7. Evaluating Tsunami Impact Metrics

Tsunamis can generate large onshore currents that can cause dramatic damage to structures and move large objects far inland. The 26 December 2004 Indian Ocean megatsunami demonstrated tsunami impact on structures in a rather dramatic fashion. Historic examples of large tsunamis setting large objects in motion abound. The most notorious is the myth of the USN *Watery*, the ship moved by the 1868, Arica, Chile tsunami 2 miles inland and then moved back to shore during the 1877 Arica tsunami so that the ship could sail on. Actually, the ship was indeed transported inland, but the 1877 tsunami just moved it closer to the shoreline, where it still rests. During the 26 December 2004 megatsunami, at least two similar-size barges were moved inland in Banda Aceh and Lhok Nga in North Sumatra.

As a measure of what even a small tsunami can do, consider the 1994 Mindoro Philippines tsunami. In an area where the vertical inundation heights did not exceed 3 m (10 ft), the generated tsunamis floated a 6000 ton generating barge, broke its mooring lines, and carried it 1 mile inland down the Baruyan River. The impact of tsunamis on structures can be observed in detail in Discovery Channel's production "Tidal Wave" (1998). The estimation of impact forces and currents is still an art and far less understood than hydrodynamic evolution and inundation computations. In what follows, different methods and formulae in the literature are described, although none has been truly validated by comparisons with field data.

In terms of assessing FIRM V-zones (zones identifying velocities exceeding certain thresholds or areas of 100-year coastal floods), in addition to inundation zones, it is useful to evaluate different combinations of flow parameters. We name them impact metrics or damage indicators, in an effort to determine a single hazard zone that helps identify areas where structural safety needs to be considered in greater detail. For example, existing formulations recommended in FEMA's Coastal Construction Manual rely on riverine flooding results, and the flow velocity and forces inferred through largely empirical relationships involving only the flow depth. Tsunami flow patterns can be counterintuitive even for fairly simple topographies of a plane beach as in Banda Aceh. During the 2004 megatsunami, particle image velocimeter techniques helped identify flow velocities 3 km inland, which suggest that the larger the depth the larger the velocity. Further, the topography of Seaside is quite unique, particularly because of the presence of the sand-spit within the broader Seaside bay, which is fronted by another sandspit. The setting is as different from the canonical geometry of a one-dimensional wave climbing up a sloping beach, described by Synolakis (1987), as one can be. As shown recently by Carrier *et al.* (2003), even for the simple geometry of the canonical problem, the highest velocity does not occur at the same location as the highest inundation depth, and the location of the region of highest velocity depends on the incoming wave, hence on the particular scenario under study.

We will describe here existing formulations to calculate forces on structures to help motivate our choices of combinations of flow parameters, acceleration, velocity, depth, amplitude, and front velocity that may be relevant in tsunami V-zone assessment. Not unexpectedly, perhaps, the momentum flux parameter appears to be the most useful for engineering applications in identifying regions where the flow forces may possibly be larger than otherwise anticipated from existing formulations. The present inundation results for Seaside for specific far-field and near-field inundation events as discussed in this report have guided this choice of the boundaries of the V-impact zone.

7.1 Forces on Structures

In principle, the calculation of wave forces on structures involves the integration of the pressure and of the shear force over the exposed area of the structure during the wave motion. To understand the development of the damage metrics, we consider first the simplest possible geometry, which involves the calculation of the instantaneous wave force at time t on a cylindrical pile of radius R, *in the direction of the wave propagation.* Given a pressure $p(R,\theta,z,t)$ and a tangential shear stress $\tau_{r\theta}(R,\theta,z,t)$, then the force is given by

$$F_T(t) = \int_0^{\eta_p+h_p}\int_0^{2\pi} p(\theta,z,t)R\cos\theta\, d\theta\, dz + \int_0^{\eta_p+h_p}\int_0^{2\pi} \tau_{r\theta}(\theta,z,t)R\sin\theta\, d\theta\, dz. \tag{7.1}$$

Here, η_p and h_p are the local amplitude and undisturbed water depth at the pile, respectively, with the assumption that they do not vary significantly over the pile diameter, hence their dependence on the radius R is not shown in the arguments. Tsunamis are long waves, and indeed the flow parameters do not vary significantly over small distances, such as those typically encountered in coastal structures.

