Spring 2012

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Recommended Citation

Mahmoudpour, Sayed G.. "The Modified Coastal Storm Impulse Parameter" (2012). Doctor of Philosophy (PhD), Dissertation, Civil & Environmental Engineering, Old Dominion University, DOI: 10.25777/7vfg-d989
https://digitalcommons.odu.edu/cee_etds/50

THE MODIFIED COASTAL STORM IMPULSE PARAMETER

by

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A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

CIVIL ENGINEERING

OLD DOMINION UNIVERSITY
May 2012

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ABSTRACT

THE MODIFIED COASTAL STORM IMPULSE (COSI) PARAMETER

Sayed Gholamreza Mahmoudpour
Old Dominion University, 2012
Director: Dr. David R. Basco, P.E.

The correlation of the morphological changes to the coast and storm characteristics is among interests of coastal engineers. Better understandings of a storm's potential forces ultimately lead engineers to safer designs and minimize the damages. Therefore, a need to quantify the storm potential forces to a storm parameter is evident. The desired storm parameter is to consider all the relative physical factors and is to present realistic results that then can be proven by actual nature response.

The concept of Coastal Storm Impulse (COSI) parameter was first introduced by Basco and Klentzman (2006) and is based on the conservation of horizontal momentum to combine storm surge, wave dynamics, and currents over the storm duration and here is referred to as original COSI parameter. The COSI parameter consists of three components of wave, surge and current momentum. The current momentum is not considered in the original COSI parameter since it was not significant in compare to the wave and surge momentum (Klentzman, 2007). It is not considered in this dissertation for the Modified COSI parameter in order to keep the consistency of the analysis.

In this dissertation, steps have been taken to examine and to redefine the criterion of storm definition, wave momentum and surge momentum in order to improve shortcomings of original COSI parameter. For the Modified COSI parameter, the estimation of wave momentum integrated over the water depth and averaged over the wave period utilizing nonlinear (Fourier) wave theory is introduced for the first time. A

computer FORTRAN code developed within the Hydraulic and Coastal Group in the Department of Civil Engineering at University of California, Berkeley is used to develop a set of empirical formulas to estimate the wave momentum. Also, the importance of tides in beach stability has been noted and is considered by applying water elevations above Mean High Water (MHW) to obtain the storm surge momentum. The Modified COSI Parameter introduced here is sum of the wave momentum and the surge momentum. For a "storm event" it was assumed that the wave height will stay at or above 1.6 meter for 12 hours to have a chance to ride on the high tide and it is based on a tidal cycle of approximately 12 hours. The data set for year 1994-2003 at USACE Field Research Facility (FRF), Duck, NC, has been reanalyzed based on the new methodology and criterion set forth in this dissertation. This new approach has produced 148 storms in compare to 160 storms from original COSI results (Klentzamn, 2007) over the period of 10 years the data (1994-2003). The analyses of the 10-year data (1994-2003) show a better proportionality of the wave momentum (60%) and the storm surge momentum (40%) to the total momentum. In general the average wave momentum resulting from empirical formulation introduced in this dissertation is in average 10 times smaller than the maximum wave momentum from Hughes (2004) formulation.

To my wife Solmaz and to my sons Abtin and Arsham.

ACKNOWLEDGMENTS

First of all, I wish to express my gratitude to Professor Dr. David R. Basco for his constant guidance, inspiration, encouragements, critical reviews and friendship. This dissertation would never have been accomplished without his support.

I also, wish to direct my thanks to the other two committee members, Dr. John Klinck and Dr. Jaewan Yoon, for reviewing the dissertation manuscript and their valuable comments. Also, my appreciation extends to Dr. Chris Klentzamn for providing his data on the original COSI parameter.

Furthermore, special thanks are expressed to Dr. Steven Hughes for providing the FORTRAN code that has been used for this dissertation and to Professor Rodney Sobey for his permission to use the code.

Appreciation is extended to Mr. William Birkemeier, director of the United States Army Corps of Engineers, Field Research Facility, Duck, NC, for his comments and intelligent conversation and guidance.

My gratitude is also directed towards Professor Dr. Ishibashi, Graduate Program Director, and Professor Dr. Akan, for their guidance throughout my study at Old Dominium University and Ms. Sue Smith for accommodating my last minute requests graciously.

I would like to appreciate my parents encouragement and moral support while they were alive throughout my life, studies and achievements.

Last, but not least, I would like to thank my wife, Solmaz, not only for her understanding and patience, but also for her love, support and encouragement throughout my Ph.D. study.

NOMENCLATURE

a	Wave amplitude; or Acceleration
A_0	Empirical coefficient for depth-integrated wave momentum flux
A_1	Empirical coefficient for depth-integrated wave momentum flux
C	Wave speed
C_E	Eulerian current or time-mean current in a fixed reference frame
$COSI$	Coastal Storm Impulse Scale
d	Water depth
F	Force
$\mathrm{F_x}$	Force in x-direction
$\mathrm{f_{p(t)}}$	Hydrostatic force due to water level
$\mathrm{f_{w(t)}}$	Depth-integrated averaged wave momentum flux
$\mathrm{f_{c(t)}}$	Force due to current
f_{total}	Total offshore force due to current and surge
FRF	Army Corps of Engineers Field Research Facility, Duck, North Carolina
g	Gravitational acceleration (9.81 m/sec^2)
h	Water depth from bottom to the still water level or mean depth
h_0	Mean water level
H	Wave height
$\mathrm{H_{mo}}$	Spectral, significant wave height
H_{limit}	Wave height breaking limit for Williams (1985) formula
H_{MHHW}	Water level greater than Mean Higher High Water
H_{MHW}	Water level greater than Mean High Water
HIS	Integrated significant wave height
I	Momentum
IH	Integrated Hydrograph

I_s	Storm Impulse
k	Wave number
L	Local wavelength
L_0	Deepwater wavelength
m	Mass
M_F	Depth-integrated maximum wave momentum flux across a unit width
M	Depth-integrated average wave momentum flux across a unit width
p_d	Wave dynamic pressure
P_{dyn}	Dynamic pressure
$p_{(x,z)}$	Water particle pressure
p_0	Hydrostatic pressure
Q	Flowrate
R	Bernoulli constant (energy per unit mass)
SEPI	Storm Erosion Potential Index
S_{2SD}	Storm surge height above two standard deviation
s	Storm surge (meters)
S_{xx}	Wave-averaged momentum flux (radiation stress) in x-direction
t	Time
T	Wave period or Kinetic Energy
T_p	Peak wave period
t_D	Integer number of hours of storm duration
u	Fluid velocity (water particle velocity) in the x-direction
$u_{(z)}$	Horizontal water velocity at a specified depth
U	Current speed in x direction
$\bar{u}$	Mean fluid speed on any horizontal line underneath the stationary waves
$\overline{U_b^2}$	Mean square bed velocity
v	Fluid velocity (water particle velocity) in the y-direction
V	Potential energy or depth-averaged current normal to the shore

W	Current speed in z direction
w	Fluid velocity (water particle velocity) in the z-direction
$\eta(x)$	Sea surface elevation relative to still water level
$\eta(c)$	Sea surface elevation relative to still water level at the crest of the wave
ρ	Mass density of water (1025 kg/m^3)
Υs	Total storm momentum (Newtons/meter)
$\Delta(t)$	Time interval
η	Elevation of the water surface
ω	Angular frequency $(\frac{2\pi}{T})$
ψ	Wave stream function
λ	Wave length

TABLE OF CONTENTS

INCLUDED IN CD:

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

A need to formulate storm parameters is evident in order to compare and to study the storms impacts and estimate their damages to the coast. The morphological changes of the coast and potential hazard for coastal communities during and after a storm can be predicted for better responses when a better understanding of storm potential forces exists and it would be helpful to predict the changes to the shoreline and to compare storms strengths and their consequential damages. Regulators, authorities and engineers can benefit from a storm parameter to help communities to plan for proper emergency responses. The desired storm parameters should consider all the relevant physical factors to present realistic results that can be then verified, proven and related to what happened in the nature. There have been several efforts to classify storms and to relate storm's physics and specifics to their impact on the coast. Among them Saffir-Simpson scale (1974) is well known and is widely used. In an effort by Basco and Klentzman (2007), a coastal storm-strength index called the original Coastal Storm Impulse (COSI) scale introduced. The concept of COSI is based on the conservation of linear, horizontal momentum to combine storm surge, wave dynamics, and currents over the storm duration. Considering parameters that other scales are applying to classify storms, COSI scale seems to consider the hydrodynamics of storm surge, wave characteristics and duration of storm all together. The other advantage of COSI scale is that it can be applied

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The Journal of Coastal Engineering is used as a format model for the references cited.

to both tropical storms (Hurricane) and extra-tropical storms (Northeaster). The COSI parameter can be applied to near shore coastal processes, risk management and possibly coastal structure design.

1.2 Objectives

Since the COSI scale has been recently introduced, more investigation is needed to test its robustness, credibility and to examine the criterions that have been considered in its development.

The study objectives are to:

1. Examine the current methodology and results for original COSI parameter,
2. Investigate more recent storm definitions and storm scale classifications,
3. Study and introduce new approaches to calculate wave and storm surge momentum,
5. Reanalyze the data set of ten year period (1994-2003) at FRF, Duck, based on the new definition of wave and storm surge momentums,
6. Calculate the Modified COSI Parameter instead of original COSI scale based on the new definition of storm condition, and
7. Analyze and to discuss the results of applying new methodology

1.3 Scope

In previous work done for original COSI parameter (Klentzman, 2007) the feasibility of this scale has been studied. Now, the concept of Modified COSI parameter has been introduced and pushed the idea further to identify previous shortcomings and to improve the methodology that can be applicable in the real world with the credible results.

The new wave momentum is depth integrated and is averaged over wave period using nonlinear (Fourier) wave theory. Considering tides in the development of the Modified COSI parameter to derive the total storm momentum is part of the scope of this study. Applying the theory and examine the results are to conclude the scope.

1.4 Limitations

One of the limitations for this study is that the data are limited to one location at Army Corps of Engineers Field Research Facility, Duck, NC. It is a good starting point, but spatial expansion of application of the Modified COSI Parameter should be considered. The other limitation is for the depth that wave height is monitored and the data extracted. At the location of the study for large storms with high waves the waves might have been already broken and can impact the results for high waves. The current has not been considered in this study and the impact of it can be investigated. Also, the Modified COSI parameter has been formulated for a 1 meter slice of the shoreline. It might need to be more investigated to apply the parameter to the entire width of the storm in time and space.

CHAPTER 2

LITERATURE REVIEW

2.1 Storm Definitions

What defines a storm condition and what would initiate a "storm" has not been uniquely defined among scientists and engineers. Depending on their field of study, different scientists have defined storm conditions differently based on parameters that they are concerned the most. Among the parameters that have been used are wind speed, beach erosion parameters and storm hydrodynamics parameters such as wave height and water levels. Our focus in this dissertation will be on the hydrodynamics parameters of storm in defining a "Storm Condition".

It might be interesting to look at one of the very first attempt to define a storm condition which was documented in the Monthly Weather Review, October 1901, by Canada Meteorological Service. When a query was received from the Chief of the United States Weather Bureau as: "What is a Storm Wave? The Standard Dictionary's definition of storm wave reads: A wave on the ocean surrounding a cyclonic area: caused by a difference in pressure. In the issue for December, 1900, of Science and Industry, Mr. Ernest K. Roden published an article entitled Revolving Storms. In this article he states that the storm wave is at the center of the storm area, and gives a sketch showing how it is formed. Would you be so kind to favor us with your judgment as to the accuracy of these statements; which would you think is correct?"

The Canada Meteorological Service, Chief of Bureau appointed a board of scientists for the purpose of considering the definition of the term storm wave. The Chief provided this additional queries “Does centrifugal force cause the water to be scooped out under the center of the cyclone, and to bank up in a ridge around its outer periphery; or does the decrease in air pressure, that is the result of centrifugal force action upon the water cause the water under the center of the cyclone to bulge up like an inverted soup plate?”

The appointed board concluded their discussion as following:

“The board finds no necessity for giving a new meaning or a specific definition to the term “Storm Wave.” Like most other words in the English language it has been used for many years and with a great variety of meanings, each of which has good authority. It would be a work of supererogation for us to attempt to restrict its use to any of these meanings. Indeed, we believe that the compiler of a dictionary of the English language will naturally desire to include all these meanings, and, therefore, we give them in detail as follows:

1. Old nautical usage. The old sailor’s term for a heavy wave without a severe wind and evidently due to a storm not far distant. (See Admiral Belcher’s Nautical Dictionary of 1867.)

2. Old usage along the Atlantic coast of North America. A long, gentle swell or ground swell felt at any point on the Atlantic coast and which is considered by local seamen to indicate the presence of a hurricane far away to the south or southeast but advancing up the coast. This storm wave or hurricane swell was formerly used in local forecasts by the navigators. It was explained by Redfield about 1833, and is the same as the swell referred to by Reid in 1849 and 1850, and by F. P. B. Martin in 1852.

3. A destructive wave or bore due to the combined effect of high tide and heavy gale sometimes occurring within the dangerous quadrant of a hurricane. (See Reid, 1849.)

4. A theoretical rise or bulging up of the water within the oval region of a very low barometric pressure and due to the greater pressure on the surrounding region of high barometer. This was argued for by Piddington (1848), and Fits Roy (1863), and Buchan (1868), but has not as yet been actually observed by any one and is in general not separable from the rise due to wind and tide.

5. A destructive wave, overflowing land and buildings and undoubtedly due to the combined effect of strong winds, high tide, and low pressure in a region where the coast lines converge and the water shoals rather rapidly. This is the general usage of to-day, and was adopted by Wilson (1875), Blanford (1876), Eliot (1878), and the Weather Bureau generally as exemplified in the Monthly Weather Review (1900, p. 154).

6. This term is not usually confined to the rise of water due to the mere decrease of pressure within a low area as was done by Roden (1900). "

Therefore, there was not any quantified criterion to define a storm condition in the 19th and early 20th centuries but it shows the concern they had defining a storm. It might be more scientifically sound to have the storm definition based on the hydrodynamic parameters of the storm such as wave height, water level and duration. Rarely a threshold values for hydrodynamic variables have been specified (Basco & Walker, 2010) in order to take into account of the severity of the storm and its impact on the coast. The most used and seems to be related parameter to define a storm condition is wave height. In addition, there are storm definitions based on the storm parameters such as water level and duration.

