THE MODIFIED COASTAL STORM IMPULSE (COSI) PARAMETER AND QUANTIFICATION OF FRAGILITY CURVES FOR COASTAL DESIGN

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A coastal storm-strength parameter, the Coastal Storm Impulse (COSI) parameter was introduced at the ICCE 2006 (San Diego) and further discussed in the ICCE 2008 (Hamburg) and ICCE 2010 (Shanghai) proceedings. COSI is based on the conservation of linear, horizontal momentum to combine storm surge, wave dynamics, and currents over the storm duration. Both tropical storms (hurricanes) and extra-tropical storms (low-pressure fronts) can produce similar COSI parameters. Analysis of coastal storms over a 10 year period (1994-2003) of measured data at the Corps of Engineers, Field Research Facility (FRF), Duck, NC showed the need to modify the original method to (1) use the mean, nonlinear wave momentum flux, and (2) use only the spikes in storm surge when elevated water levels are above the mean high water level of the tide. This paper presents the full details of how to calculate the modified COSI parameter; the modified results for the 10-yr Duck data set and suggest possible applications to develop fragility curves for coastal engineering design. Clearly, fragility curves are needed to quantify risk and hence resilience in coastal systems design. The intensity of the "load" or "disturbance", i.e. the severity of the coastal storm must be quantified to develop fragility curves. Excess water levels (storm surge), wave conditions (height, period, direction) and storm duration all contribute to the intensity of a coastal storm. How to combine these three factors has long been a concern of coastal scientists and engineers.

Keywords: coastal storms; storm surge; wave height; storm duration; momentum; storm impulses; storm-strength parameter, and fragility curves

1 INTRODUCTION

Quantification of the hydrodynamic intensity of coastal storms is of interest in Coastal Engineering. Increased wave heights, elevated water levels, and strong currents over the duration of the storm event will result in damage to property, infrastructure, and possible beach erosion. In general, the more intense or severe the storm event, the greater the resulting damage.

All four hydrodynamic variables—waves, water levels, currents and storm duration—have been combined into the Coastal Storm Impulse (COSI) parameter (Basco and Klentzman, 2006; Basco, Mahmoudpour, and Klentzman, 2008). The COSI parameter applies the principle of conservation of momentum to physically combine the hydrodynamic variables per unit width of shoreline. This total momentum is then integrated over the duration of the storm to determine the storm's impulse to the coast. Figure 1 schematically illustrates how the offshore storm momentum is reduced to zero after impacting the coast. This change of momentum is the impulse produced by the storm. Correlations of the total storm magnitude (as represented by the COSI parameter) with property/infrastructure damage and beach erosion may then be possible for historical events and as a predictive tool for future storms. The COSI parameter can be used to develop fragility (damage) curves for use in coastal design.

Fragility curves are functions that describe the probability of failure that is dependent on the "load" (i.e. force) over the full range of the "loads" to which the coastal system might be exposed. (Schultz, Gouldby, Simm, and Wibowo, 2010). How to define the "load" for coastal systems is not discussed. Herein, we define the "load" as the coastal storm. The probability of failure is the convolution of the probability of exceedance for the hazard (i.e. coastal storm) and the probability of coastal system damage from the hazard (Kamphuis, 2010). Coastal risk is then simply the summation of the probability of failure times all the consequences (economic (structural, functional), loss of life, environmental, etc.) over the full range of coastal storms.

Section 2 presents a brief review of the literature including the original method to calculate the COSI parameter and its shortcomings as learned over the past few years. The new, modified method for calculating the storm impulse to the coast is then reviewed in detail in Section 3. It incorporates a revised method to calculate the storm surge momentum for only that part of the elevated water level that is above the MHW level as illustrated in Figure 2 (from Munger and Kraus, 2010). The FRF data set for wave and water levels to calculate the modified COSI parameter is presented in Section 4, along with analysis and discussion of the results. Section 5 considers some applications of the COSI parameter for the development of fragility curves. Our conclusions, ongoing research efforts, and recommendations follow in Section 6.

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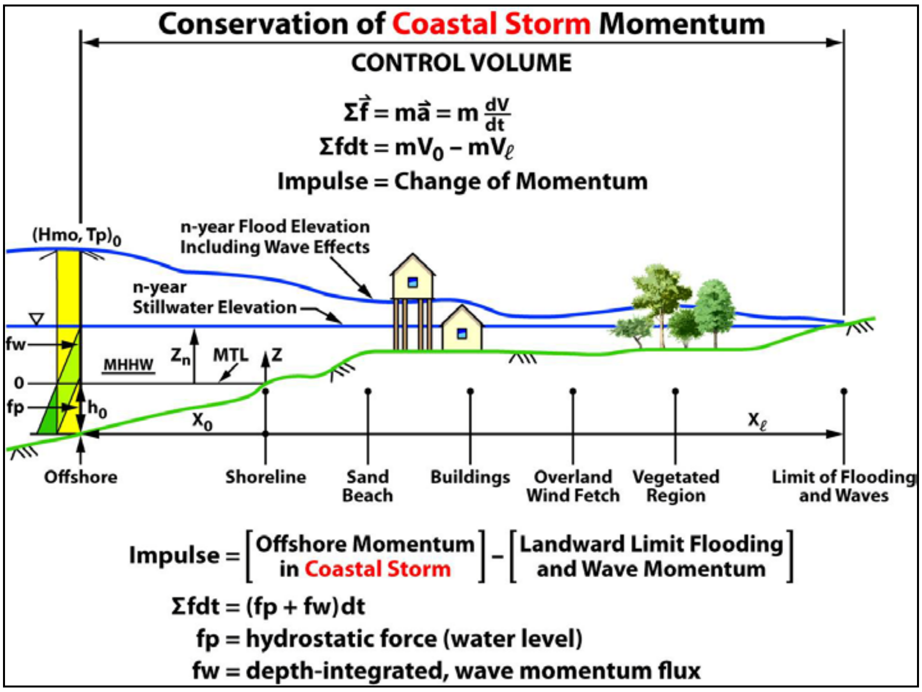

Figure 1. Control volume graphic illustrating offshore, water level, and wave forces impacting a slice of the coast.

