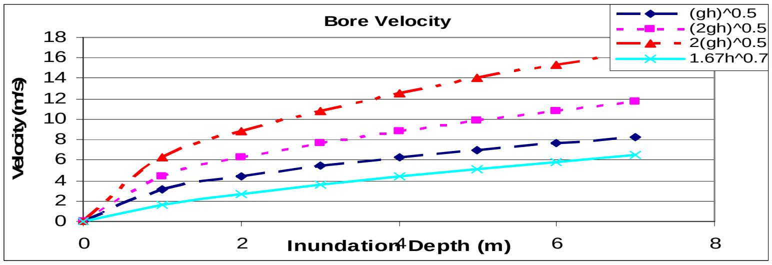


Figure-7: Bore Velocity Distribution

Figure-8 presents the loads calculated by SDMBTR and listed as Asakura-1 as in equation 23a for a wall which is a minimum of '3h' high. Also included are effect of solition break-up as Asakura-2 and the proposal of Ohmori following equations 23b and 23c. It is clear that all results are well in agreement with the other methods displayed in the diagram and that this simple proposal adequately describes the tsunami loads. For walls shorter than '3h', the model recommends curtailing the pressure distribution above the wall. This means SDMBTR may be giving lower loads for shorter walls. Pressure distribution to '3h' high run-up against walls on dry-land is likely to be too high. Also triangular distribution adopted is also questionable

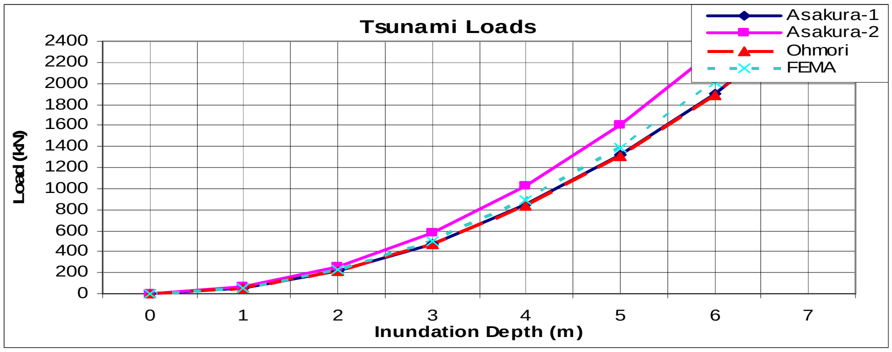


Figure-8: Tsunami Load on Wall

It was also seen that the hydrodynamic loads induced by a tsunami consists of inertial, dynamic/drag & impulse/shock in Ohmori's model and dynamic/drag & wave breaking (including static) in the FEMA model. A comparison with other models indicates that impulse/shock or wave breaking could account to about 50% or more of the loading. As discussed in section-4, that most bores run inland without breaking. Therefore it is likely that these models may over-estimate the on-shore tsunami loads in zone-B. Ohmori's model does not directly specify pressure distribution above the inundation depth.

With the characteristics discussed above a new model is suggested as shown in Figure-9. Pressure distribution in this model consists of static, dynamic/drag and impulse/shock components. The static pressure is triangular distribution with a base of 'ρgh'. Dynamic/drag is uniform '1.25ρgh' acting on the height 'h', assuming a velocity $u = (1.67gh)^{1/2}$ and drag coefficient Cd = 1.5. Impulse/shock pressure is obtained using equation 23c.3

with β = 30 degrees (also compare equation 21). This is approximately '1.75ρgh' at the surface, decreasing to '0.75ρgh' at the base and zero at 'h_w=h' above the hydraulic surface.

The total pressure becomes constant '3ρgh' within the inundation depth 'h' and decreases to zero 'h' above the surface. Although the suggested pressure distribution is somewhat different the model gives the same force 'F_i' as the SMBTR (Asakura-1) and Ohmori as presented in Figure-8. These pressures are applicable if the design exposed surface area is greater than $24m^2$ and double these values should be used for localized pressures on elements of area less than $6m^2$. Linear interpolation is applicable for intermediate values. Plan showing pressure distribution around the perimeter of a typical rectangular building is shown in Figure-10 below. Loads are to be calculated as the summation of pressures directly against the exposed wall area.