2.1.1 Storm Definitions Based on Wave Height

One of relatively recent definition of a coastal storm in the Mid-Atlantic is "any synoptic weather system that produces waves in deep water of at least 1.6 meters" (Dolan, Lins, and Hayden, 1988). They based this storm definition on combination of wave momentum and surge momentum which would cause some degree of beach change along mid-Atlantic barrier islands (Dolan, Hayden, Bosserman, and Lisle, 1987).

Kriebel and Dean (1985) demonstrated a strong correlation between storm duration and beach erosion. According to their Atlantic Coast winter storms definition a storm should produce at least a significant deep- water wave height of 5.0 feet (1.5 m) at Cape Hatteras, North Carolina. Also, they consider the duration of a storm based on confirmed field evidence for significant beach face erosion caused by a 5 foot (1.5 m) deep-water wave. Based on this definition a total of 1,347 northeast storms have been identified over 42 years period. This threshold is used for a northeast storm and to calculate storms duration.

The US Army Corp of Engineers Field Research Facility (FRF) at Duck, North Carolina, is considering the wave heights above 2.0 m and duration of more than eight hours as a storm condition. This threshold wave height is calculated as the long-term mean wave height plus two times the standard deviation of the mean (0.9m +2*0.57m = 2.04 meters) (William Birkemeier personal communication, 2010). This criterion is used to identify and extract a "storm" from the overall FRF dataset (http://frf.usace.army.mil/storms.--shtml). Since this method identifies relatively minor events, a larger multiplier (3 or 4) of the standard deviation is used to filter out more significant events. Regardless of the storm initiation threshold, a storm ends when the wave height drops below the 2.0m threshold. Mean wave height should be based on a minimum of one year, non-breaking data record. This is not a formal policy of the Corps of Engineers (Basco & Walker, 2010). Based on this definition, FRF has identified 219 storms from year 1997 to the end of year 2011.

In order to identify the wave height as a threshold, the Universitat Politecnica de Catalunya for the Catalan coast of Spain has employed the identical calculation method (Basco & Walker, 2010).

The measured "large waves" in Southern California from 1900 to 1983 have been discussed by Seymour, Strange, Cayan, Nathan (1984) and a major storm event is defined when the significant wave heights exceeded 3.0 meters (10 feet) for more than 9 hours (Basco and Walker, 2010). Since 1974, the New South Wales (NSW) Australia Department of Natural Resources has measured deep-water wave heights at seven locations in the Tasman Sea. Kamphuis (2010) employed the Peak-Over-Threshold analysis method to estimate recurrence intervals of extreme 3 wave height events. You and Lord (2008) concluded that individual storm events are when the significant wave heights are higher than 3.0 meters (Basco & Walker, 2010).

It becomes evident that relying just on hydrodynamics parameters to define a coastal storm would be site specific and can be determined by analyzing long-term wave data or water level information.

2.1.2 Storm Definitions Based on Water Levels

Astronomical tidal elevations and physical processes (wind stress, atmospheric pressure gradients, and wave setup) that elevate the normal tidal levels can be considered as threshold water levels to define a storm condition (Basco et al., 2010). Storm water level is not normally used as a threshold to define a "storm" event since it is as companied by large wave height events (Basco & Walker, 2010).

Recently, Munger and Kraus (2010) considered Mean Higher High Water (MHHW) as a threshold for storm definition. Storm conditions have been considered when wave height or storm surge is higher than MHHW. Duration is defined as the amount of time the storm surge exceeded 0.3 m. Their rational is based on the fact that the higher water level allows for waves to impact the beach at higher elevation and cause more erosion and damages. They introduced two new parameters called the integrated hydrograph (IH) and the integrated significant wave height (IHS). These two parameters have integrated over the storm duration which is based on the wave and surge elevations above MHHW. As a result, these two parameters have incorporated over the duration of the storm as a parameter.

Zhang, Douglas and Leatherman (2001) worked with MHHW and two standard deviations (SD) of all the annual hourly surge level. They argued that there is a strong relationship between surge and wave height in large storms (Tancreto, 1958) and it would be reasonable to use storm surge as a replacement for storm waves (Zhang et al., 2001). Their analysis is based on their investigation of data at FRF, Duck, North Carolina. They used storm surge greater than 2 SD and wave height greater than 2 meters and found a linear relationship between wave height and storm surge with $R^2 = 0.6323$ (Zhang et al, 2001). The MHHW seems suitable since it is calculated from long-term tide gage records approximates the beach berm elevation and would not include the local wave setup effect (Zhang et al., 2001).

2.1.3 Storm Definition Used for Original COSI

In previous COSI study by Klentzman (2007), for the available data at FRF Duck, NC, storm condition has been defined based on two criteria for different time periods. For the period of 1994 to1998, Klentzman considered the same storms as defined by FRF Duck, NC which is any wave height above 2 m with 8 hours duration. For the period of 1999 to 2003, the wave height of greater or equal than 1.62 m without surge at the depth of 8 meter is considered as the initial storm definition threshold to investigate the rest of the criteria. Then, the momentum of each data point is calculated based on the wave height and period and surge elevation to be compared to the momentum of 1.62 meter wave height. If the actual data point momentum was above the 1.62 m wave height momentum and it extended for 3 data points above it (9 hours), then it would be qualified as a storm. Forty eight hours is used as an interval between storms. Applying these definitions of storm resulted in 160 storms for the period of 1994 to 2003 at FRF, Duck, NC, which Klentzman (2007) analyzed and discussed in his dissertation. This storm definition is the only one that considered and combined all the four variables of wave height, storm surge, duration and currents all together in a physically related approach (Basco, Walker, 2010). Later, the same storm condition which was used for 1999 to 2003, applied to the same data set and resulted in 249 storms and results were presented in a paper titled "Statistical Analysis of the Coastal Storm Impulse (COSI) Scale at the Corps of Engineers, FRF, DUCK NC" by Basco, Mahmoudpour and Klentzman at International Conference on Coastal Engineering, (ICCE) 2008.

2.2 Storm Scales Classifications

The coastal professional community has long recognized a need to categorize storm strength pounding the coast in order to forecast and mitigate storm's damages. The correlation of storm damages to the meteorological and hydrodynamics parameters has been a subject of many studies. This correlation can be defined as a storm scale or storm parameter. One of the purposes of introducing a storm scale or parameter is to simplify the complex variation involved developing the scale for risk analysis and response management (Cooper & McLaughlin, 1998). There is a variety of parameters used for storm classifications, for instance: wind speed, wave characteristics such as height and period and storm surge which most of them are used in conjunction with their storm duration. In this chapter a summary of previously discussed storm scales which were discussed in Klentzamn (2007) dissertation is presented. Also, two other storm scales introduced by Zhang, Douglas and Leatherman (2001) and Munger and Kraus (2010) will be discussed. At the last, the Coastal Storm Impulse Scale will be discussed with its advantages and its shortcomings.

2.2.1 Summary of Previously Discussed Storm Scales

In his dissertation, Klentzman (2007) has reviewed and summarized some of the storm scales. Among them are Saffir-Simpson (1977), Dolan and Davis (1992), Halsey (1986), U.S. Geological Service Scale or Sallenger Scale (2000), Kreibel and Dalrymple (1995), Hurricane Impact Scale (Buch, 2003) and Hurricane Hazard Index (Kantha, 2006).

A Hurricane scale proposed by Saffir-Simpson (Saffir, 1977) is best known by the public. Saffir-Simpson scale is categorizing hurricanes based on central pressure, sustained wind speed and surge height. This scale has its limitation which most importantly does not consider the wave characteristics and the hydrodynamics of the storm.

The Dolan-Davis Scale (Dolan & Davis, 1992) is developed to categorize Northeasters based on wave height (above 2.1 m) and duration. This scale does not consider storm surge as a parameter to evaluate Northeasters. The Halsey Scale (Halsey, 1986) is based on the level of damages to the beach and the tide cycle that beach has been impacted by storm.

U.S. Geological Service or Sallenger Scale (Sallenger, Howd, Brock, Krabill, Swift, Manizade, & Duffy, 1999; Sallenger, 2000) considers parameters of swash zone relative to a fixed vertical datum (R) and the elevation of the dune relative to a fixed vertical datum (D). This scale categorizes the impact levels to four regimes: Swash, Collision, Overwash and Inundation regimes. The storm duration is not considered in this scale. Kriebel-Dalrymple Scale developed by Kreibel and Dalrymple (1995), for Northeasters using outputs from numerical modeling to predict the severity of erosion along the Delaware shoreline. The intensity scale considers wave height, storm surge and duration. This scale is a local scale and can not be used in other areas with different coastal morphology and different storm type. Its unit is ft^2 which does not relate to storm erosion. Bush (2003) proposed a Hurricane Impact Scale (HIS) that utilizes maximum elevation of storm surge, storm surge spread (coastal length impacted by higher water level), and wind speed to rank Hurricanes. This scale does not consider wave characteristics as a qualified parameter. Hurricane Hazard Index (HHI) has introduced by Kantha in 2006. The parameters used in this index are maximum sustained near-surface wind speed, the radius to which hurricane intensity winds extend and the translation speed of the hurricane. These parameters are wind field parameters and produce storm surge using numerical models. This scale does not consider waves parameters.

Miller and Livermont (2008) defined a Storm Erosion Index for predicting shoreline recession through storm surge and wave height integrated over the duration of a storm. Miller and Livermont (2008) indicate 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 (Basco et al., 2010).

In conclusion, the shortcomings of these scales have been discussed as following (Klentzman, 2007):

1) Only two of the scales (Kreibel-Dalrymple and HHI) have values that are quantitative and are calculated using actual measurements from storm data. The remaining five scales are all qualitative/category rankings of storm events.
2) Five of the scales are specific to either a hurricane or northeaster event. The two that are not storm-type dependant (Halsey and Sallenger) are limited to the type of coastline to which they can be applied (sandy dune beaches).
3) The scales applied specifically to Hurricanes (Saffir-Simpson, HIS, and HHI) use wind speed as a primary factor in the scale.
4) The scales applied specifically to Northeasters either ignore storm surge (Dolan-Davis) or are limited to use on only one coast (Kreibel-Dalrymple).

2.2.2 Storm Erosion Potential Index

Zhang, Douglas and Leatherman (2001) introduced a storm erosion potential index (SEPI) for northeasters which is the sum of the products of hourly storm surge and corresponding storm tide water levels. They documented that SEPI is correlates well with observed erosion (Zhang, et al, 2001). The SEPI proposed as the sum of the product of hourly values of storm surge height above two standard deviations, $S_{2SD}(t)$, and water level greater than Mean Higher High Water (H_{MHHW}) as (Zhang et al, 2001):

$$SEPI = \sum_{t=0}^{t_D} S_{2SD}(t) H_{MHHW}(t) \Delta(t) \qquad 2.1$$

where $\Delta(t)$ is the time interval and the quantity t_D is the integer number of hours of storm duration. In Figure 2.1 an example of SEPI scale at Sandy Hook, New Jersey, during March 5- 9, 1962, is presented.

Zhang et al. (2001) argues that even though there are several erosion indexes for large storms based on storm intensity measured by wind speed or wave energy and duration, but none of them considers the importance of the storm tide fully and has incorporated it into the index. Zhang et al. (2001) found that the erosion potential of severe northeasters is more dependent on storm tide than wave energy and duration. The SEPI limitations are that it was studied for northeasters and not for hurricanes and the wave parameters such as wave height and wave period have not been considered and their role is missing in their analysis.

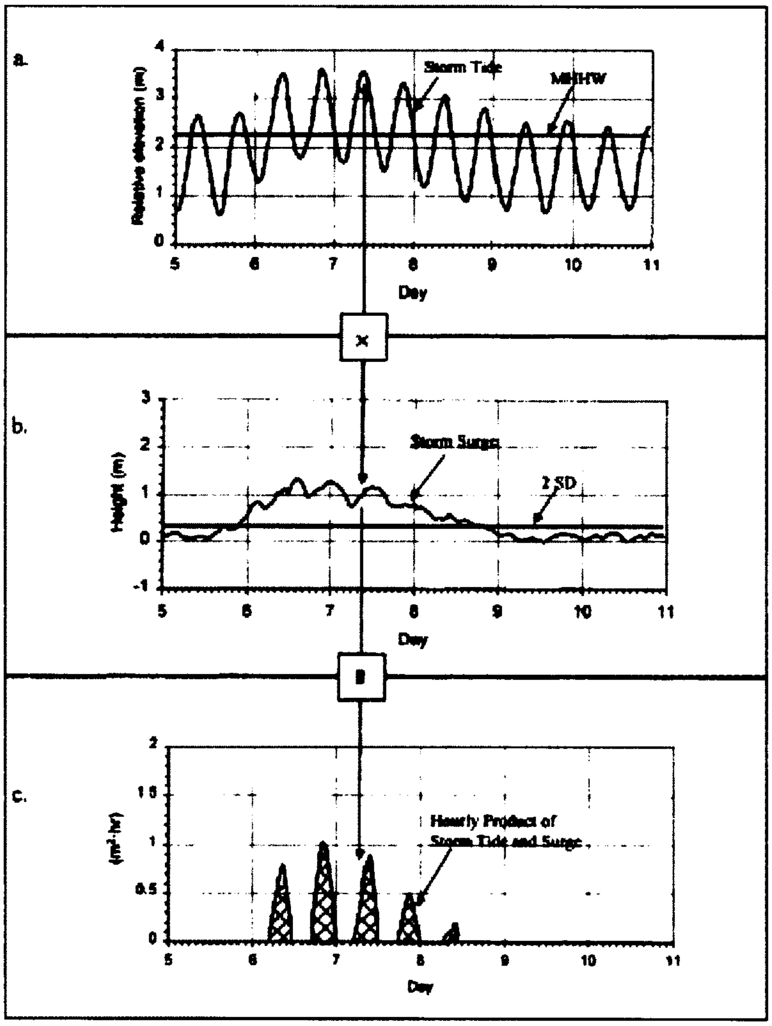

Figure 2.1. (a) Storm tides (sum of the astronomical tide and storm surge) relative to local datum (b) storm surge and (c) is the storm erosion potential index (SEPI) value (adapted from Zhang et al, 2001).

2.2.3 Storm Parameters Introduced by Munger and Kraus (2010)

Munger and Kraus (2010) have examined morphologic responses to storms at northern Assateague Island, Maryland. They applied time series of hindcast waves and water level as an input to drive the SBEACH beach erosion and overwash numerical model and have estimated the beach response which was verified by available data that caused significant morphologic change at the site. They have examined five storm related parameters and their correlation with volume of beach erosion. The parameters were peak surge, peak water level (surge plus tide), storm duration, and two new parameters called the integrated hydrograph (IH) and the integrated significant wave height (HIS).