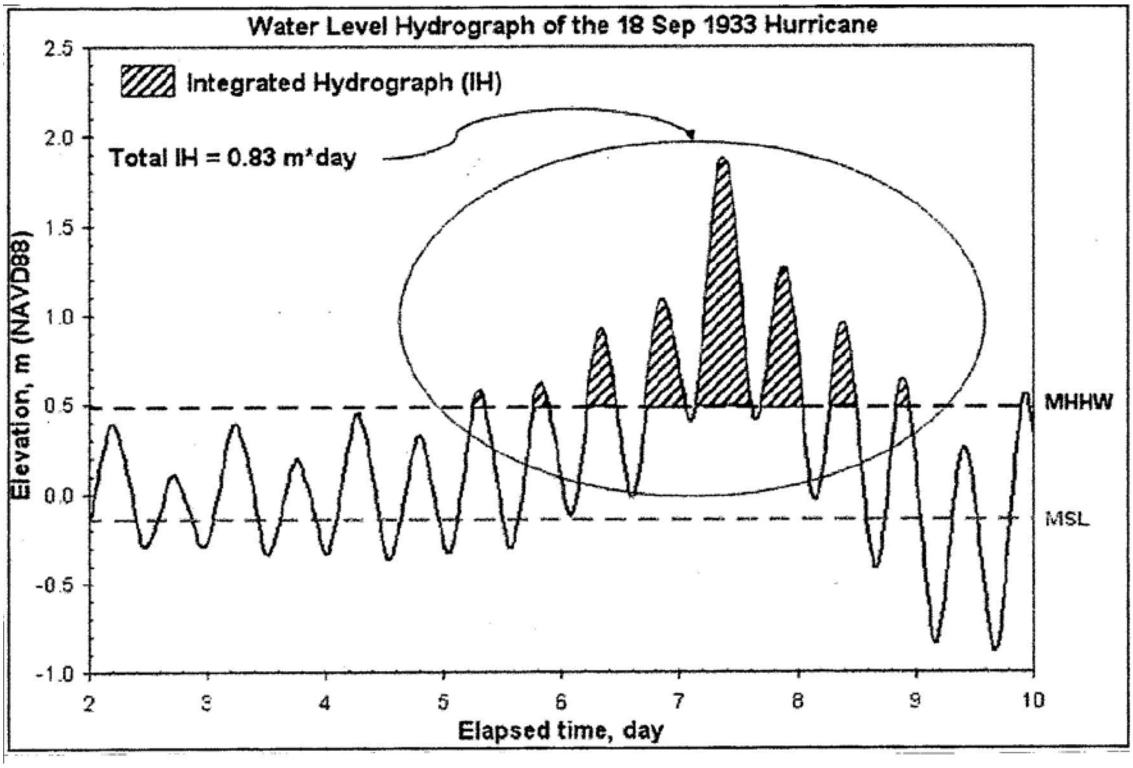

Figure 2. Definition sketch for a "integrated hydrographic" parameter (Munger and Kraus, 2010)

2 LITERATURE REVIEW

2.1 Storm Definition

Dolan and Davis (1992) defined the start of a coastal storm as when the significant wave height exceeded 1.5 meters (5 feet) in “deep water” for the middle Atlantic Ocean coastal region of the United States. They claimed that wave heights greater than 1.5 meters result in “… measurable beach face erosion along the North Carolina coast” (p.842) although no profile data is presented. In this same region, since 1985, the U.S. Army Corps of Engineers FRF has employed a measured, threshold, significant wave height value of 2.0 meters (6.6 feet) at the end of the research pier (water depth 7.6 meters; see FRF, 1985) to identify and extract a “storm” from the overall dataset (http://frf.usace.army.mil/storms.shtml). This threshold wave height is calculated as the long-term mean wave height plus two times the standard deviation of the mean and currently 0.9m +2*0.57m) = 2.04 meters (Birkemeier, 2010, personal communication). The storm “ends” whenever the significant wave height drops below 2.0 meters. The identical calculation method to identify the threshold wave height is employed by the Universitat Politecnica de Catalunya (Mendoza, 2010, personal communication) for the Catalan coast of Spain.

Near shore waves are stronger on the West Coast of the United States in the Pacific Ocean. Seymour et al. (1984) discuss measured “large waves” in Southern California from 1900 to 1983 and arbitrarily defined a major storm event when the significant wave heights exceeded 3.0 meters (10 feet) for more than 9 hours. The New South Wales (NSW) Australia Department of Natural Resources has measured deep-water wave heights since 1974 at seven locations in the Tasman Sea. The Peak-Over-Threshold analysis method is employed (Kamphuis, 2010) to estimate recurrence intervals of extreme wave height events. Individual storm events are defined when the significant wave heights are higher than 3.0 meters (You and Lord, 2008).

Clearly, the threshold wave height to define a coastal storm is site-specific and can be theoretically determined from long-term wave data or wave information.

2.2 Storm Strength Parameter

In urban coastal areas throughout the world, the threshold, coastal “storm” water levels are often defined by impacts to transportation infrastructure (roads, bridges, railway lines, etc.). When roads are flooded deep enough to impede traffic, a coastal “storm” is said to exist. Low-lying transportation corridors are constructed above the normal, high tide levels plus some additional elevation at a given frequency of exceedance that is based on local economic and environmental consequences. Therefore, there is generally no standard for the elevation of the water level above the mean high water (MHW) tidal elevation to be the threshold defining a storm event.

Because storm high water level events are often directly correlated with large wave height events, storm water level is not normally employed as a threshold to signify a “storm” event in the literature. Storm surge, though, can be employed to define storm duration.

To rank storms for a statistical analysis, Munger and Kraus (2010) defined the storm duration as the amount of time the storm surge exceeded 0.3 meters (1.0 feet). This storm duration definition was different than most in that it was not dependent on wave height. Miller and Livermore (2008) state that when threshold (wave height or water level) exceedances are separated by less than 72 hours, they are considered to be the same storm event; however, they failed to specify the threshold for water level.

The length of storm durations is different between tropical storms (hurricanes, typhoons) and extra-tropical storms (low pressure fronts). Extra-tropical storms have relatively longer durations (days) whereas tropical storms are normally fast moving with short durations measured in hours at a specific coastal site. The minimum duration for consideration of a single storm is subject to debate; however, the need for statistical independence exists for measured conditions (wave heights, water levels, etc.) for an exceedance frequency analysis (i.e., the POT method). Kamphuis (2010) states the minimum duration must be greater than one hour.