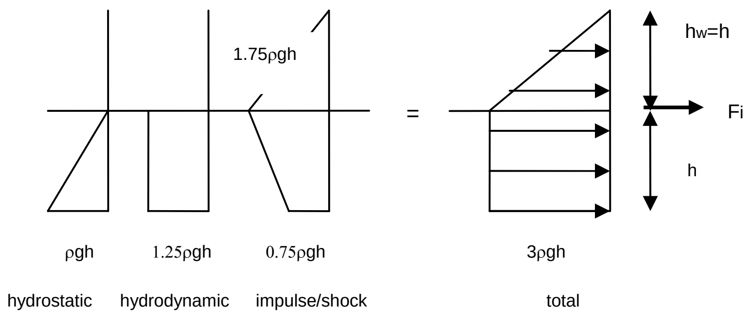


Figure-9: Proposed Hydraulic Pressure Distribution

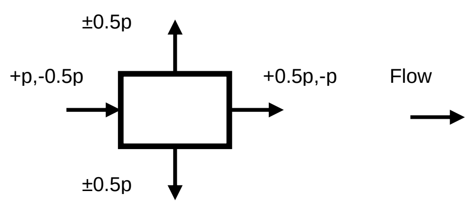


Figure-10: Hydraulic Loads on an Idealized Building

Piles could be designed for a uniform pressure distribution of '3ρgh' for square sections and '2ρgh' for circular sections. Also piles which could be directly exposed to impact from debris should be checked for half the above loads + impact load as given in equation-22b.1 to 22b.3 (FEMA). Assessment of the 450kg debris mass adopted The load is assumed to act at the surface level of the inundated water, and is $F_i = m_a u_a/t$, as given in eq-22b.4. Debris velocity u_a = 2/3 of 'u' could be assumed.

Velocity $u = (gh)^{1/2}$ and coefficient Cd = 2 are more likely to be appropriate for zone-B tsunami and general floods at a given depth 'h' as discussed in the FEMA manual. This gives constant 'ρgh' dynamic/drag pressure within the inundated depth and impulse/shock pressure of approximately 'ρgh' at the surface, decreasing to zero at base and height 'h_w=h/2' above the surface. As a general rule 2/3 of the hydraulic loads and 1/2 the debris load calculated for a zone-A tsunami to a given inundation depth may be used for zone-B tsunami and flood loads in the absence of more refined methods or data.

Soil scour at footings are a serious cause of building failures as was seen in the recent Indian Ocean tsunami. Although the FEMA recommendation for piles is appropriate, the expression given for strip footings appear conservative, especially at smaller inundation depths. A new proposal is suggested for zone-A tsunami as below.

Footing depth $d_s = (wh+1)^{0.65}$ is suggested to a length of 'd_s' from the corners of the buildings and is illustrated in Figure-11 for a footing width w = 0.6m. Depth of '0.6d_s' could be adopted in between the above corner areas. Minimum 'd_s' of 1m should be adopted throughout. In sandy soils footing derived depths should be increased by 50%. 2/3 of zone-A tsunami design scour depth could be used for zone-B tsunami and floods.

Reduced footing sliding resistance due to buoyancy as discussed in the last section also needs to be considered. Added with scouring, reduced sliding resistance could produce the worst mechanism of structural failure of buildings in most cases. Consideration of this would govern the type of footings (spread footings, piles etc).

The above factors are vital in the selection of appropriate structural framing, construction materials and stability system (brace wall, portal etc) for the building and the extent of sacrificial walls etc to resist the design hydraulic forces. The loads discussed are ultimate limit state by definition. Dynamic criteria of the selected system, other than that treated before, are beyond the scope of this paper.

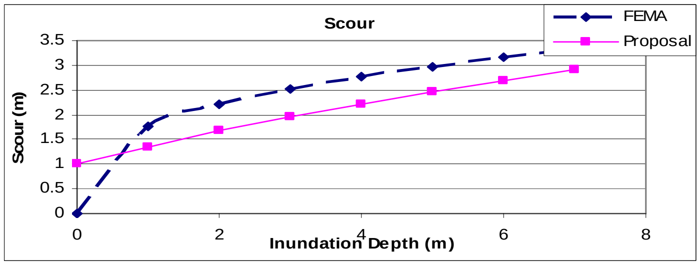


Figure-11: Footing Scour Depths for Zone-A Tsunami (w=0.6m)

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