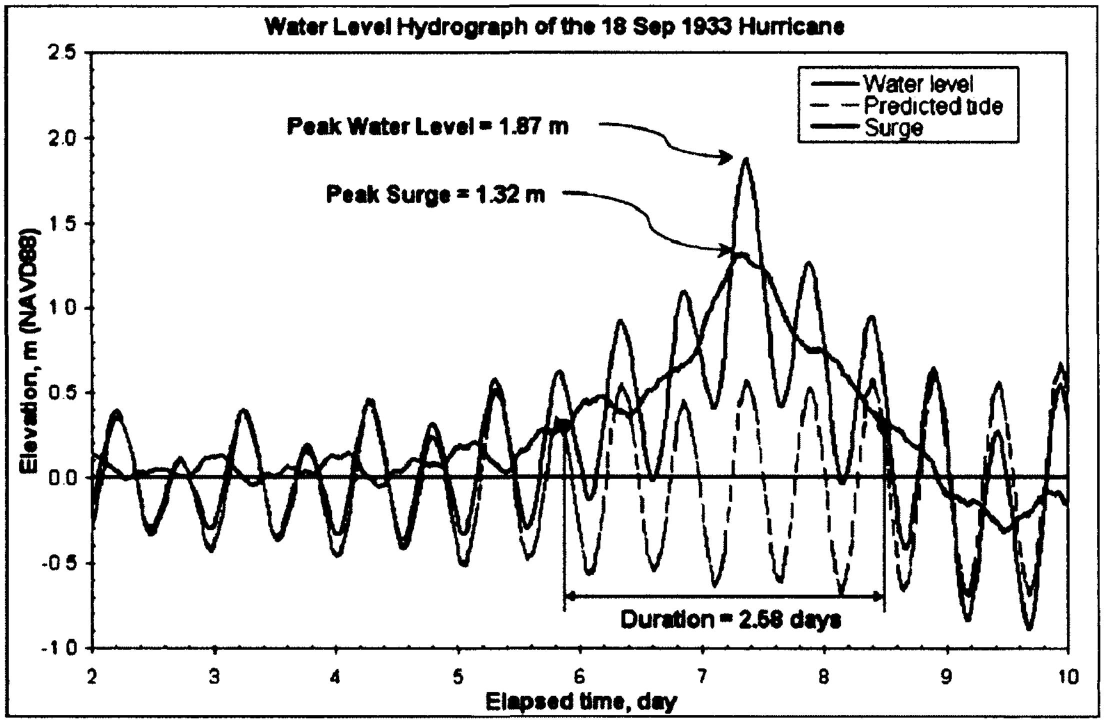

Figure 2.2. Definition sketch illustrating peak total water level and peak surge (adapted from Munger and Kraus, 2010)

They have found that storm-induced erosion was to be only weakly correlated or not correlated with the individual parameters of peak storm surge and peak water level. For tropical storms, erosion is strongly correlated with integrated wave height, and to a lesser extent with storm duration and integrated hydrograph, whereas for extratropical storms, erosion is found to be significantly correlated with the integrated hydrograph and to a lesser extent with integrated wave height and storm duration (Munger and Kraus, 2010).

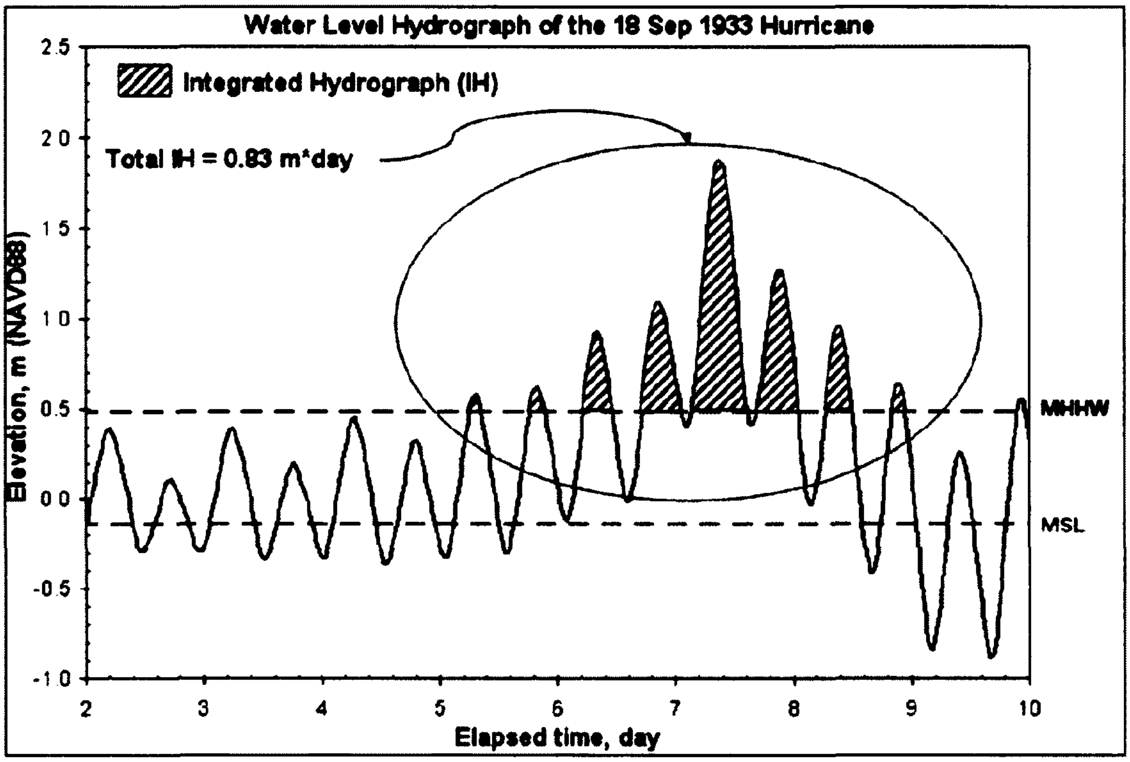

Figure2.3, Definition sketch for the IH parameter (adapted from Munger and Kraus, 2010)

Incorporating tide levels in a storm index is important since wave tank experiments and numerical models demonstrate that a 20% increase in storm tides results in 60% more dune erosion (Steetzel, 1991).

The work done by Munger and Kraus (2010) has been reviewed and following findings have been outlined:

1. Duration is defined as the amount of time the storm surge exceeded 0.3 m.

2. The two duration related parameters of Integrated Hydrograph (IH) and Integrated Significant Wave Height (IHS) are found to strongly correlate with beach erosion. Peak surge and peak total water level do not correlate to beach erosion.
3. Parameters from storms studied in this paper are from hindcast simulation and not from actual data. Storm-induced BEAch CHange (SBEACH) numerical model (Larson and Kraus 1989) has been used for beach erosion volume with hindcast input data not the actual survey data.
4. Wave period is not considered as a parameter in this study.
5. Tropical and Extratropical storms are considered and analyzed as two separate populations due to their origin and meteorological conditions.

2.3 Original Coastal Storm Impulse Parameter

Coastal Storm Impulse (COSI) parameter was first introduced by Basco and Klentzman (2006). In order to measure the storm strength, COSI utilizes the wave, current and the storm surge characteristics. The depth-integrated horizontal wave momentum flux is based on radiation stress theory introduced by Longuet-Higgins and Stewart (1964). The maximum wave momentum flux introduced by Hughes (2004) considers wave height, period, and water depth and it has been used in developing COSI parameter. In order to calculate the depth-integrated horizontal pressure and flow-induced momentum of the current the uniform, open-channel flow theory is used to developing the COSI scale. Dividing the total momentum of the waves and surge by a synthetic storm resulted in COSI scale with the maximum of number 10.

Thus far, the efforts have been done for COSI are all employed (1) the maximum, nonlinear wave momentum flux following Hughes (2004) and (2) the storm surge hydrograph to calculate the storm surge momentum. It is herein called the "original" COSI parameter method.

2.3.1 Original COSI Method Issues and Shortcoming

The original COSI research was more focused on developing the theory and applying the theory to a 10-year data set obtained from the Army Corps of Engineers Field Research Facility (FRF) in Duck, North Carolina. Since it was newly introduced the results were not fully investigated and hypothesis of correlation with beach damages not verified in details. Even though there are advantages in using original COSI such as application of it to both hurricanes and northeasters, considering the hydrodynamics parameters of storm, there are still issues and shortcomings.

There were two definitions of storms used for the period of 1994-1997 and for the period of 1995-2003 data sets which caused an inconsistency in the data.

In order to determine the COSI the maximum wave momentum (Hughes, 2004) is used. It was found that the surge accounts on average for 19% of the impulse to the coastline, while the wave action accounts for the remaining 81%. This ratio seems to underestimate the surge momentum portion in total momentum which is not physically realistic.

One of the other short comings of the original COSI is the fact that it calculates the surge value (difference between actual and predicted tides) for hydrostatic momentum. This approach does not differentiate the water levels above and below certain level such as the Mean High Water (MHW) and does not considers the importance of tides as a component. According to the recent research the beach erosion correlates to the water levels above MHHW during the storm (Munger and Kraus, 2010). Complete details for the calculation of the COSI scale for (1) the standard storm, (2) the location (water depth) of the near shore site, and (3) the methodology to calculate the maximum, depth-integrated wave momentum for a given wave height, period and directional parameters are presented in Basco and Klentzman (2006).

2.3.2 Application of Original COSI Parameter

Since the original COSI theory was introduced, there have been attempts for application of this theory. A paper, titled "Statistical Analysis of the Coastal Storm Impulse (COSI) Scale at the Corps of Engineers, FRF, Duck, NC", presented at ICCE, by Basco, Mahmoudpour and Klentzman (2008) in order to (1) present the results of a reanalysis of the 10-year data set (1994-2003) using a consistent storm definition that resulted in 249 storm events; (2) present the basic and extreme-event statistics; and (3) discuss the discrepancy between the Saffir-Simpson (wind speed) scale and the original COSI scale. The comparison of Saffir-Simpson scale to COSI scale for four largest original COSI scale is shown in Table 2.1 (Klentzman, 2007). It shows that the effect of large-scale coastal erosion is relatively independent of the Saffir-Simpson scale. Hurricane Dennis which was Category I in Saffir-Simpson scale has the large original COSI scale because of its duration and has caused extensive beach erosion (Beven, 2000). Klentzman suggested that the impulse of the storm, as reflected by original COSI is a better indicator of beach damages.

Table 2.1. Comparison of Saffir-Simpson Scale to COSI Scale (adopted from Klentzman 2007)

Hurricane	Date	COSI	Saffir-Simpson	Remarks
Dennis	Aug 29-Sep 5, 1999	10.4	1	Approached from south, reaching 200km east of Cape Hatteras where it remain until 2 September, having been downgraded to a Tropical Storm. Made landfall as a Tropical Storm on 5 September, Because of duration offshore, significant beach erosion occurred (Baron et al., August 1999).
Isabel	Sep 7-19, 2003	10.1	5 2 at landfall	Reached maximum intensity on 11 September, well out into the Atlantic. Gradually weakened until landfall as a Category 2 on 18 September. Considered one of the most significant tropical cyclones to effect North Carolina since Hurricane Hazel in 1954. (Beven and Cob, December 2003).
Felix	Aug. 12-21, 1995	7.6	3	Reached maximum value on 15 August. Approached closest to North Carolina coast on 17 August as a Category 1. Never made landfall. Considerable beach erosion (Baron, et.al., August 1995).
Gordon	Nov 16-22, 1994	5.8	1	Gordon never made landfall, following an erratic path until dissipating off of South Carolina on 20 Nov. Significant coastal erosion (Pasch, January 1995).

Also, a paper titled "Application of the Coastal Storm Impulse (COSI) Parameter to Predict Coastal Erosion", presented at ICCE, by Basco and Walker (2010), in order to apply the COSI parameter to predict beach erosion or accretion at the USACE, FRF in Duck, NC.

The hypothesis was that as the original COSI parameter increases or in other words as the strength of the storm increases, the volume of erosion on the sub-aerial beach also increases. This approach was opposite of the approaches that would consider the amount of beach erosion (or property/infrastructure damage) to classify storm intensity. They investigated the relationship between coastal storm impulse, and a storms impact to the volume change of the sub-aerial beach. The observation for appropriate storm conditions and existence of survey intervals to allow an analysis was resulted in both erosion and accretion in a seemingly random fashion. They discovered that for high original COSI values there are both high and low amounts of volume change, for both erosion and accretion. Similarly, storms with low original COSI values resulted in high and low amounts of volume change in both erosion and accretion (Basco & Walker, 2010).

The reason for getting mixed results was explained based on the condition of pre-storm profile and it can determine an erosion or accretion since a pre-storm profile can already been eroded in comparison to a healthy and stable beach. Further investigation has been suggested on the pre-storm beach conditions; type of beach profile, namely, reflective, dissipative, or intermediate; presence of near shore bars; swash zone slopes for individual storm events; shoreline changes during the time up to the pre-storm profile; and adjacent profiles (Basco & Walker, 2010).

2.4 Linear and Fourier Wave Theories

There are different types of wave theories depending on the criterion being considered to classify them. In general, waves can be classified as regular waves with constant height and period and irregular wave train with random characteristics. Applying different simplification to the continuity and momentum equations is the fundamental of having different wave theories.

2.4.1 Linear Wave Theory

The basic theories of regular waves are linear wave theory developed by Airy (1845) and nonlinear wave theories developed by other scientists.