2.3 Original COSI Parameter

For storm events we herein assume that the wave crests are approximately parallel to the shoreline at the shallow water depths of interest for definition of the wave momentum flux parameter. Depth-integrating and time-averaging the instantaneous horizontal flux of momentum beneath the waves results in the radiation stresses. Gradients in the shear stress components force the long shore currents and gradients in the shore normal components of the radiation stress create wave set down and setup.

Hughes (2004) argued that the depth-integrated wave momentum flux varied significantly over the wave length (or period) so that the wave-averaged value (that is, the radiation stress) is relatively small compared to the maximum wave momentum flux values. For this reason, Basco and Klentzman (2006) adopted the **maximum**, depth-integrated, wave momentum flux) for implementation in the **original** COSI parameter. For highly nonlinear waves (Fourier wave theory) in shallow water, Hughes (2004) empirically derived a curve fit equation with two coefficients dependent on the relative wave height to water depth ratio. For irregular waves, Hughes (2004) recommended using the frequency-domain parameters, H_{mo} and T_p.

Threshold water levels are closely associated with astronomical tidal elevations and physical processes (wind stress, atmospheric pressure gradients, and wave setup) that elevate the normal tidal levels to impact man's activities at the coast. The **original** COSI parameter used the **full elevation** of the storm surge hydrograph over the water depth for the pressure momentum component of the total horizontal momentum.

2.4 Shortcomings of Original COSI Method

Analysis of 10 full years of wave and water level data for coastal storms at the Corps of Engineers, Field Research Facility (FRF) at Duck, NC (Basco, Mahmoudpour & Klentzman , 2008) revealed that the total momentum (sum of maximum, wave momentum flux and full elevation, pressure momentum) was heavily skewed toward the wave momentum flux. Over 90% of the total momentum was due to the wave momentum. This was due to use of the **maximum** value for the wave momentum flux. And, the influence of the local, normal tidal elevation was not considered in the pressure momentum term. For a given storm surge elevation, using the **full elevation** for the pressure momentum produced the same results whether the tide range was 1 meter or 10 meters. Clearly, for a storm surge elevation of 11 meters, for example, the pressure momentum impact on the coast would be far greater where the tide range is only 1 meter

3 THEORY OF THE MODIFIED COSI PARAMETER

3.1 Wave Momentum

A stress is by definition equivalent to a flow of momentum. The radiation stress (Longuet-Higgins and Stewart, 1964) is defined as the excess flow of momentum due to the presence of waves. The normal and shear stress components are normally computed using linear wave theory. As mentioned above, Hughes (2004) was the first to apply nonlinear (Fourier) wave theory to calculate the momentum flux (i.e., the radiation stress) and focused on the maximum value over the wave period. Herein, we will also apply nonlinear (Fourier) wave theory but calculate the **mean**, time averaged **M**. The modified COSI parameter employs the **mean, nonlinear (Fourier) wave momentum flux**, time-averaged, over the wave period.

The software (FORTRAN) code for the Fourier approximation method for steady, progressive waves as developed within the Hydraulic and Coastal Group in the Department of Civil Engineering at the Univ. of California (Berkeley) was employed (Sobey, Goodwin, Thieke, and Westberg, 1998). [Our thanks to Dr. Steve Hughes (formerly, ERDC, Corps of Engineers) for providing the code and to Professor Sobey (UC, Berkeley) for permission to use the code] Table I displays the output of the FORTRAN program for the Fourier wave theory and Table II shows the dimensionless parameters for the FORTRAN program output. The key variables are: H = wave height, T= wave period, h= water depth, and M= mean wave momentum flux. Other variables use standard coastal engineering nomenclature and definitions for g, ρ, ω, T, etc.

The results for the dimensionless, **mean (Fourier) wave momentum flux** parameter (**M**/$\rho g h^2$) for relative wave heights, H/h = 0.1, 0.2, 0.3, 0.4, 0.56, and 0.6 before wave breaking are plotted versus the relative, deepwater wave steepness H/gT^2 in Figure 3. It is clear that the results for the nonlinear wave theory (red lines) are very different than that for linear (radiation stress) theory (blue lines) especially at small values of relative steepness h/gT^2 and large values of relative water depth, H/h.

Table I Output of FORTRAN program for Fourier Wave Theory

```
FOURIER Wave Theory for progressive waves of permanent form
     ****************************************************
    * Department of Civil & Environmental Engineering *
    *          University of California             *
    *             Berkeley, CA 94720                 *
    ****************************************************
 FOURIER 18 Solution - Sobey (1989) Formulation -  Version 2.10
  Order:     18          Mpoints:     25
 Height:    2.0000
  Depth:    5.0000
 Period:    8.0000
 Current:     .0000      Criterion: EULER
      g:    9.8100           Rho:    1025.0
 Fnorm =  2.92709E-09/SSq =  8.43326E-18/Info = 2/ICall =  359
 SOLUTION of order 18 /Overspecification   7
                 Nondimensionalized by Omega, g and rho
 Water Depth (h)                          .31440
 Wave Height (H)                           .12576
 Wave Number (k)                            1.7614
 Wave Speed (C)                            .56774
 Mean Fluid Speed wrt Wave (ubar)         .56774
 Mean Eulerian Fluid Speed (CE)           .0000
 Mean Mass Transport Speed (CS)          9.85986E-03
 Wave Volume Flux (q)                  3.09993E-03
 Bernoulli Constant wrt MWL (R)          .16294
 SURFACE ELEVATIONS - Crest to Trough
  .090487   .087509   .079331   .067729   .054578   .041314   .028833   .017608
  .007823  -.000517  -.007504  -.013280  -.018006  -.021840  -.024928  -.027400
 -.029369  -.030926  -.032151  -.033105  -.033839  -.034391  -.034792  -.035064
 -.035221  -.035272
 FOURIER COEFFICIENTS
  1 5.28235E-02   2 1.18541E-02   3 2.67690E-03   4 5.22395E-04   5 7.38347E-05
  6 2.23315E-06   7-2.71999E-06   8-9.75692E-07   9-1.43838E-07  10 2.48672E-08
 11 2.34113E-08  12 8.16319E-09  13 1.58679E-09  14 2.59854E-11  15-1.25653E-10
 16-2.68821E-12  17-2.39372E-11  18-3.02553E-12
 INTEGRAL QUANTITIES
 Set-up (Etabar)                       5.23748E-16
 Energy Grade Line (Bbar)                 1.77746E-03
 Mass Flux (I)                        3.09993E-03
 Kinetic Energy (T)                     8.79981E-04
 Potential Energy (V)                    8.30114E-04
 Mean Square of Bed Velocity (Ub2)       3.55493E-03
 Radiation Stress (Sxx)                 2.14725E-03
 Energy Flux (F)                       8.79009E-04
 Group Speed (Cg)                         .51401
```