In practice, for all but the simplest steady flows, determining either the pressure or the tangential shear stresses through calculation of the velocity gradients is impossible at this state of knowledge, as it involves solution of the Navier-Stokes equation. Shallow-water wave (SW) equations used in inundation mapping are depth-averaged approximations of the Navier-Stokes equations for inviscid flow, and there are no velocity gradients perpendicular to the axis of the pile, that is, there is no depth variation. The classic simplification is to consider a mass coefficient C_M that incorporates some of the dynamic pressure effects, and a drag coefficient C_D which in turn accounts for the form drag that results from flow separation and incorporates all the effects of the viscous forces on the cylinder. In terms of these coefficients, the force on a cylinder is given by

$$\vec{F}_T(t) = \int_0^{\eta_p+h_p} \pi C_M \rho R^2 \frac{d\vec{V}}{dt} dz + \int_0^{\eta_p+h_p} C_D \rho R \vec{V}\left|\vec{V}\right| dz. \tag{7.2}$$

Here $\vec{V}$ is the instantaneous horizontal velocity *in the direction of wave motion*, while $d\vec{V}/dt$ is the instantaneous water particle acceleration. Clearly $\vec{F}$ is a vector in the same direction as the velocity vector $\vec{V}$, hence, again the force given by (7.2) is in the direction of wave propagation. The absolute value is used to underscore that the force may change direction as the water particle velocity changes direction. For example, $\vec{V} = u\vec{i} + v\vec{j}$ and $V = |\vec{V}| = \sqrt{u^2 + v^2}$ with u, v the horizontal particle velocities in x, y. If the flow is primarily one-dimensional and onshore, $\vec{V} = u\vec{i}$, and u is positive under the crest and negative below the crest, if x is pointing toward the pile. Dean and Harleman (1966) note that the expression (7.2) for the drag force was determined empirically for steady flows, yet for lack of better knowledge, the same formulation is used for strongly unsteady flows such as the impact of bores and surges. In these cases, the coefficients C_D and C_M have to be carefully evaluated. The variation of C_D with the Reynolds number $Re = uD/v$ is shown in Fig. 8.2, page 344, in Ippen (1966). In the range of $10^3 < Re < 5 \times 10^5$, then $C_D \sim 1$. We note that C_D does depend on the roughness of the cylinder, although for tsunamis a usual assumption is that the pile is hydrodynamically smooth, given the wavelength of the tsunami wave train.

There are a few cases where (7.2) can be used directly to calculate tsunami forces. As an example, consider small amplitude wave theory. This theory is irrotational, requiring that the curl of the velocity vector is zero vector ($\nabla \times \vec{V} = \vec{0}$), an assumption which is not correct when waves are breaking. Shallow water wave theory (SW) is also irrotational, with no vertical velocity gradients perpendicular to the direction of wave propagation. However, shallow water wave theory is valid for larger amplitudes, for $L/h_p \gg 1$, while small amplitude theory applies when $a/h_p \ll 1$. Assuming that the pile is located at $x = 0$, and assuming a wavenumber $k = 2\pi/L$ and celerity $\sigma/k = \sqrt{gh_p}$, then

$$F_T(t) = -\rho g \left(\pi R^2 akh_p\right) C_M a \sin(\sigma t) + \rho g C_D a^2 R \cos(\sigma t) |\cos(\sigma t)|, \qquad (7.3)$$

with the understanding that (7.3) is valid for small-amplitude long waves. Dean and Harleman (1966) note that the inertial force is inversely proportional to the period, while the drag force is independent of the period. Equation (7.3) might be an adequate approximation for calculating forces on piles offshore for tsunamis generated by far-field earthquakes or by landslides, that is, for tsunami wave trains with more than one wave. For tsunamis generated in the near-field, where there is not sufficient distance for a wavetrain to fully emerge, then these equations can only be used with caution.

The total moment is formally calculated from $M_T(t) = \int_0^{\eta_p + h_p} zF_T(t)dz$, that is, it is the first moment of the force from the ocean floor to the free surface. To the same level of approximation as (7.3), then

$$M_T(t) = \tfrac{1}{2}\rho g C_D R a^2 h_p \cos(\sigma t) |\cos(\sigma t)| - \tfrac{1}{2}\rho g C_M \pi R^2 akh_p^2 \sin(\sigma t). \qquad (7.4)$$

Note that consistent to the SW approximation, the moment is equal to the force times a moment arm of $h_p/2$, given that SW implies that the force is uniform over the depth. Note also that the drag force does not depend on the period of the wave motion.