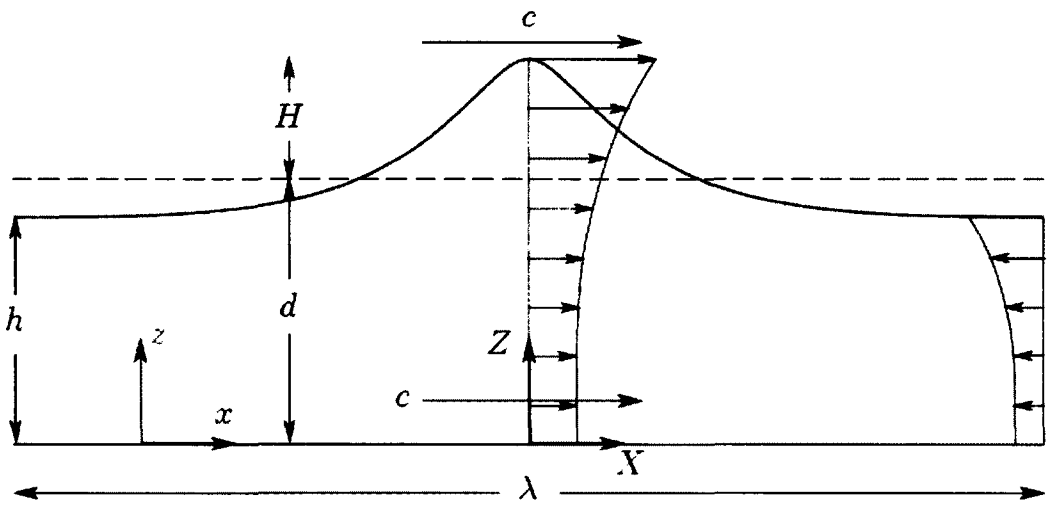

Figure 2.4. One wave of a steady train, showing principal dimensions, co-ordinates and velocities (adapted from Fenton 2010)

The Airy wave theory provides reasonable answers for water surface profile, particle velocities, particle accelerations, and particle displacements. The linear wave theory recommends a sinusoidal wave profile which can describe the free surface as a function of time t and horizontal distance x as following form:

$$\eta = \frac{H}{2}\cos\left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right) \qquad 2.1$$

where η is the elevation of the water surface relative to the still water elevation, H is wave height, L is the wave length and T is wave period. Other wave characteristics of wave such as horizontal and vertical water particle velocities, accelerations, displacements and pressure can be formulated as well as other wave characteristics. Depending on the relative depth ($\frac{h}{L}$) shallow ($\frac{h}{L} < \frac{1}{20}$), transitional ($\frac{1}{20} < \frac{h}{L} < \frac{1}{2}$), and deep water ($\frac{h}{L} > \frac{1}{2}$), wave theories can be utilized for more accurate results. The nonlinear wave theories such as Stokes are more appropriate for deep water while Cnoidal wave theory is more suitable for shallower water. Fourier approximation method does not have the limitation of Stokes and Cnoidal wave theories and can be applied to any water depth.

The nonlinear wave theories development has improved obtaining the wave parameters for specific case. Among nonlinear wave theories Stokes (1847, 1880), Boussinesq (1871) and Fourier approximation by Fenton (1985) are well known and widely used. The very basic solution of the Boussinesq equation is the Solitary wave theory (Russell 1844, Fenton 1972, Miles 1980). The Cnoidal wave theory was developed by Korteweg and de Vries (1895) based on Boussinesq theory but progresses in one direction. Figure 2.5 shows different wave profiles by different wave theories.

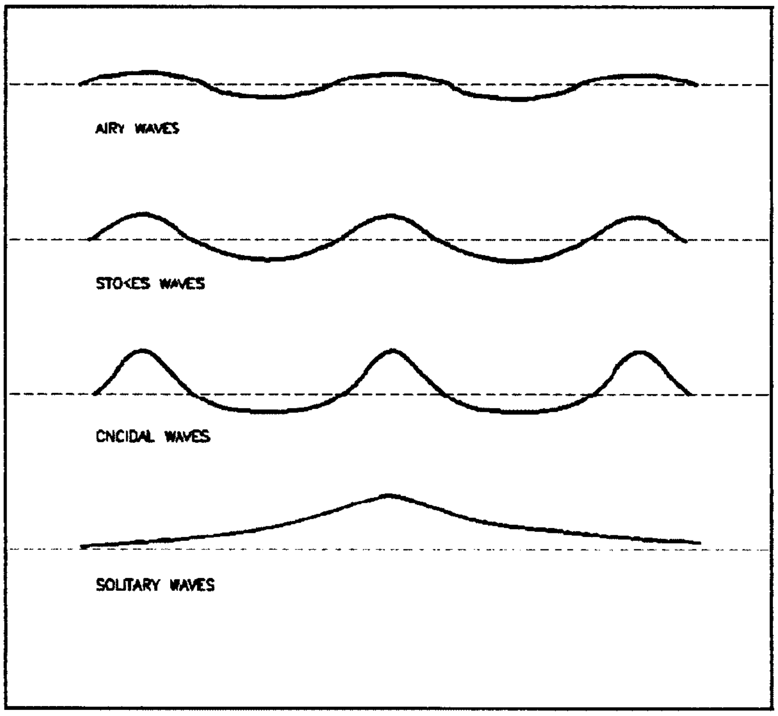

Figure 2.5. Wave profile shape of different progressive gravity waves (adapted from CEM, Demirbilek and Vincent 2008)

Fenton's Fourier approximation is a numerical solution and is recommended for all of the coastal applications as discussed in Coastal Engineering Manual (CEM) by Demirbilek and Vincent (2008).

2.4.2 Fourier Wave Theory

Fenton (1979) explains the impossibility of solving a general case of water wave motion analytically. Fenton (1979) offers a set of simplifications in order to obtain analytical solution for a single periodic wave train which propagates steadily without change of form. Fourier approximation method is a numerical solution and can be used for deep, transitional and shallow water.

It is most accurate to represent wave stream function (ψ) with velocity components of:

$$U = \frac{\partial \psi}{\partial y}, \qquad W = -\frac{\partial \psi}{\partial z} \tag{2.1}$$

and if fluid motion is irrotational, it satisfies the field equation (Laplace) of:

$$\frac{\partial^2 \psi}{\partial^2 x} + \frac{\partial^2 \psi}{\partial^2 z} = 0 \tag{2.2}$$

and the kinematic bottom boundary condition, so no water passes through the bottom ,

$$\psi(X, 0) = 0 \tag{2.3}$$

and the lateral periodicity boundary conditions (Sobey, Goodwin, Thieke, Westberg, 1987).

$$\psi\big(X, \eta(X)\big) = -Q \quad at \quad z = \eta(x) \tag{2.4}$$

where Z = η(X) on the free surface and Q is a positive constant denoting the volume rate of flow per unit length normal to the flow underneath the stationary wave in the (X, Z) co-ordinates. The dynamic free-surface boundary condition is an expression of specifying the pressure at the free surface that is constant and equal to the atmospheric pressure. In terms of the stream function this condition may be stated as below in which *R* is the Bernoulli constant.

$$\frac{1}{2}\left\{\left[\frac{\partial \psi}{\partial x}\right]^2 + \left[\frac{\partial \psi}{\partial z}\right]^2\right\} + g\eta = R \quad at \quad z = \eta(x) \tag{2.5}$$

The basis of the Fourier method is to write the analytical solution for ψ in separated variables form (Sobey et al., 1987) as:

$$\psi(x,z) = -\bar{u}z + \left(\frac{g}{k^3}\right)^{1/2} + \sum_{j=1}^{N} B_j \frac{\sinh jkz}{\cosh jkh} \cos jkx \qquad 2.6$$

where $\bar{u}$ is the mean fluid speed on any horizontal line underneath the stationary waves, the minus sign showing that in this frame the apparent dominant flow is in the negative **x** direction. The $B_1,\ldots, B_N$ are dimensionless constants for a particular wave, and N is a finite integer. The truncation of the series for finite N is the only mathematical or numerical approximation in this formulation. The quantity k is the wave number ($k = {}^{2\pi}/_{L}$) where L is the wavelength, which may or may not be known initially, and h is the mean depth (Fenton, 2010).

Sobey, Goodwin, Thieke and Westberg (1987) studied and compared Fenton's numerical method for steady water wave problems to other methods. They found that even for waves close to breaking, accurate results can be obtained from Fourier series. Also, experimental data and other wave theories were compared to Fourier series by Fenton and McKee (1990) and Sobey (1990) and confirmed the consistency of the results. Also, they proved that Fourier series is applicable to a wide range of wave height, wave period, and water depth (CEM, Demirbilek and Vincent, 2008).

Based on Fourier wave theory the instantaneous water surface elevation $\eta_{(x)}$ and water particle pressure are given by:

$$\eta_{(x)} = \frac{1}{2} a_N \cos Nkx + \sum_{j=1}^{N} a_j \cos jkx \qquad 2.7$$

$$p_{(x,z)} = \rho(R - gh - gz) - \frac{1}{2}\rho(u^2 + w^2) \qquad 2.8$$

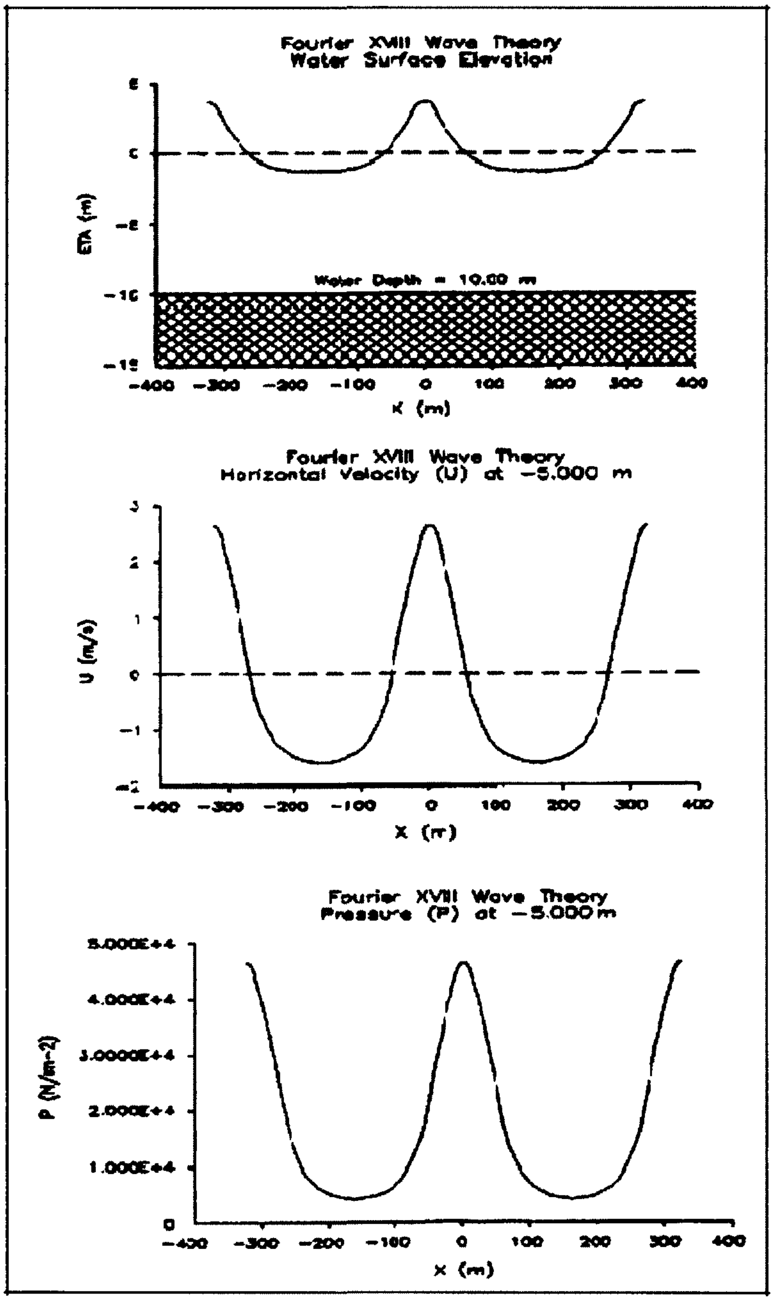

Figure 2.6. Surface elevation, horizontal velocity, and pressure for wave height of 5 m and period of 10 sec at a depth of 10 m (adapted from CEM, Demirbilek and Vincent, 2008)

In shallow water for the wave height of 5 m and period of 10 sec at a depth of 10 m, Figure 2.6 shows the wave profile, particle velocity and pressure using Fourier numerical approximation.

2.5 Wave Momentum Flux and Radiation Stress

Utilizing an analogy to Electro Magnetic waves and the pressure, or stress, Longuet-Higgins and Stewart (1962), explained the principal that gravity water waves produce a net horizontal thrust (force) above the local hydrostatic force when integrated over the water column and averaged over the wave period (Basco, 1982). Even though the units for this wave–induced thrust were force per unit length, it was referred to as "radiation stress" (Basco, 1982, page 43). At the same time, Lundgren (1962, 1963) has discussed the same principles which were corrected by Danish Technical University (1969). Radiation Stress is now accepted as general term to refer to this forcing function (Basco, 1982).

Longuet-Higgins and Stewart (1964) noted the relevance of radiation stress or wave momentum flux as "Surface waves possess momentum which is directed parallel to the direction of propagation and is proportional to the square of the wave amplitude. Now if a wave train is reflected from an obstacle, its momentum must be reversed. Conservation of momentum then requires that there be a force exerted on the obstacle, equal to the rate of change of wave momentum. This force is a manifestation of the radiation stress" (page 530). It continues "A stress is by definition equivalent to a flow of momentum. The radiation stress may thus be defined as the excess flow of momentum due to the presence of waves" (page 530).

In basic terms, there is more momentum flow in the direction of wave propagation because when the water surface is at the crest of the wave the velocity u is in the direction of wave and in the opposite direction when the water surface is at the trough. Also, the pressure stress acting under the wave crest is greater than the pressure stress under the wave trough leading to a net stress over a wave period. Radiation stress exists because of the finite height of the waves. Linear wave theory can be used to reasonably approximate radiation stress but it has its limitations.

The present wave momentum formulas are driven from radiation stress theory and from different wave theories. Longuet-Higgins and Stewart (1964) defined the component of "radiation stress" perpendicular to the wave crest as "the mean value of the total flux of horizontal momentum across a plane x=constant, with respect to time, minus the mean flux in the absence of waves".

Or the component S_{xx} of the radiation stress can be formulated as:

$$S_{xx} = \overline{\int_{-h}^{\eta(x)} (p + \rho u^2)\, dz} - \int_{-h}^{0} p_0\, d_z \tag*{2.9}$$

Where:

S_{xx} = Wave averaged momentum flux (radiation stress) in x- direction with units of force per unit length of wave crest.

p = instantaneous wave pressure at a specified position

u = instantaneous horizontal water velocity at the same specified position

ρ= water density (1025 kg/m3)

p_0 = hydrostatic pressure

$\eta(x)$= Sea surface elevation relative to still water level

h = Water depth from bottom to still water level

The radiation stress theory plays a significant role in explaining wave caused phenomenon such as the mystery of how oblique wave attack can generate longshore currents. In addition, it has been used to develop theories for nearshore circulation systems, wave setdown and setup, and rip currents (Basco, 1982).

Radiation stress or momentum flux formula can be simplified and its value can be determined by applying different wave theories. In the next two sections wave momentum flux formulas utilizing the Linear wave theory and Fourier wave theory will be explained.