Table II Dimensionless parameters for Fourier program output

Dimensionless water depth, $\omega^2 h/g$	Dimensionless setup of datum,
Dimensionless wave height, $\omega^2 H/g$	Dimensionless energy grade line,
Dimensionless wave number, gk/ω^2	Dimensionless mass flux, $\omega^3 I/\rho g^2$
Dimensionless wave speed, $\omega C/g$	Dimensionless kinetic energy, $\omega^4 T/\rho g^3$
Dimensionless mean fluid speed, $\omega\bar{u} / g$	Dimensionless potential energy, $\omega^4 V/\rho g^3$
Dimensionless Eulerian current, $\omega CE/g$	Dimensionless mean square of bed velocity
Dimensionless Stokes drift, $\omega CS/g$	Dimensionless radiation stress, $\omega^4 S_{xx}/\rho g^3$
Dimensionless volume flux, $\omega^3 q/g^2$	Dimensionless energy flux, $\omega^5 F/\rho g^4$
Dimensionless Bernoulli constant, $\omega^2 r/g^2$	Dimensionless group speed, $\omega C_g/g$

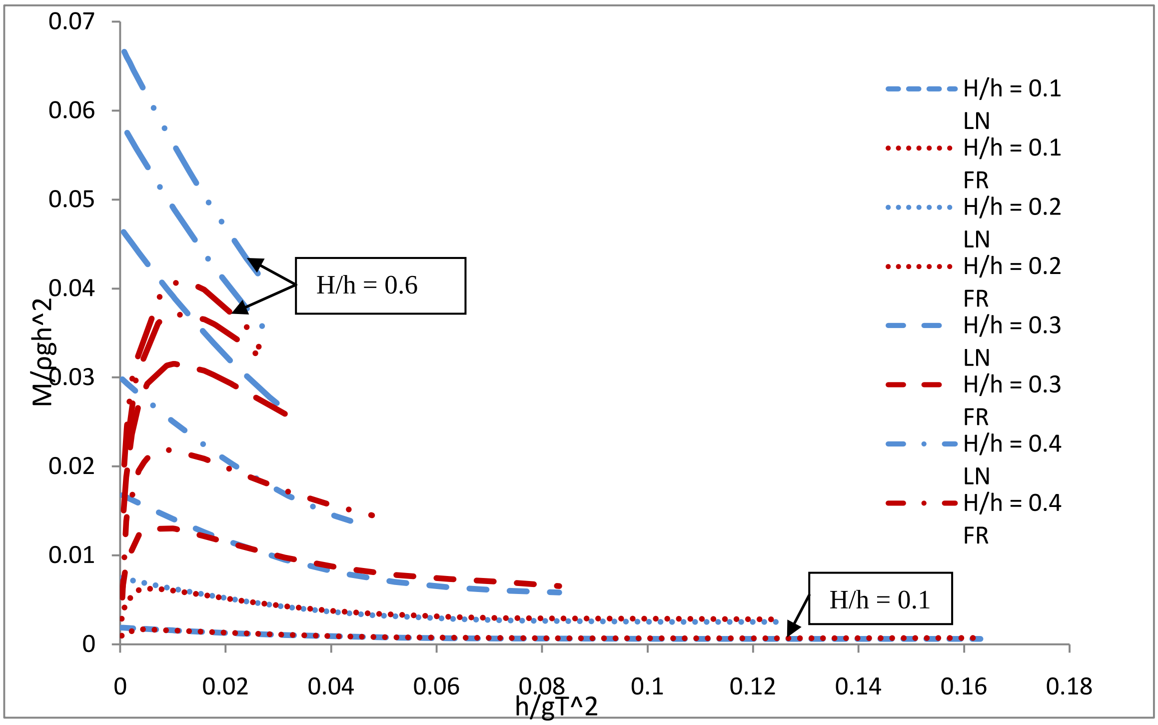

Figure 3 **Dimensionless wave momentum flux for linear, radiation stress theory (blue) and nonlinear (Fourier) theory (red)**

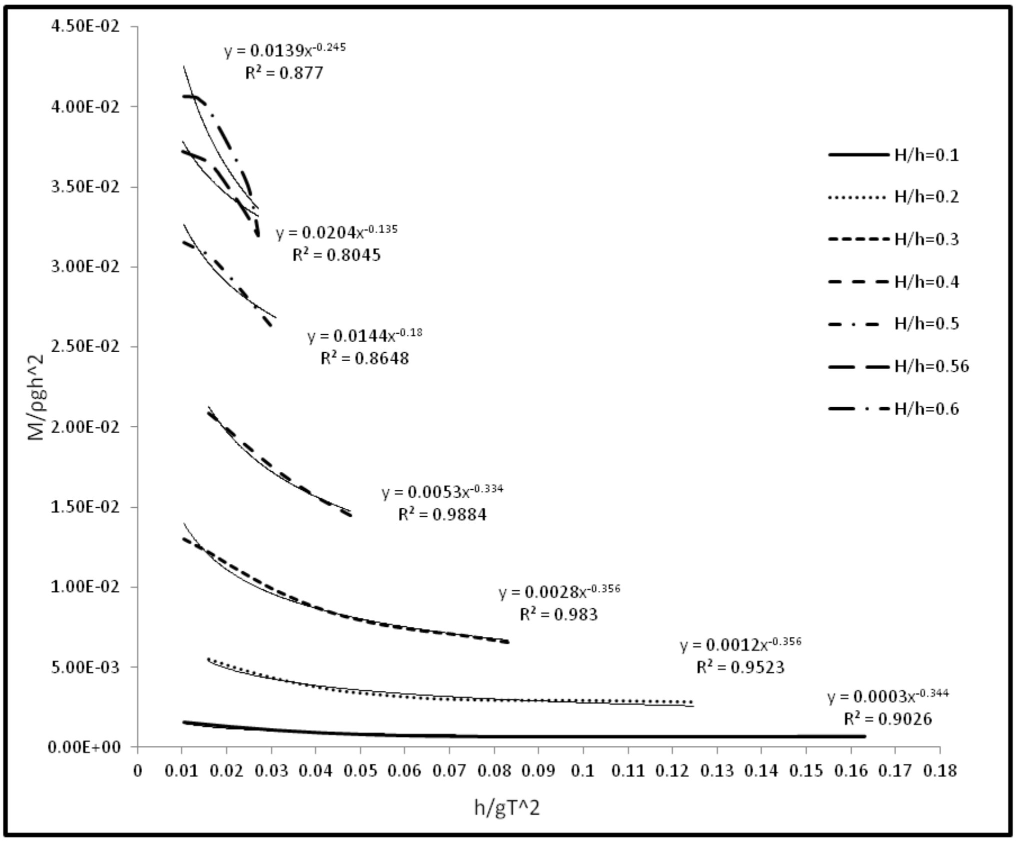

Figure 4 **Dimensionless nonlinear (Fourier) wave momentum flux: Computer (solid) vs curve-fit equations (dotted) for deepwater steepness range > 0.01.**