Impact forces on structures are calculated by different methods depending on whether or not the breaking wave forms a surge or a bore. On the vertical front face of a structure, they have been traditionally estimated using the classic formula of Cross (1967). He proposed that the force on a b wide seawall is given by

$$F_{\text{wall}}(t) = \frac{1}{2}\rho g b \eta^2 (x = X_w, t) + C_f(t)\rho b \eta (x = X_w, t) C^2 \tag{7.5}$$

where $\eta_w = \eta(x = X_w, t)$ is the water surface elevation on the wall located at some $x = X_w$, b is the width of the wall, C is the surge or bore velocity and $C_f = \left(1 + \tan^{1.2}\theta\right)$ is a computed force coefficient. $\tan\theta$ is the slope of the front face of the bore as it impacts the wall. For practical applications, Cross suggested calculating $\eta(x = X_w, t)$ as if the wall were not there, that is, the bore would pass through the wall relatively unchanged. In computational terms, this implies using a numerical code without the structure present, and then using the calculated values and applying them on the structure. This may well be a good assumption if there is sufficient distance between structures. Even if it is not a good assumption for a densely built town such as Seaside, the objective here is to identify a damage metric that captures the V-zone and not to calculate individual forces.

$C_f(t)$ could be a function of time, since the front slope of the wave may change as the wave evolves. Ramsden and Raichlen (1990) reformulated the same equation and integrated laboratory measurements to calculate values for C_f in terms of the bore strength H/h_p, the ratio of the bore height H to the local depth h_p, recognizing that the wave height at the front face of the structure might be difficult to calculate a priori.

Ramsden (1993) points out that when $b/H \sim 1$, then three-dimensional effects dominate and are believed to reduce the overall force. On the other hand, when $b \ll H$, that is, the width of the wall is smaller than the effective crest length of the wave, the force is thought to be primarily the drag force. When overtopping occurs, that is, the wall height is smaller than the expected runup R. The resulting forces might be significantly less. Since there are no established and validated formulas for overtopping, at least this theory provides a worst-case scenario for the forces on the wall.

The limitations of calculating tsunami forces and moments from (7.3) and (7.4) are obvious when the tsunami evolves over dry land, which is the region of interest for developing high-hazard zones. One then has to rely on (7.4) using results from shallow water wave theory, with the numerical predictions for the depth-averaged u and v, substituted directly into (7.2) with $V^2 = u^2 + v^2$.

Calculating the $x - y$ tsunami current distributions and magnitudes and their time variation is possible using numerical solutions of the SW equations and was done in this study. However, harbor resonances effects, breakwaters, and seawalls with characteristic sizes smaller than the grid spacing are transparent to the numerical computations. For example, a typical grid size Δx, $\Delta y \sim 100$ m (333 ft) will miss all coastal structures smaller than 100 m, unless the grid is positioned appropriately. This is not as simple as it appears, for numerical grids are calculated so as to model the hydrodynamic evolution correctly by attempting to maintain a constant number of grid points per wavelength as the wavelength changes.

Recently, Hughes (2004) revisited the radiation stress parameter S_{xx} perpendicular to the wave motion per unit wavelength as proposed by Longuet-Higgins and Stewart (1964),

$$S_{xx} = \tfrac{1}{L}\int_0^L \int_0^{h_p+\eta(x)} \left(p_d + \rho u^2\right) dz dx, \tag{7.6}$$

p_d is the dynamic pressure and u the horizontal particle velocity. The radiation stress is averaged over one wave period. For small amplitude wave theory and a periodic wave of the form $\eta(x,t) = a\sin(kx - \sigma t)$, then

$$S_{xx} = \tfrac{1}{2}\rho g a^2 \left(\frac{1}{2} + \frac{2kh_p}{\sinh 2kh_p}\right). \tag{7.7}$$

Hughes (2004) proposed the momentum flux parameter

$$M_t(x,t) = \int_0^{h_p+\eta(x)} \left(p_d + \rho u^2\right) dz, \tag{7.8}$$

as characterizing the flow kinematics better than other parameters. He noted that at the front surface of a perfectly reflecting seawall, M_t is the instantaneous dynamic force. Note that rewriting the momentum flux parameter $M_t(x,t)$ for SW waves, that is, if one performs the integration in (7.8), one obtains

$$M_t(x,t) = p_d\left(\eta_p + h_p\right) + \rho u^2\left(\eta_p + h_p\right). \tag{7.9}$$