2.5.1 Wave Momentum Flux Utilizing Linear Wave theory

Longuet-Higgins and Stewart (1964) defined the component of "radiation stress" perpendicular to the wave crest as the wave momentum flux integrated over the water depth and averaged over the wave. Hughes (2004) has presented a simplified form of the above equation as:

$$S_{xx} = \frac{1}{L} \int_{0}^{L} \int_{-h}^{\eta(x)} (p_d + \rho u^2)\, dx\, dz \qquad 2.10$$

Where p_d is instantaneous wave dynamic pressure at a specified position.

By substituting linear wave theory expressions for horizontal velocity and integration, the wave averaged momentum flux, also known as radiation stress, can be expressed as:

$$S_{xx} = \frac{1}{2} \rho g \left(\frac{H}{2}\right)^2 \left(\frac{1}{2} + \frac{2kh}{sinh2kh}\right) \qquad 2.11$$

In this formula, the first-order wave kinematics above the still water level have been applied, which is not strictly first order theory, it makes the results "extended linear theory" (Hughes 2004).

Hughes (2004) concluded that "wave momentum flux is the property of progressive waves most closely related to force loads on coastal structures or any other solid object placed in the wave field" (page 1071). He argued that wave momentum flux can be a good candidate to relate the characterization of waves in near shore region to coastal processes (Hughes, 2004). He found that it would be reasonable that a parameter representing the rate of change of wave momentum be used in estimation of nearshore sediment transport processes. Using the Linear wave theory to drive the radiation stress formula would have its limitations for shallow water and it is not considered as an accurate methodology to be applied to any water depth specifically when wave approaching its limiting relative wave height $(\frac{H}{h})$ of breaking.

2.5.2 Wave Momentum Flux Utilizing Nonlinear (Fourier) Wave Theory

Sobey, et al. (1987) compared Fenton's Fourier approximation to other wave theories and concluded that it produces accurate results even for waves close to breaking. Also, Sobey et al. (1987) derived the formulas for wave kinematics, dynamics, and wave integral properties for Fenton's theory and results were summarized.

From Sobey et al. (1987) the instantaneous pressure can be calculated as:

$$P_{dyn}\,(x,z) = \rho R - \rho g h - \frac{1}{2}\,\rho(u^2 + w^2) \qquad 2.12$$

and radiation stress can be computed as:

$$S_{xx} = \overline{\int_0^{\eta} (P + \rho U^2)\,dz} - \frac{1}{2}\rho g h^2 = 4T - 3V + \rho h \overline{U_b^2} - 2C_E I \qquad 2.13$$

Where:

Momentum/unit horizontal area:

$$I = \overline{\int_0^{\eta} \rho U\,dz} = \rho(Ch - Q) \qquad 2.14$$

Kinetic Energy/unit horizontal area:

$$T = \overline{\int_0^{\eta} \frac{1}{2}\rho(U^2 + W^2)\,dz} = \frac{1}{2}(CI - \rho C_E Q) \qquad 2.15$$

Potential Energy/unit horizontal area:

$$V = \overline{\int_0^{\eta} \rho g(Z + h)\,dz} = \frac{1}{2}\rho g\left(\overline{\eta^2} - h^2\right) \qquad 2.16$$

Mean Square Bed Velocity:

$$\overline{U_b^2} = \frac{1}{L}\int_0^{L} U^2(X, 0, t)\,dx = 2(R - gh) - C^2 + 2C_E C \qquad 2.17$$

Wave speed:

$$C = \frac{2\pi}{kT} = \overline{u} + C_E \qquad 2.18$$

Where C_E is Eulerian current

In this dissertation, the nonlinear Fourier numerical approximation wave theory has been used to compute the wave average radiation stress for different mix of wave height, period and water depth. A computer FORTRAN Codes have been used to accurately determine the average radiation stress based on Fourier wave theory. Sobey et al (1987) recommend that the Fourier theory at 18th order would be accurate and any corrections are approaching typical machine precision and that is the order used for this work.

2.5.3 Wave Momentum Flux used for Original COSI Parameter

In the original COSI parameter a nonlinear (Fourier) approximation of maximum wave momentum flux has been used (Klentzman, 2007) from Hughes (2004) empirical formula. The rationale behind using the maximum wave momentum flux was that the average value of radiation stress flux is small since it is depth integrated over a wavelength from large positive values at the crest to large negative values in the trough (Klentzman, 2007). And, it would be more rational parameter to use when discussing wave force on structures or on the coastline. Therefore, the maximum, depth-integrated wave momentum flux that occurs at the crest during the passage of a wave is used to develop original COSI parameters (Klentzman, 2007). Using the Fourier approximation wave theory provides complete kinematics for finite amplitude waves spanning the range covered by Stokes and Cnoidal wave theories. Unfortunately, each parameter such as maximum wave momentum flux must be calculated numerically and it reduces the utility of the maximum wave momentum flux for its applications (Hughes, 2004). For these reasons, a simple empirical approximation for the maximum wave momentum flux parameter of finite amplitude waves has been developed using a Fourier wave computer program (Hughes, 2004) which is shown as follow:

$$\left(\frac{M_F}{\rho g h^2}\right)_{max} = A_0 \left(\frac{h}{gT^2}\right)^{-A_1} \qquad 2.19$$

Where:

$$A_0 = 0.6392\left(\frac{H}{h}\right)^{2.0256} \qquad 2.19a$$

$$A_1 = 0.1804\left(\frac{H}{h}\right)^{-0.391} \qquad 2.19b$$

and M_F is depth-integrated maximum wave momentum flux across a unit width which is maximum at the crest of the wave.

Klentzman (2007) utilized the empirical formulae 2.19, 2.19a and 2.19b to calculate the maximum wave momentum flux at each data point.

2.6. Summary

In this chapter, related literature to the COSI parameter have been critically reviewed. The most updated storm definitions and storm scales have been studied and their pros and cons have been discussed. The Linear and Nonlinear (Fourier) wave theories have been explained and formulations for different parameters have been described. The history and the basics of wave momentum flux and radiation stress has been fully explained and related formulation explained. For the Original COSI parameter, the theory and its development as well as its advantages and shortcomings have been discussed.

The reason to investigate and introduce a new approach to Original COSI Scale is that the wave momentum and surge momentum are not proportionally distributed in respect to the total momentum. Application of Original COSI concept does not seem to correlate very well to what has been expected for beach erosion (Basco & Walker, 2010). Investigating the previous work revealed that the influence of tides have been omitted. It seems necessary and reasonable to consider tides according to other studies and should be included in developing the COSI parameter concept.

In the next chapter the development of the Modified COSI Parameter will be discussed in order to overcome the shortcomings that have been mentioned for Original COSI parameter.

In the present dissertation, for the first time the wave momentum flux that is averaged over the phase of the wave and integrated over depth will be formulated in an empirical formula by using Fourier wave theory approximation and will be applied to the same data set.

CHAPTER 3

DEVELOPMENT OF THEORY

3.1 Development of The Modified COSI Parameter

In this chapter, the theory and development of the Modified Coastal Storm Impulse (COSI) Parameter will be discussed. Combining two fundamentally different physical phenomenon of wave and storm surge is an essential challenge in developing a coastal storm parameter. According to different wave theories, it is possible to estimate the wave momentum over the storm, but storm surge momentum is not simple to estimate (Basco & Klentzman 2006). In order to combine the wave momentum and the storm surge momentum, Klentzman (2007) proposed that "the principles of conservation of horizontal momentum are applied to combine the forces of the storm surge and water waves at the coast" (page 16). This is the fundamental benefit of COSI to combine elevated water levels caused by storm surge and wave dynamics at a site along the coast. The horizontal momentum in a storm approaching the coast is altered by the land mass (bathymetry, shoreline configuration, topography, dune/beach profile, infrastructure, etc.) that interferes with the storm movement. The change in momentum is equal to the impulse according to an altered Newton's 2nd Law of motion. This momentum is then integrated over the storm duration to determine the storm impulse on the coast. Calculating storm impulse due to the changes in momentum can be quantified and is more practical than quantifying the change in storm momentum which is storm mass multiply storm velocity (Basco, et al. 2008). The sum of all the external forces integrated over the storm duration is simply storm impulse that causes the change in storm momentum (Basco and

Klentzman, 2006). Considering the conservation of momentum for control volume, this can be formulated by utilizing the Newton's Second Law of Motion ($F = \overrightarrow{m}.\overrightarrow{a}$) to find impulse ($F.d_t$) which is balanced by the change in momentum ($m.\overrightarrow{dv}$).

$$F = \sum f = \overrightarrow{m}.\overrightarrow{a} = m\,\frac{\overrightarrow{dv}}{dt} \qquad 3.1$$

Impulse equals to change in momentum or

$$Impulse = \begin{bmatrix} Offshore\ Momentum\ in \\ Coastal\ Storm \end{bmatrix} - \begin{bmatrix} Landward\ Momentum\ of\ Limit\ of \\ Flooding \end{bmatrix}$$

or

$$\sum f d_t = m v_0 - \ m v_l \qquad 3.2$$

Since the landward momentum of limit of flooding would be zero then

$$\sum f d_t = \left(f_{p(t)} + f_{w(t)} + f_{c(t)}\right) d_t \qquad 3.3$$

Where:

$f_{p(t)}$ = hydrostatic force due to water level

$f_{w(t)}$ = depth-averaged, integrated wave momentum flux

$f_{c(t)}$ = force due to current

In order to be consistent with previous work for the Original COSI, the current momentum is not being considered. In the Original COSI, comparing to the wave and surge momentum the current momentum is determined to be minimal and can be neglected (Klentzman, 2007).

Considering the momentum at any time (t) the total storm momentum would be:

$$\Upsilon_s = f_{p(t)} + f_{w(t)} \tag{3.4}$$

where:

Υ_s = total storm momentum (Newtons/meter).

$f_{p(t)}$ = storm surge momentum (Newtons/meter).

$f_{w(t)}$ = wave momentum (Newtons/meter).

The calculation of $\Upsilon_s,\ f_{p(t)}\ and\ f_{w(t)}$ are all per unit width of coastline.

Finally for the application in the COSI parameter the storm impulse (I_s) can be determined as the integration of total storm momentum over the duration of the storm:

$$I_s = \int_0^D \Upsilon_s d_t \tag{3.5}$$

As has been discussed, the total storm impulse consists of two components of the total depth integrated time averaged wave momentum and the storm surge momentum.

In this dissertation the horizontal force of the storm surge above the Mean High Water level and the wave horizontal average thrust determined by Fourier wave theory are basically added together to determine the total horizontal force of the storm at any time. When integrated over the storm duration, the total change in momentum (impulse) is determined. This is the fundamental of the Modified COSI parameter.

3.2 Derivation of Average Wave Momentum

The original COSI, as discussed in chapter two, was based on the maximum wave momentum for the wave momentum parameter. The maximum wave momentum parameter was calculated based on Hughes (2004) empirical formula. Since there were some concerns regarding the overestimation of the wave momentum in comparison to the storm surge momentum in original COSI, therefore redefining of this new approach has been initiated.

Utilizing nonlinear Fourier wave theory and FORTRAN computer codes resulted in a set of empirical formula to calculate the wave momentum parameter averaged over the wave period. Applying this average over wave phase momentum instead of maximum momentum is the main difference in estimating the wave momentum in the Modified COSI Parameter to original COSI. In the next sections the development of this parameter will be discussed in details.

3.2.1 Fourier Wave Theory Computation program

A FORTRAN code for the Fourier Approximation method for Steady Progressive Waves was obtained and used to estimate the average wave momentum flux. The theory and formulation were discussed in Chapter 2. The codes were developed within the Hydraulic and Coastal Group in the Department of Civil Engineering at University of California, Berkeley by Rodney J. Sobey, Peter Goodwin, Robert J. Thieke and Robert J. Westberg, Jr., (1989). The codes were repeatedly run for selected combinations of relative wave height ($H/_h$) and relative depth ($h/_{gT^2}$). For each set of data the estimate of non-dimensional depth-integrated average wave momentum flux is calculated as part of the output data.

Tables 3.1 and 3.2 show an example of input and output data respectively for wave height of 2 meter at the depth of 5 meter and the wave period of 8 seconds. This data is used in computing set of the relative wave height of $^{H}/_{h} = 0.4$ and relative depth of $^{h}/_{gT^2} = 0.00796$.

Table 3.1. Input data sample for Fourier program for wave height of 2m, depth of 5m and period of 8 sec.

```
        2         5          8.0          0.0          'EULER'
        9.81      1025
        18        25
        10        50
```

The first line in Table 3.1 shows the wave height, water depth, wave period and uniform Eulerian current velocity. Current velocity for all of the runs assumed to be zero to just account for wave momentum and not wave-current interaction. The second line shows the other relative input data such as water density and gravitational acceleration. Units of g and ρ define a consistent system of units for the entire computation. Typical values for sea water would be $\rho = 1025\ \text{kg/m}^3$ and $g = 9.81\ \text{m/sec}^2$. The third line includes the truncation order of Fourier theory (N) and number of uniformly spaced intervals between surface nodes (M). Line four, defines an x, z grid in the steady reference frame for output of field variables such as velocities, accelerations and pressures. This line has number of uniformly spaced intervals between crest and trough variables and number of uniformly spaced intervals between lower z elevation for output of field variables.

Table 3.2. Output data sample for Fourier program for wave height of 2m, depth of 5m and period of 8 sec

```
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
```

The output file is shown in Table 3.2, for the same input data as Table 3.1 for wave height of 2 m and 8 sec period at the depth of 5 m.

Table 3.3. Dimensionless to units conversion parameters for Fourier 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, $\omega C_g/g$

The output file summarizes the input file in the beginning and dimensionless parameters based on ω, ρ and g shown in Table 3.3.

The solution file is completed by a number of dimensionless derived integral quantities and is shown in Table 3.2.

3.2.2 Matrix of Input Data

The input data for the range of relative wave height have been considered in order to cover the values for relative depth from deep to shallow water. The ranges for the input matrix are shown in Table 3.4

Table 3.4. Matrix parameter ranges for Fourier program input data

Relative Wave Height (H/h): 0.1, 0.2, 0.3, 0.4, 0.5, 0.56, 0.6
Relative Depth (h/gT^2): Ranges from Minimum 0.000283 to Maximum 0.163099.