And, that for very small values of the relative wave height, H/h, the results for the nonlinear (Fourier) wave theory (red) are similar to that for linear wave theory (blue) and the radiation stresses. Clearly, the theory for the nonlinear (Fourier) wave theory converges to that for linear wave theory for small amplitude waves.

Empirical, curve-fit formulations have then been derived to replace the need for the computer code listed in Table I and make the calculation of the mean, nonlinear wave momentum, **M** simply dependent on the three primary variables H, T and h involved in the computation. Figure 4 displays the results when $h/gT^2 > 0.01$ and using the results listed below to calculate the coefficients, A_0 and A_1.

$$\left(\frac{M}{\rho g h^2}\right) = A_0 \left(\frac{h}{gT^2}\right)^{A_1}$$

Where:

$$For\ \frac{h}{gT^2} \leq 0.01, \qquad A_0 = 0.5468 \left(\frac{H}{h}\right)^{2.1264}\ and\ \ A_1 = 0.3615 \left(\frac{H}{h}\right)^{0.3516}$$

$$For\ \frac{h}{gT^2} > 0.01, \qquad A_0 = 0.057 \left(\frac{H}{h}\right)^{2.3393}\ and\ \ A_1 = -0.1685 \left(\frac{H}{h}\right)^{-0.398}$$

The graph of the results for when $h/gT^2 < 0.01$ is not shown. Other empirical, curve-fit formulations are possible and are being investigated that may give more accurate results.

3.2 Storm Surge Momentum

Consider the conservation of linear momentum (with no waves) for the control volume from the offshore to the landward limit of storm surge. The total horizontal force, f_{total} is the sum of the (1) hydrostatic pressure force for the reference water depth plus the storm surge, $(h_0 + s)$ and (2) the current momentum force, $\rho(h_0+s)U^2$ where U is the average velocity. We herein assume the shore normal current, U is zero.

All the worlds coasts have adjusted to the local tidal variations and coastal high water level events are only considered as “storms” when the water levels exceed the predicted tidal levels, i.e. the storm surge. We herein adopt the mean high water (MHW) level as the base water level. Therefore the modified, storm surge parameter, **fp** $= f_{total} - f_{MHW} = \frac{1}{2}\rho g(h_0+s)^2 - \frac{1}{2}\rho g(h_0 + h_{MHW})^2$ and is the horizontal storm surge momentum above the Mean High Water (MHW) during the storm event for any time, t. This is the modified, storm surge and totally different than in the original COSI model.

3.3 Total Momentum and the Modified COSI Parameter

The total storm momentum is simply the sum of the storm surge momentum parameter, $\mathbf{fp_{(t)}}$ and the mean, wave momentum parameter, **M (t)**. The COSI parameter ($\mathbf{I_S}$) is then found by integrating in time over the storm duration, D as defined in the following equation. The current momentum is neglected.

$$\mathbf{I_S = \int [\, fp_{(t)} + M_{(t)}]\, d_t}$$

where:

$\mathbf{I_S}$ = the COSI parameter

D = the duration of the storm

4 THE FRF DATA SET and ANALYSIS

The USACE FRF is located on the Atlantic Ocean in Duck, North Carolina (see Figure 5). Since 1981, the FRF has collected near shore oceanographic data on a routine basis. This data set now covers nearly thirty years and is unmatched worldwide in terms of accuracy and temporal coverage

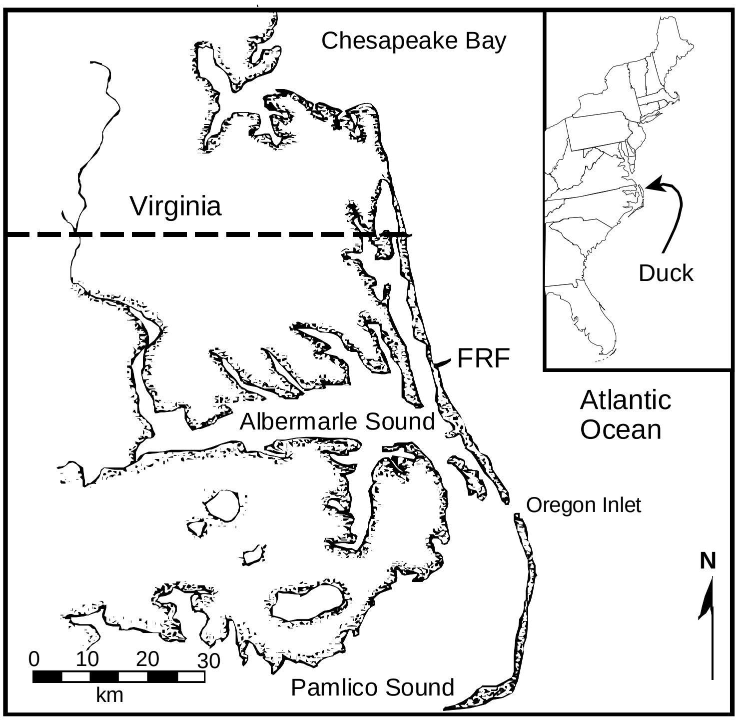

Figure 5 Site location map of the USACE Field Research Facility. Courtesy USACE, FRF