Observing that the instantaneous dynamic pressure gradient in z reflects the instantaneous fluid acceleration in z, equation (7.9) is reminiscent of the force equation for the total force on a pile. Rewriting (7.3) for shallow water waves where both $\vec{V}$ and $d\vec{V}/dt$ are depth-independent, then

$$\vec{F}_T(t) = C_M \rho R^2 \frac{d\vec{V}}{dt}\left(\eta_p + h_p\right) + C_D \rho R \vec{V}\left|\vec{V}\right|\left(\eta_p + h_p\right). \tag{7.10}$$

All earlier results have been developed for steady state flows, and are usually applied to calculate forces on piles and coastal structures subject to storm waves. Tsunamis are transient waves. For the purpose of determining tsunami impact zones, and consistent with both (7.9) and (7.10), we conjecture that tsunami forces can be thought of as consisting of two parts, an inertial component (proportional to depth times acceleration) and another due to the dynamic effects of the moving flow (proportional to depth times velocity squared). Once the accelerations and current velocities are known, drag C_D and inertial mass C_M coefficients can be determined for the specific shapes of structures, depending on the zone boundaries. Damage metrics of use in planning and possibly zoning, must reflect the distribution of the force over the entire impacted area and identify areas of exceptional force. Therefore, the following parameters are of interest in assessing tsunami impact:

- the flow depth $h = \eta_p + h_p$,
- the current speed $V^2 = u^2 + v^2$,
- the acceleration $d\vec{V}/dt$,
- the inertial component $hd\vec{V}/dt$,
- and the momentum flux hV^2.

Since V-zones must reflect the hazards, we use the detailed inundation computations for both near-field and far-field scenario events that may impact Seaside to make detailed calculations of the four different damage metrics over the entire region, and compared their distributions. We note that while the tsunami evolves in the surf zone, the speed of the front decreases as the depth decreases. However, the flow is accelerating. In this case, the relevant velocity is the depth-averaged flow velocity. Once the tsunami hits the initial shoreline, the front suddenly accelerates. This phenomenon was explicit in many earlier investigations (Synolakis, 1987), but only recognized after Sumatra 2004. It appears to be one of the reasons why tsunami victims appear mesmerized into inaction, as they are seen in countless videos from the 2004 tsunami to watch the tsunami front approaching. They seem to expect that it will continue moving on dry land with a similar diminishing speed (Synolakis and Bernard, 2006). V-zones must reflect the largest velocity, i.e., the flow velocity offshore, and the velocity of the moving tsunami front on dry land.

While one might have expected that regions of large flow depths might correlate with regions of large velocities, this is not always the case. For example, as a tsunami evolves over dry land, the flow depth decreases up to the point of maximum runup, and the velocity of the shoreline tip becomes zero. Here, both h and V are small. During rundown, the flow depth remains small, but the current speed can be substantial, leading to higher hV^2 values in regions of the flow field that are unexpected, as suggested in a simple one-dimensional setting by Carrier *et al.* (2003). The acceleration $d\vec{V}/dt$ may diminish as the wave runs up, but may be substantial during rundown.

The distribution of the above four parameters for both near-field and far-field events for Seaside suggests that while individual differences exist among the different scenario events, the momentum flux represents the most suitable damage indicator. In contrast to what one might have expected based on 1-dimensional considerations for overland flow over a narrow spit of land, flow velocities appear to correlate well with inundation depths over the two sand spits in Seaside. Hence, the momentum flux shows a similar distribution as the inundation depths and currents. While small-scale differences exist, overall, the inertial component appears to have a similar geographical distribution as the momentum flux. We therefore recommend that the momentum flux be used as a determinant for the V-zone.

We note that our results are based on calculating the parameter V^2/gh, where h is the entire depth. During the calculation of tsunami propagation and inundation, this parameter was calculated every time step, allowing direct construction of a map of its distribution of maximum values to guide the V-zone. We recommend that all future inundation mapping studies monitor this parameter, in addition to archiving u, v, η for all times. We also recommend that, whenever possible, the moving front velocities be monitored and that the normalized momentum flux parameter V^2/gh be calculated using the front velocity. The higher of the two values, the one based on the flow velocity and the other based on the front velocity, should be employed in the maps. Maps of the V-zone can then be used to identify areas of higher risk, where a detailed analysis using time histories of u, v, η at the specific locations would be useful.