Also, the wave breaking has been considered as limitation to input matrix data. The wave steepness limitation is given for the breaking criterion tabulated by Williams (1985) and expressed by Sobey (1998) as the rational approximation of

$$\frac{\omega^2 H_{limit}}{g} = c_0 \tanh\left(\frac{a_1 r + a_2 r^2 + a_3 r^3}{1 + b_1 r + b_2 r^2}\right) \qquad 3.6$$

Where: $r = \omega^2 h/g$, *a1 = 0.7879, a2 = 2.0064, a3 = -0.0962, b1 = 3.2924,*

b2 = -0.2645, and C_0*= 1.0575.*

Sobey noted the above expression has a maximum error of 0.0014 over range of Williams' table. Williams (1985) tabulation of limit waves is more accurate than the traditional limit steepness given by:

$$\frac{H_{limit}}{L} = 0.142\,tanh(kh) \qquad 3.7$$

Equation 3.7 overestimates limiting steepness for long waves and underestimates limiting steepness for short waves (Hughes 2004).

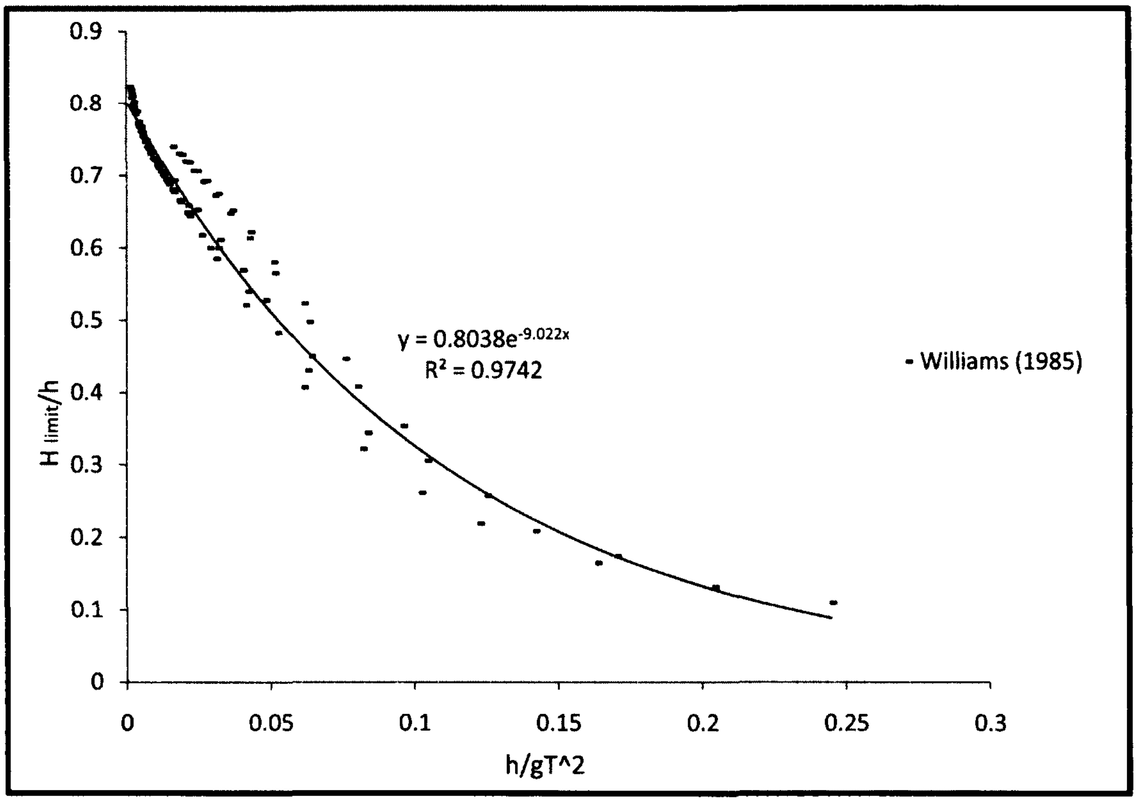

Figure 3.1. Results from Williams (1985) wave height breaking limit ratio ($\frac{H_{limit}}{h}$) versus relative depth ($\frac{h}{gT^2}$)

The results of Williams (1985) wave breaking relationship has been plotted and a power equation is fitted to the data in order to know the limitation of the relative wave height in the computation. Figure 3.1 shows the results for the Williams breaking equation based on relative depth ($h/_{gT^2}$) and breaking limit of wave steepness ($\frac{H_{limit}}{h}$). The data range from depth of 5 m to 60 m and wave period from 5 sec to 20 sec, which resulted in the wave height of minimum 2.10 m and maximum 43.72 m.

3.2.3 Results of Fourier Computer Program

After running the program for the range of relative wave height and relative depth, the results were processed to obtain the dimensionless wave momentum $M/\rho gh^2$. Results are presented as set of curves shown in Fig. 2.1. Coding accuracy is checked by assuring that estimates of ($M_{Avrg)}$) for small amplitude, deepwater waves were the same as estimates given by the first-order analytical solution in the following section.

3.2.4 Verification of Fourier Wave Theory

The verification of data is done by comparing the results for the linear wave theory. The linear wave theory average radiation stress formula is utilized and applied to the same input matrix to obtain the values of linear wave momentum.

$$Sxx = \frac{1}{2}\ \rho g a^2 \left(\frac{1}{2} + \frac{2kh}{sinh2kh}\right) \qquad 3.8$$

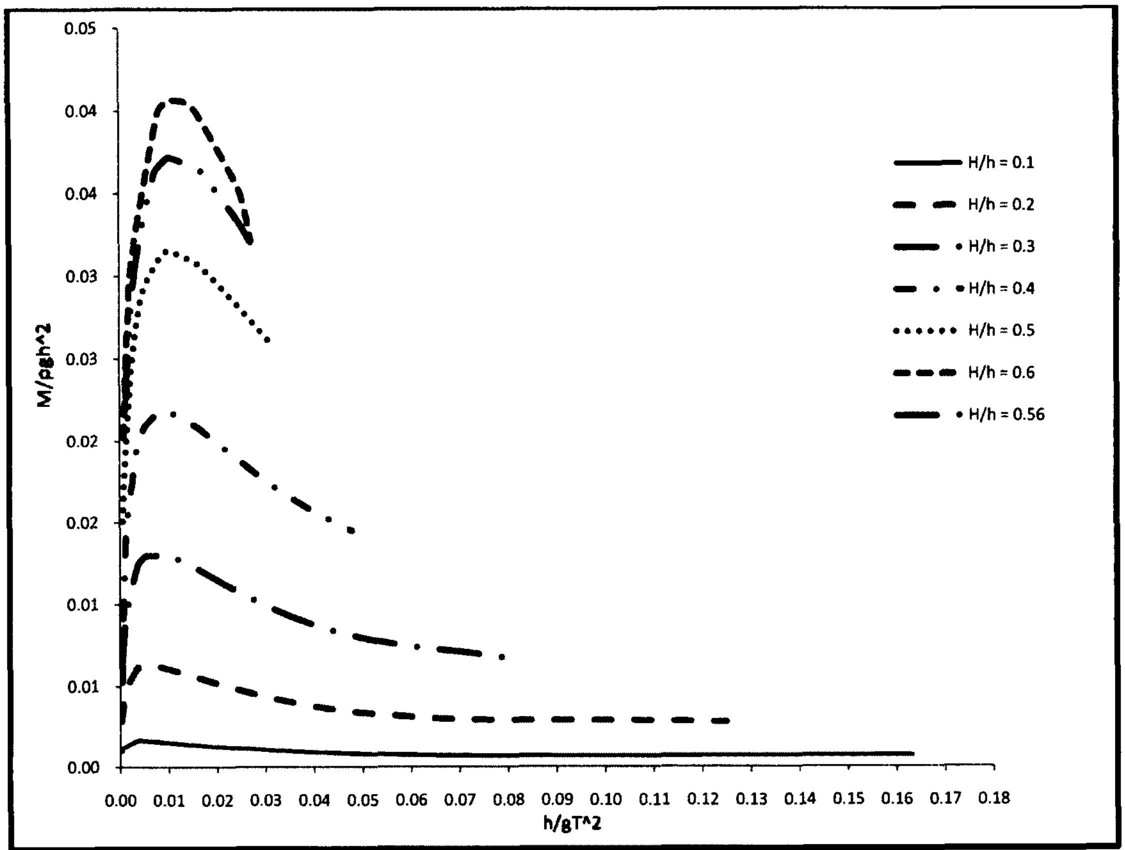

Figure 3.2. Fourier Wave Momentum Parameter versus h/gT^2 for range of H/h

The comparison of the data shows that for low relative wave height of $H/h = 0.1$ there is a good match to where the relative depth is around $h/gT^2 = 0.005$ which linear wave theory starts to overestimate the dimensionless average momentum. This divergence becomes more apparent as relative wave height is increasing. The following figures show the comparison of wave momentum from the Fourier wave theory and the linear wave theory. The difference between linear and Fourier wave theory estimates of the wave momentum flux parameter is illustrated on Fig. 3.3, 3.4, 3.5, and 3.6 which show curves representing relative wave height of H/h= 0.1, 0.2, 0.3, 0.4, 0.5, 0.56 and 0.6.

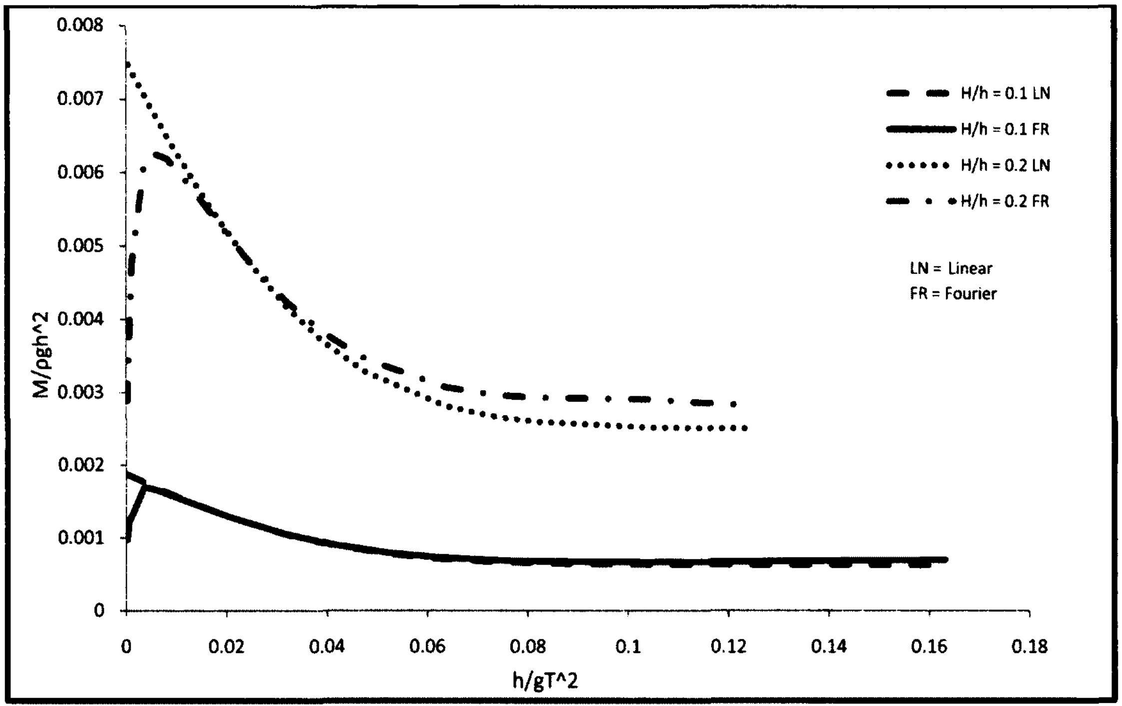

Figure 3.3. Linear and Fourier wave momentum flux parameter versus $\frac{h}{gT^2}$ for different $\frac{H}{h}$

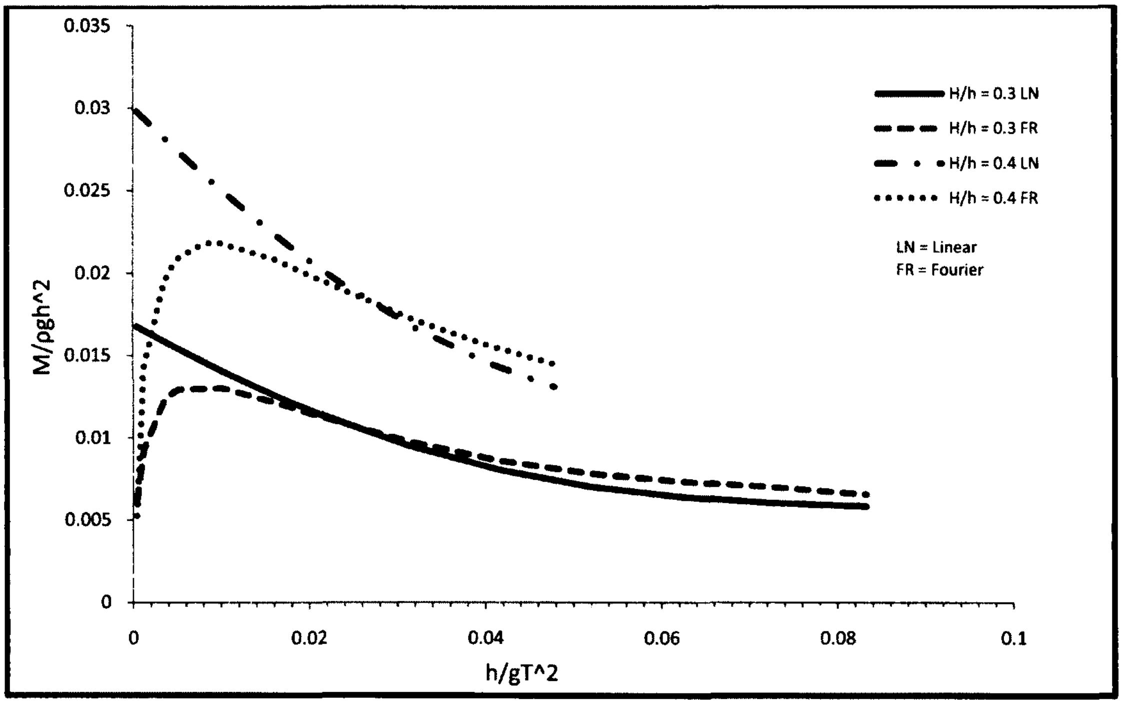

Figure 3.4, Linear and Fourier wave momentum flux parameter versus $\frac{h}{gT^2}$ for different $\frac{H}{h}$