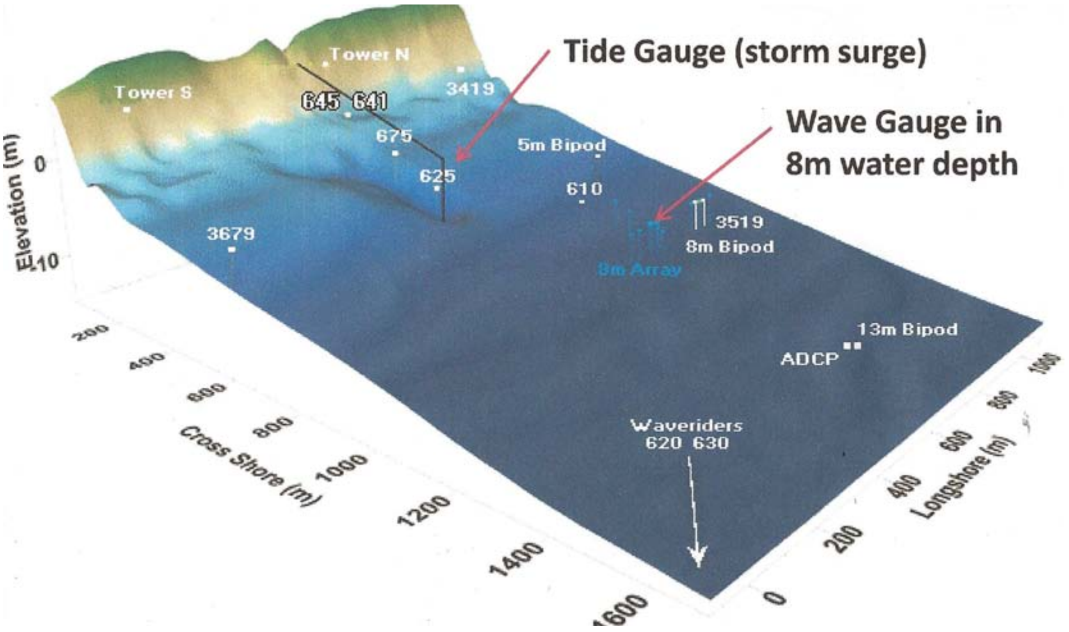

Figure 6. Location of data taken at the FRF (Courtesy of USACE)

The storm duration was taken as the length of time (hours) that wave heights were equal or greater than 1.6 meters for at least a 12 hour, continuous period. Wave heights were measured in 8 meters water depth shown in Figure 6. Data was recorded at one hour time intervals. By this process, 148 coastal storms were identified for the 10-year period, 1994-2003. The water levels were recorded by a NOAA/NOS tide gauge at the end of the pier as illustrated in Figure 6.

Tables III and IV present the results for year 1994 in which 16 storms were identified. Table III lists the storm type (N means Northeaster); start/end days and time; storm duration and some maximum values for surge level and wave conditions during the storm. Table IV presents the surge momentum, wave momentum, total momentum, i.e. the modified COSI parameter and ratios for wave relative to surge momentum. Similar tables for the nine following years, 1995-2003 can be found in Mahmoudpour (2012, PhD dissertation) and could not be included here due to space limitations. Note that with the modified COSI parameter formulation, the wave momentum is now more balanced with the surge momentum than in the original formulation. The maximum modified COSI parameter in 1994 was due to Hurricane GORDON in November and was over 3 million N-hrs/m (Newton-hours/meter) for the 123 hour storm event.

The full results for the modified COSI parameter for the 10-year data set are shown in Figure 7. The maximum value was over 7 million N-hrs/m for Hurricane DENNIS in Aug/Sep 1999 and lasting over 153 hours. The average storm duration was 47 hours and gave an average, modified COSI parameter of 0.72 million N-hrs/m for the 149 storms in the 10-year period.

See Mahmoudpour (2012) for full details including a log-normal probability distribution model for the data. For example, for extreme storm events with a 1% chance of occurrence each year (100-yr return period) the modified COSI parameter was 4.4 million N-hrs/m. Other extreme value distributions methods are under investigation using Peak-Over-Threshold (POT) methods that are better able to handle the outlier of Hurricane DENNIS.

The previous 10-year period (1982-1993) and the following 8-year period (2004-2012) need to be addressed. For example, Figure 8 shows the results for the wave momentum (dotted), surge momentum (dashed), and total momentum (solid) variation in time for Hurricane IRENE in August 2011. The modified COSI parameter was 0.63 million N-hrs/m. It may be possible to see some trend in the strength of coastal storms over this 30-year period relative to climate change and sea-level rise.

The distribution of the duration of the coastal storms (hours) is shown in Figure 9.

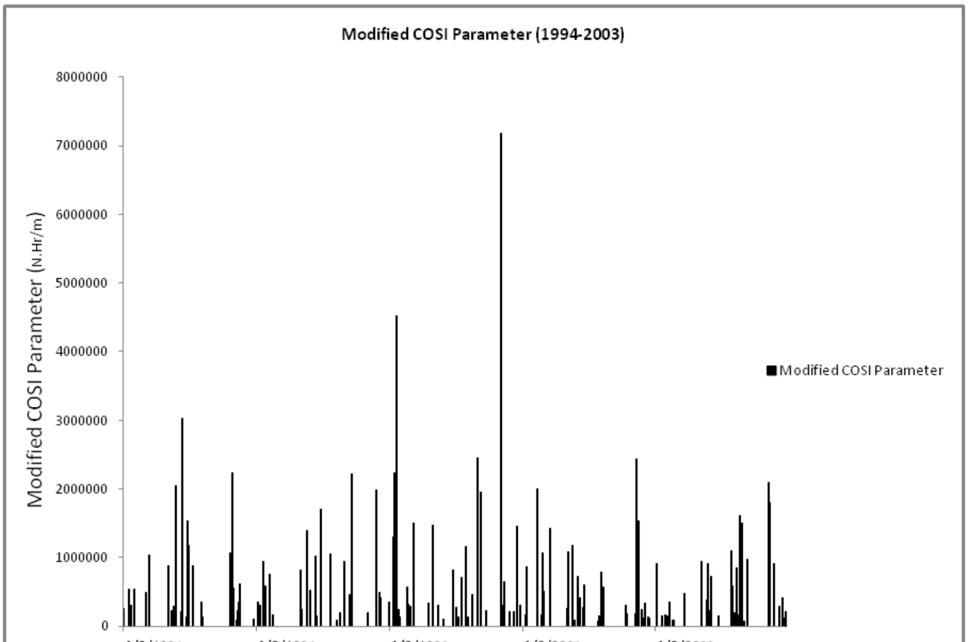

Figure 7. The modified COSI parameter for the 10-year data set, 1994-2003 at the FRF, Duck, NC