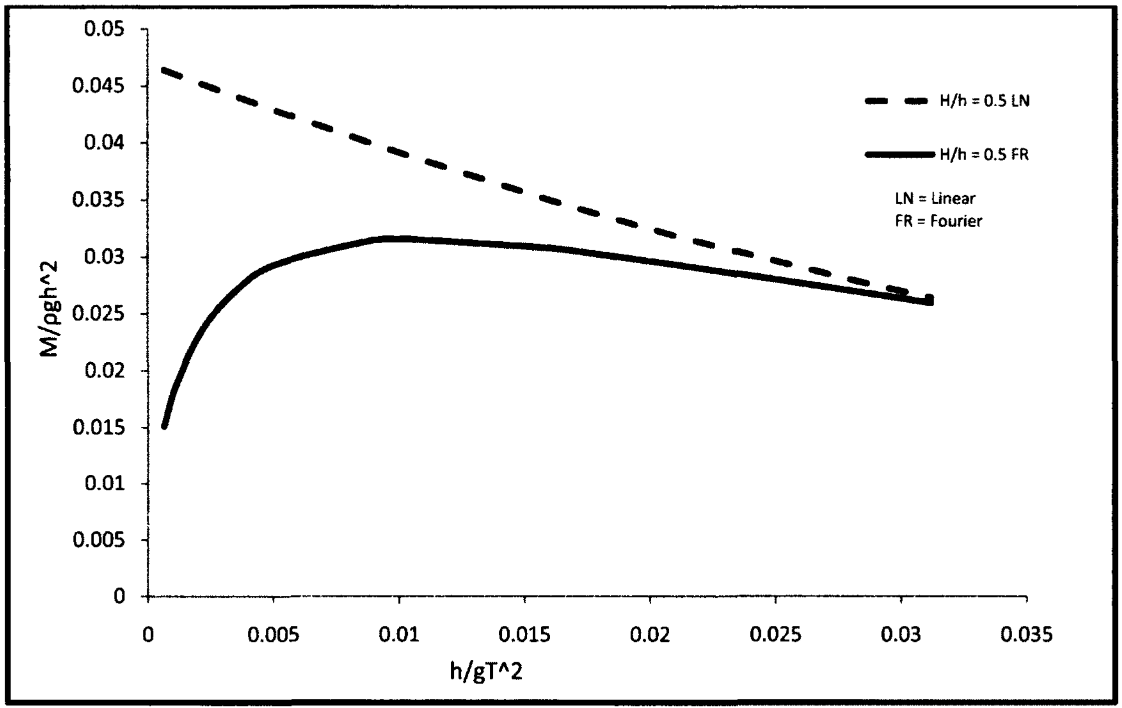

Figure 3.5. Linear and Fourier wave momentum flux parameter versus $\frac{h}{gT^2}$ for different $\frac{H}{h}$

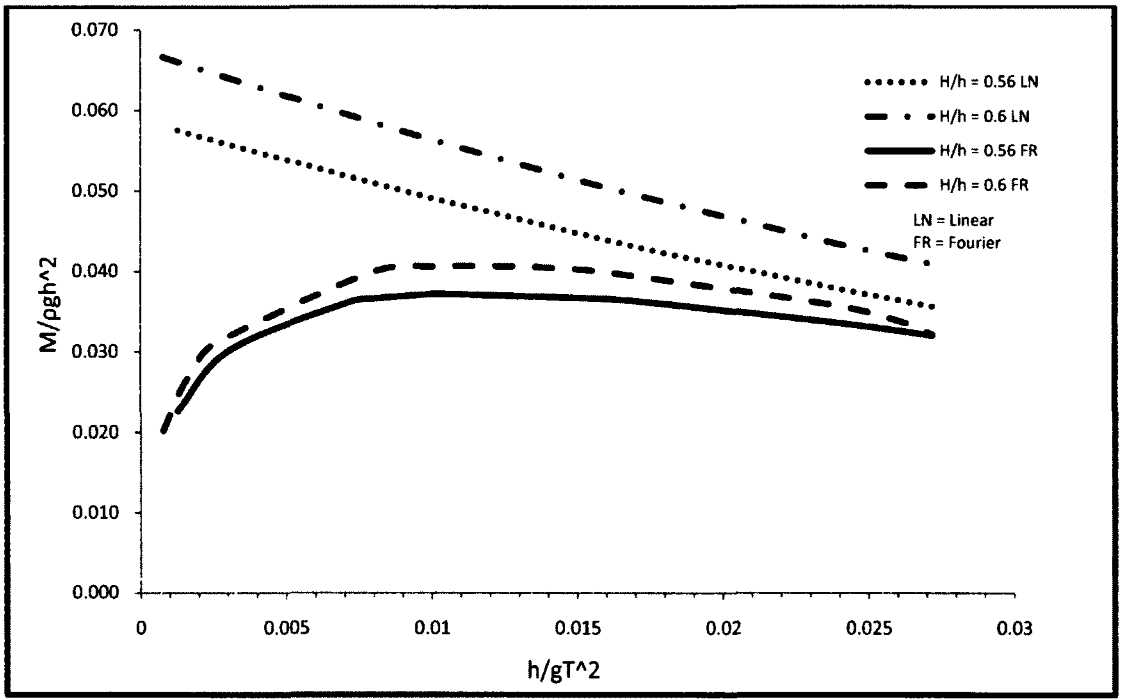

Figure 3.6. Linear and Fourier wave momentum flux parameter versus $\frac{h}{gT^2}$ for different $\frac{H}{h}$

For the lower relative wave height of H/h=0.1, 0.2, 0.3, and 0.4 there are better correspondence between linear and Fourier approximation for values of $h/_{gT^2}$ greater than about 0.025. As the relative depth decreases from 0.025 to 0.01, there is increasing divergence which illustrates the importance of nonlinear wave shape. And, as relative depth decreases from 0.01, the divergence is much greater. The linear theory over predicts the values of radiation stress over Fourier theory in the range of $h/_{gT^2}$less than 0.025. For relatively high values of H/h=0.6, linear theory estimation clearly over estimates the correct value of the wave momentum flux parameter. For example, at a value of relative depth of $h/_{gT^2} = 0.00127$, the linear approximation estimate of dimensionless momentum $(\frac{M}{\rho g h^2})$ is 2.3 times greater than the Fourier estimate. This difference increases as relative depth decreases, emphasizing the importance of nonlinearities in nearshore waves. In general the Fourier average momentum is 10 times lower than Fourier maximum momentum which Hughes (2004) calculated.

3.2.5 Average Wave Momentum Empirical Formulas

A set of empirical equations for estimating the wave momentum flux parameter for finite amplitude steady waves was established using the calculated curves of constant H/h shown in Figure 3.2. After careful examination of the data, two regions were proposed and data divided at the relative depth of $h/_{gT^2}$= 0.01 to consider the fact that for lower relative depth, the nonlinearity of the waves influence the results in a greater extent. For each set, a nonlinear best-fit of a two-parameter power curve was performed for each calculated H/h curve for each region. Then, the resulting power curve coefficients and exponents were plotted as a function of H/h, and fortunately, both the coefficients and exponents could be reasonably represented by power curves. Figure 3.7 shows the region of relative depth less than 0.01 and Figure 3.8 shows the region of relative depth more than 0.01 with their power fitted curves.

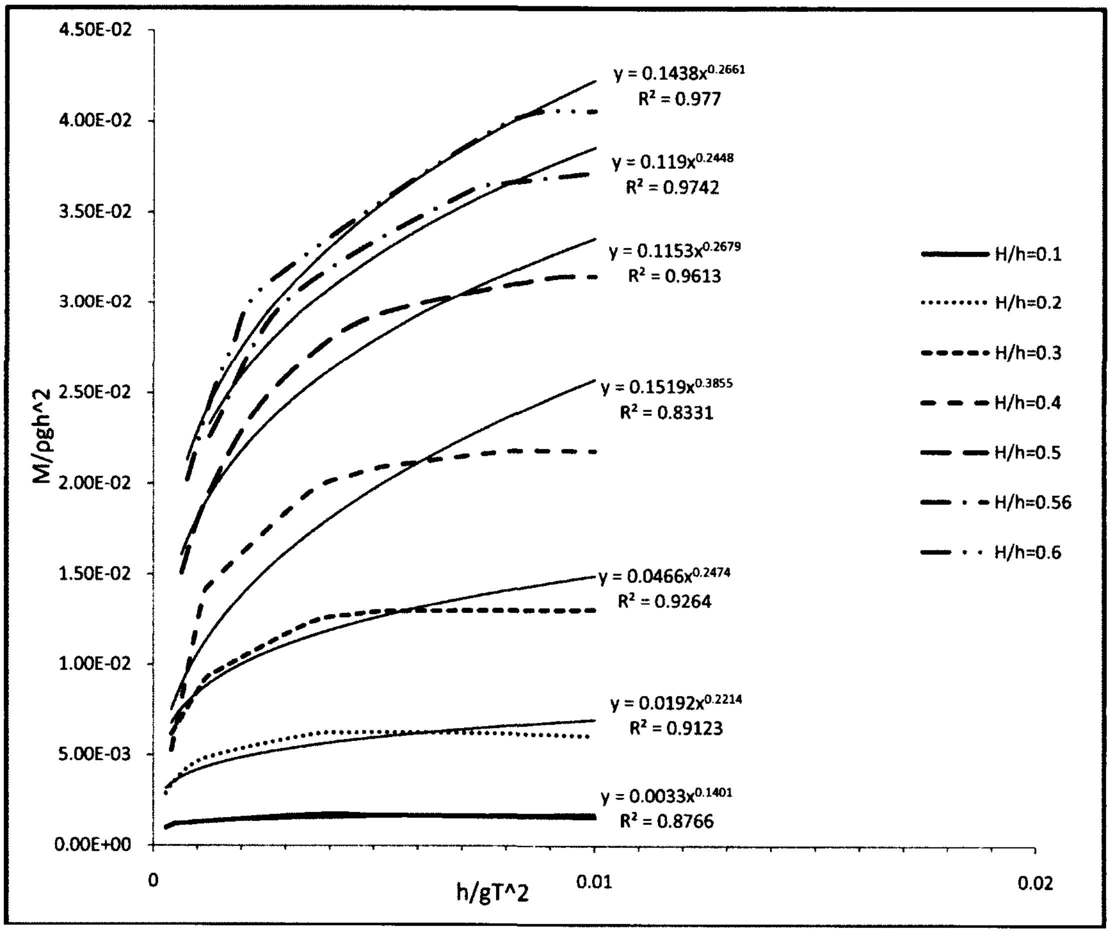

Figure 3.7. The Fourier wave momentum flux parameter versus $\frac{h}{gT^2}$ for different $\frac{H}{h}$

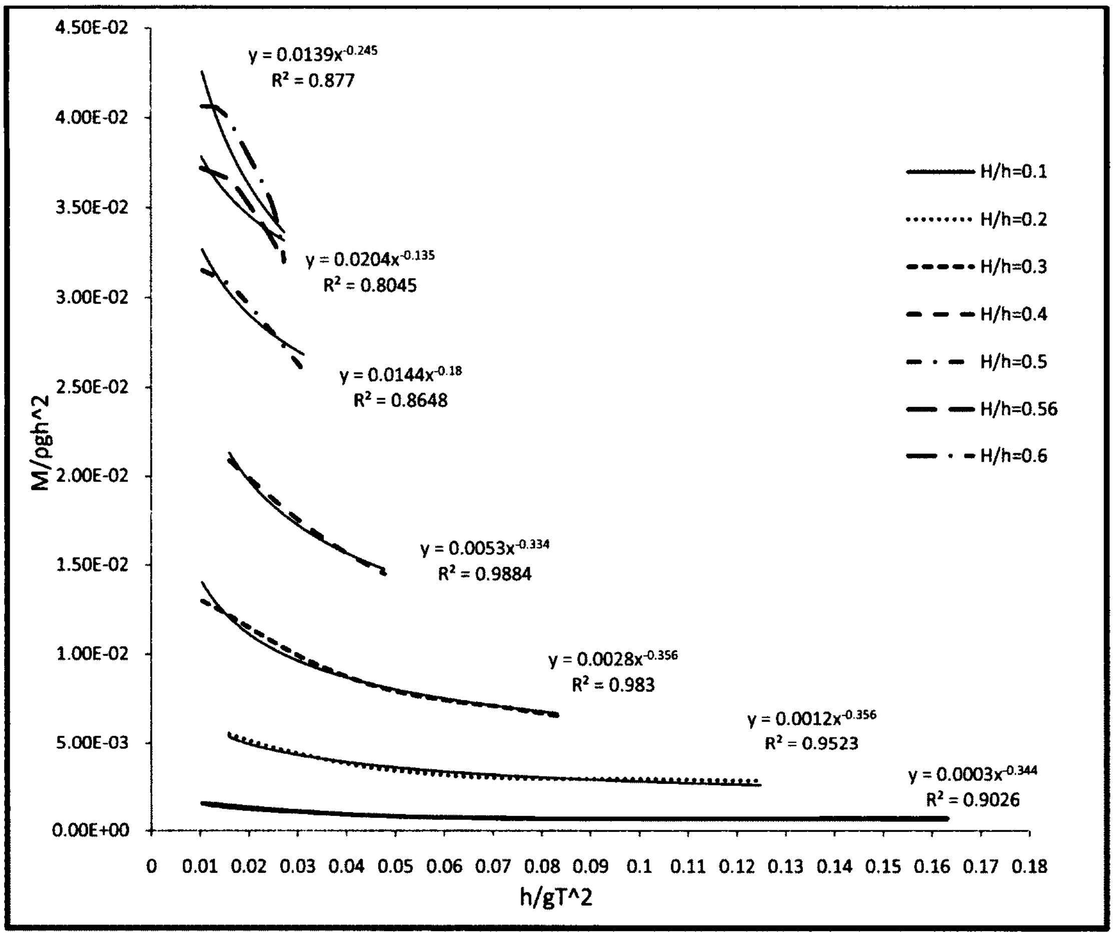

Figure 3.8. The Fourier wave momentum flux parameter versus $\frac{h}{gT^2}$ for different $\frac{H}{h}$

The resulting, purely empirical equation representing the curves shown on Figures 3.7 and 3.8 is given as:

$$\left(\frac{M}{\rho g h^2}\right) = A_0 \left(\frac{h}{gT^2}\right)^{A_1} \qquad 3.9$$

Where:

$$For\ \frac{h}{gT^2} \leq 0.01, \qquad A_0 = 0.5468\left(\frac{H}{h}\right)^{2.1264} \quad and \quad A_1 = 0.3615\left(\frac{H}{h}\right)^{0.3516} \qquad 3.9a$$

$$For\ \frac{h}{gT^2} > 0.01, \quad A_0 = 0.057\left(\frac{H}{h}\right)^{2.3393} \quad and\ A_1 = -0.1685\left(\frac{H}{h}\right)^{-0.398} \qquad 3.9b$$

As a final step and to verify the empirical formula results against the Fourier computer codes, the values computed by Fourier computer codes are plotted versus the values estimated from the empirical equation. A goodness of fit comparing these values is shown in Figure 3.9.