Table III Storms and their characteristics for year 1994 at the FRF, Duck NC

Storm Type	Start	End	Duration (Hrs)	Max Surge (m)	Max Wave (m)	Max Period (sec)
N	1/3/1994 16:00	1/4/1994 4:00	12	1.0	3.0	10.7
	1/26/1994 19:00	1/28/1994 19:00	48	0.9	2.8	12.0
	1/30/1994 7:00	1/31/1994 13:00	30	0.8	2.3	8.2
N	2/10/1994 1:00	2/11/1994 7:00	30	1.0	2.2	7.6
N	3/2/1994 1:00	3/3/1994 19:00	42	1.0	3.1	13.6
	5/3/1994 19:00	5/5/1994 10:00	39	0.9	3.6	12.0
	5/19/1994 10:00	5/22/1994 10:00	72	1.1	2.3	10.7
	9/3/1994 10:00	9/5/1994 16:00	54	1.2	2.8	12.0
	9/22/1994 1:00	9/22/1994 13:00	12	1.0	2.7	9.7
	10/3/1994 7:00	10/3/1994 22:00	15	0.9	2.5	7.0
	10/10/1994 7:00	10/18/1994 10:00	195	1.0	4.1	12.0
	11/10/1994 10:00	11/11/1994 13:00	27	0.9	2.5	8.9
H/Gordon	11/16/1994 16:00	11/21/1994 19:00	123	1.6	5.1	15.6
	12/11/1994 10:00	12/12/1994 7:00	21	0.8	2.1	7.0
	12/13/1994 16:00	12/19/1994 10:00	138	0.9	3.4	15.6
N	12/22/1994 10:00	12/25/1994 16:00	78	0.9	4.3	13.6

Table IV Modified COSI parameter for storms in year 1994.

Storm Type	Start	End	Duration (Hrs)	Surge Mom (N-Hrs/m)	Wave Mom (N-Hrs/m)	Modified COSI (N-Hrs/m)	Wave Ratio	Surge Ratio
N	1/3/1994 16:00	1/4/1994 4:00	12	136925.2	124476.0	261401.2	0.5	0.5
	1/26/1994 19:00	1/28/1994 19:00	48	180060.6	356715.7	536776.4	0.7	0.3
	1/30/1994 7:00	1/31/1994 13:00	30	72620.9	156897.8	229518.7	0.7	0.3
N	2/10/1994 1:00	2/11/1994 7:00	30	147877.6	150946.8	298824.3	0.5	0.5
N	3/2/1994 1:00	3/3/1994 19:00	42	219051.3	316909.1	535960.4	0.6	0.4
	5/3/1994 19:00	5/5/1994 10:00	39	149002.0	328237.3	477239.3	0.7	0.3
	5/19/1994 10:00	5/22/1994 10:00	72	650166.3	392210.6	1042377.0	0.4	0.6
	9/3/1994 10:00	9/5/1994 16:00	54	458416.4	420835.6	879252.0	0.5	0.5
	9/22/1994 1:00	9/22/1994 13:00	12	128794.1	102132.1	230926.2	0.4	0.6
	10/3/1994 7:00	10/3/1994 22:00	15	207043.9	86055.8	293099.7	0.3	0.7
	10/10/1994 7:00	10/18/1994 10:00	195	655052.8	1386147.7	2041200.5	0.7	0.3
	11/10/1994 10:00	11/11/1994 13:00	27	80842.6	124627.9	205470.5	0.6	0.4
H/Gordon	11/16/1994 16:00	11/21/1994 19:00	123	1769675.1	1260883.5	3030558.6	0.4	0.6
	12/11/1994 10:00	12/12/1994 7:00	21	27811.2	104371.0	132182.2	0.8	0.2
	12/13/1994 16:00	12/19/1994 10:00	138	412623.8	1117149.1	1529772.9	0.7	0.3
N	12/22/1994 10:00	12/25/1994 16:00	78	340361.1	832844.6	1173205.7	0.7	0.3

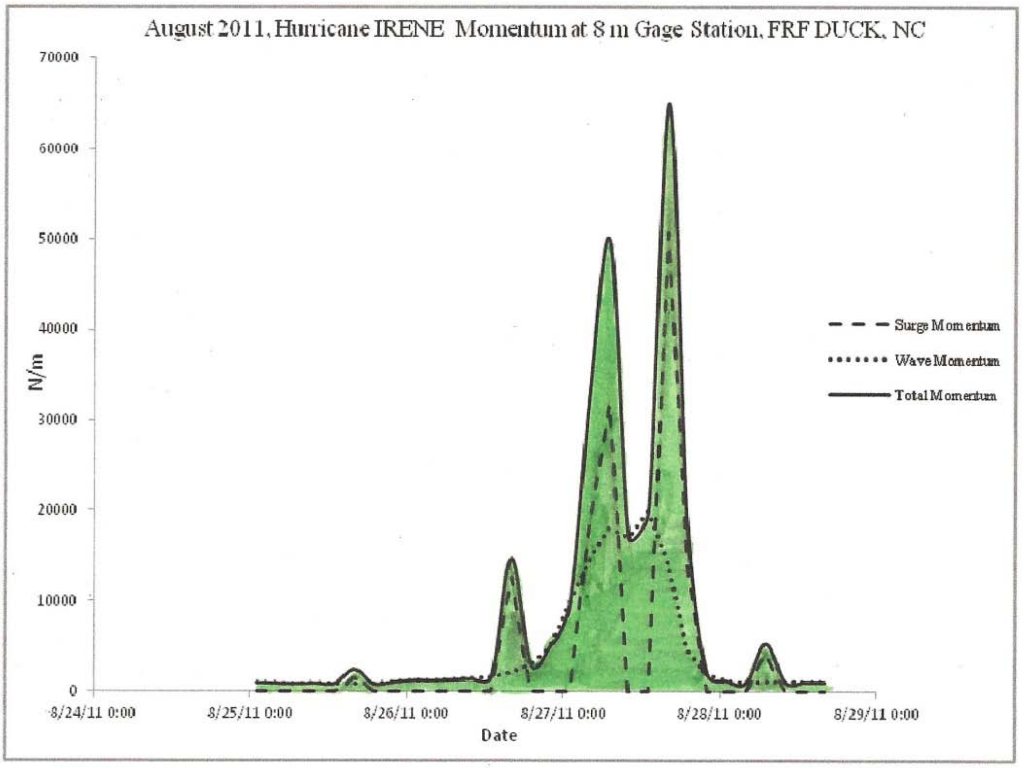

Figure 8. Example of total momentum for Hurricane IRENE (Aug 2011) over storm duration to calculate the modified COSI parameter

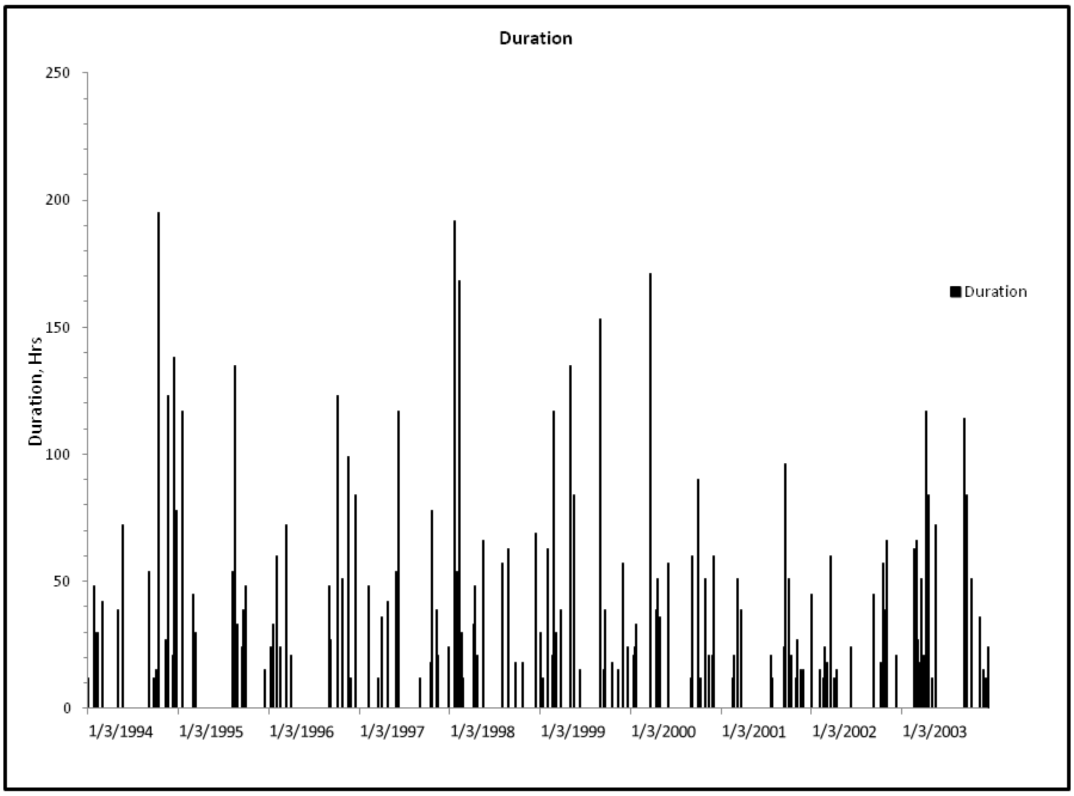

Figure 9. The storm durations in hours for the 149 coastal storms at the FRF (1994-2003)

5 APPLICATIONS IN COASTAL ENGINEERING

Whenever and wherever all three storm intensity parameters (water levels, waves and storm duration) are important, the COSI parameter (modified) can be used to develop fragility curves for use in quantifying risk and resilience. For example, in rubble-mound structures design, “damage” curves can be modified as a function of the COSI parameter and not just wave heights above the design wave height. In vertical seawall design, the wave run up and overtopping rates depend on both storm water level and wave conditions so that the COSI parameter is better suited to develop a fragility curve for design. In beach nourishment design, use of fragility curves with the COSI parameter to replace the Monte Carlo method in the Beach-fx model (Gravens, Males, and Moser, 2007).

A second application is to develop a Coastal Storm Strength Index (for water levels, waves and duration) for the media and general public that is NOT a wind speed scale (Saffir-Simpson) and holds for both tropical and extra-tropical storms. The COSI Index will require a base level of the parameter by which to divide all the values of the COSI parameter to obtain an Index in the range of 1-5. What to use for the base level has yet to be determined.

A third application is to develop numerical models to calculate the COSI storm intensity in time as the storm moves toward the coast.

6 CONCLUSIONS AND RECOMMENDATIONS

The original formulation for the COSI parameter (Basco and Klentzman, 2006) has been modified and improved. Use of the nonlinear Fourier wave theory and the mean wave momentum and use of the storm surge momentum above the local MHW level results in a balance of these two forces that is more realistic and means that both water level and waves are important to characterize the strength of a coastal storm (Mahmoudpour, 2012). Use of the conservation of momentum principle and that impulse equals the change of momentum (Newton’s 2nd Law of Motion) provides the proper way to combine water level and wave forces. The mean, non-linear wave momentum reduces to the radiation stress theory for linear wave theory that is commonly employed to calculate wave set-down and set-up and long shore currents

Resilience is the ability of a system to maintain and recover its structural and functional performance following a disturbance. (Schultz, McKay, and Hales, 2011). The “disturbance” is the short-term excess of forces (i.e., the load or coastal storm) acting on the coastal system components and processes that may impair the system function. These authors discuss three types of resilience (ecological, engineering, community) for coastal systems; focus on engineering resilience; and cite the Saffir-Simpson wind speed scale for hurricanes as an example of a coastal storm disturbance scale. If the level of disturbance (coastal storm) exceeds a critical level, both the level of performance impairment and the duration of performance impairment may exceed management objectives for the resilience of the coastal system.

The long term goal is to understand and quantify the “evolution” of resilience (Schultz, McKay, and Hales, 2012) associated with potential, accelerated, sea-level rise rates. Climate change may create more coastal storm and rising water levels will mean larger waves reaching the coast. Use of the COSI parameter to quantify fragility curves is the first step to understand how the fragility of coastal infrastructure is being reduced and “evolving” in time

We now feel confident that the modified COSI parameter captures the true, combined, total strength of each coastal storm as one number for a fixed location at the coast. But coastal storms are two dimensional when striking the coast. The COSI parameter varies along the shoreline, COSI(x), so that the spatial distribution along the coast must be known to determine the total strength of the full extent of the coastal storm. Research is needed in this regard and will be aided by the third application cited above through the use of numerical models that combine storm surge and water wave dynamics.

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