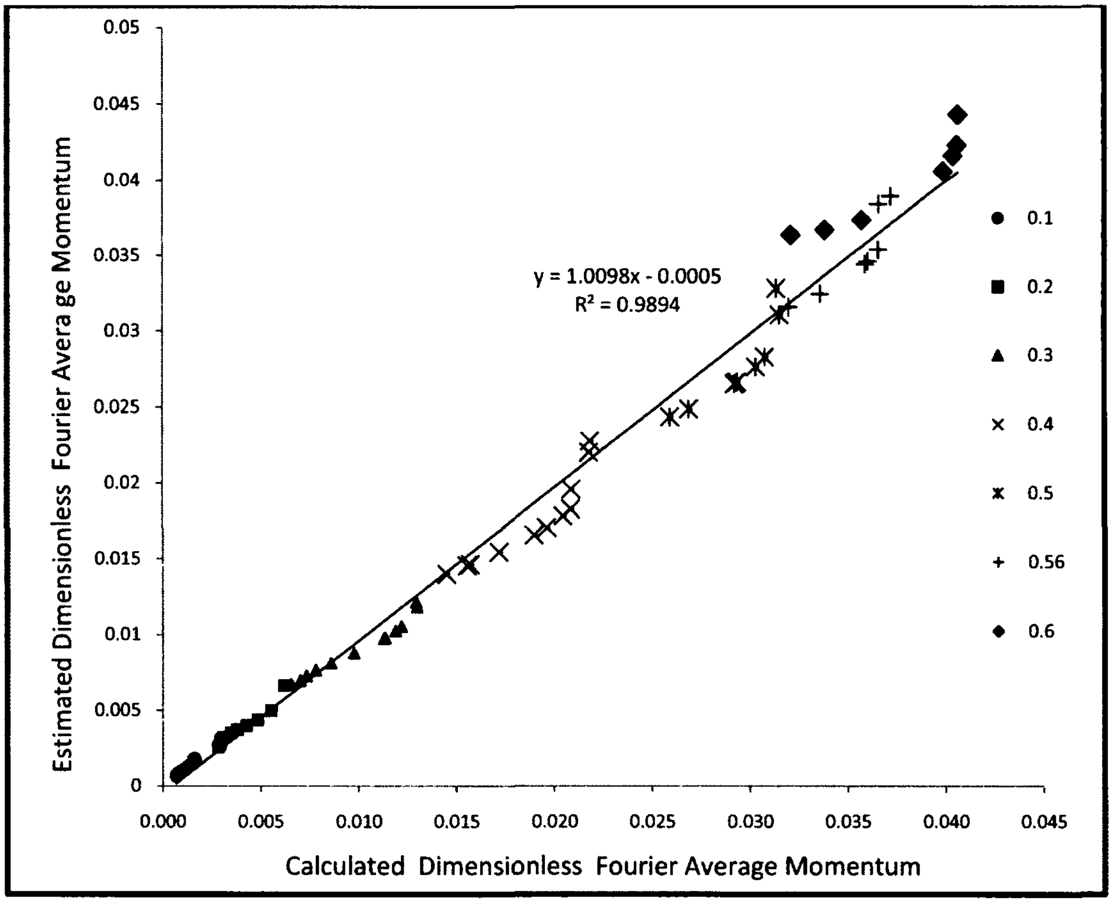

Figure 3.9. Goodness-of-fit of nonlinear momentum flux empirical equation (Fourier wave theory)

For smaller values of non-dimensional $\frac{M}{\rho g h^2}$, there is a reasonable correspondence. For the values above 0.015 the values are starting to diverge and as non-dimensional momentum increases the divergence seems to grow. The poorly fitted curves are for $\frac{H}{h}$ equal to 0.56 and 0.6 which are closer to the limit of wave breaking and greater nonlinearity. The overall R^2 of the curve-fit is 0.9894. There is an under estimating by the empirical formula with the maximum of 4% and minimum of 0.067%.

As it has been mentioned before, for different relative wave height and relative depth below 0.01, the wave momentum starts to decrease. To help describe the significant changes in the momentum, Figure 3.10 shows wave profiles from crest to trough for different relative depth above and below 0.01 and for the constant relative wave height of 0.3. For waves that are longer, the trough is stretched over the long distance (long through and flatten waves), the average momentum over the wave period would become smaller because the portion of the wave above water depth is decreasing and it is not balancing the long trough of the wave. The shorter waves seem to have relatively large portion of the wave above the water depth and would have larger wave momentum. The empirical form of average wave momentum flux parameter for finite-amplitude, steady regular waves presented here is straightforward to use.

The empirical formulation presented in Equations 3.9, 3.9a and 3.9b are representing the momentum flux as a depth integrated and averaged over the wave period and is recommended for calculation of the Modified COSI Parameter.

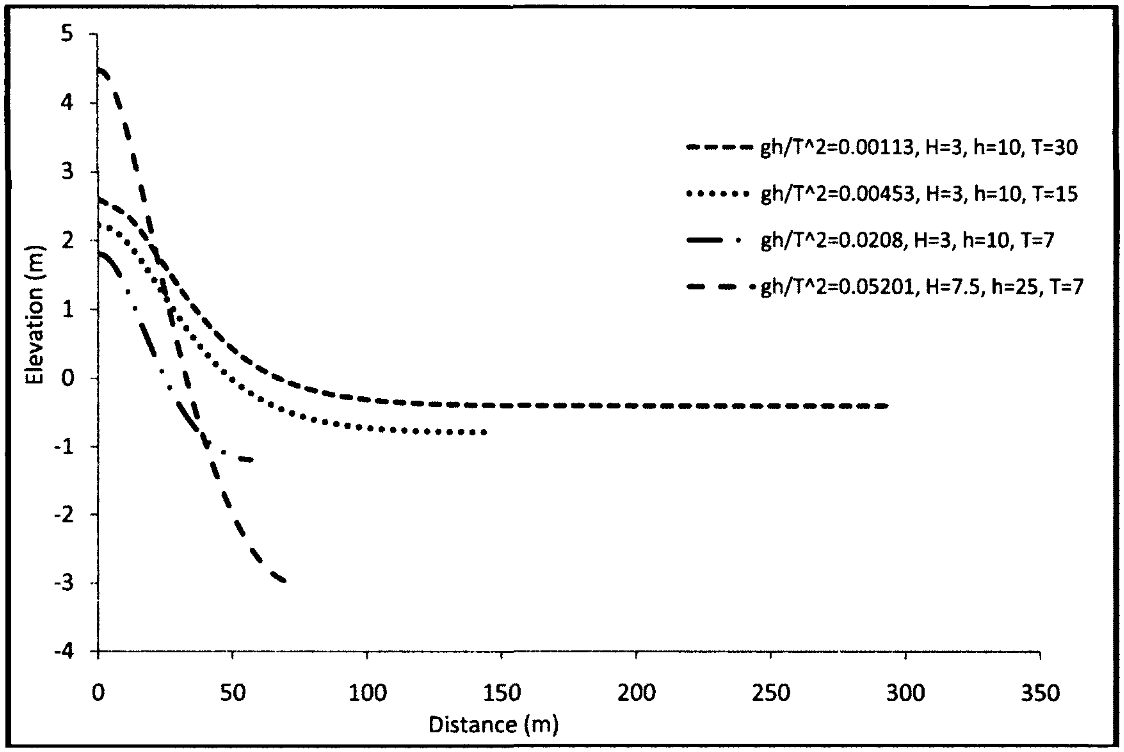

Figure 3.10, Wave surface profiles for different range of relative depths

3.3 Derivation of Storm Surge Momentum

The horizontal momentum for free surface flow is found by integrating the pressure distribution and the velocity distribution in the shore normal direction over the water depth (Basco, et al., 2008). As a result, the estimate of the storm surge momentum boils down to determining the horizontal hydrostatic pressure force due to water levels at reference water depth (h_0). In the previous COSI effort, Klentzman (2007) utilized just the momentum corresponding to the storm surge (measured – predicted) prism value. Since the effect of tides and the proportionality of the storm surge momentum and wave momentum is a concern of this study a new approach has been undertaken to determine this value. In this section, the methodology will be explained.

3.3.1 Computation of Storm Surge Momentum Parameter

It is obvious that waves that ride on higher surge or tides have more impact on the shoreline since they attack the coast at higher elevations. In order to account for the water level that is less being experienced by the shore and at the same time it is below some high storm surge to be more damaging to the coast, the Mean High Water (MHW) is chosen as a base level. Thus, water levels below Mean High Water would not be accounted for their momentum in the calculation of the storm surge momentum.

Considering the conservation of momentum for a control volume from the offshore to the landward limit of storm surge, the horizontal hydrostatic pressure force due to water levels at reference water depth (h_0) can be calculated. Simplifying for a rectangular channel of one-meter width as it has been used in open channel flow (Chow, 1959), it would be:

$$f_{total} = \frac{1}{2}\rho g(s + h_0)^2 + \rho(s + h_0)V^2 \qquad 3.10$$

Where, f_{total} is the total offshore force due to current and surge, s is the storm surge (observed water level – predicted water level), h_0 is the mean water level, V is the depth-averaged current normal to the shore, ρ is the fluid mass density and g is the gravitational constant.

In this dissertation, the hydrostatic momentum due to storm surge is the momentum of the measured water level subtracted by the momentum of MHW level.

For the purpose of this study, current velocity has not been considered for the computation of total momentum in order to compare the results to previous work that has been done. Klentzman (2007) neglected the current velocity because it was minimal compared to the surge momentum and wave momentum. Assuming no current exists and considering the storm condition as surge above mean high water by subtracting the mean high water, total hydrostatic pressure term would become:

$$f_{p(t)} = f_{total} - f_{MHW} \qquad 3.11$$

$$f_{p(t)} = \tfrac{1}{2} \rho g \,(h_0 + s)^2 - \tfrac{1}{2} \rho g \,(h_0 + h_{MHW})^2 \qquad 3.12$$

Where $f_{p(t)}$ is the horizontal storm surge momentum above the Mean High Water, during the storm event for any time (t).

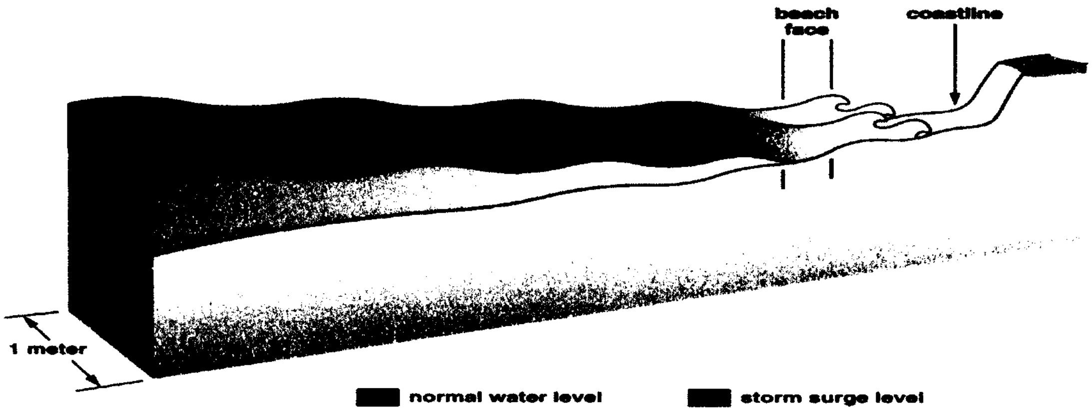

Figure 3.11. Showing the water levels in a unit width of shoreline that the Modified COSI parameter applied (adopted from Klentzamn, 2007)

3.4 Summary

In this chapter, an empirical formula to calculate wave momentum averaged over the wave period has been introduced for the first time. Also, in calculating storm surge momentum, the tides influence has been accounted for by considering the water levels above Mean High Water. These two major improvements in addition to the concept of COSI are significant to call the revised momentum the Modified COSI Parameter in order to distinguish between Original COSI parameter and what has been newly introduced.

Referring to Equations 3.4 and 3.5 at the beginning of this chapter and to note that

$$f_{w(t)} = M \qquad 3.13$$

the total momentum or the Modified COSI Parameter over storm duration can be computed as:

$$\mathrm{I}_{\mathrm{s}} = \int_{0}^{D} \left(M + f_{p(t)}\right) d_t \qquad 3.14$$

In the next chapter the location of where the data has been obtained and the methodology that has been applied to the year 1994-2003 data set will be discussed.

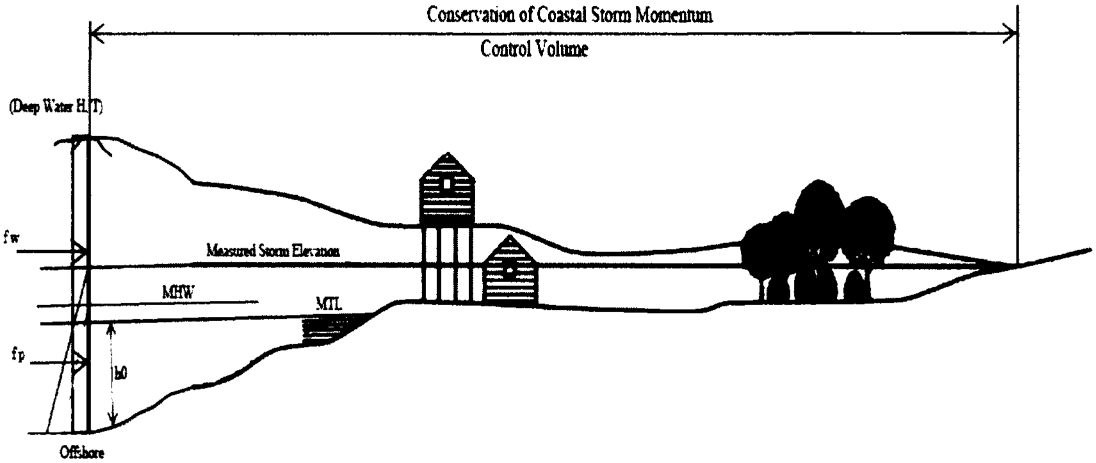

Figure 3.12. Showing the control volume and conservation of storm momentum

CHAPTER 4

DATA

4.1 Location of Data

The US Army, Corps of Engineers, Field Research Facility (FRF) at Duck, NC, routinely measures water levels and wave characteristics (height, period, direction). Table 4.1shows the sensors locations, depth, distance from shore, the years and type of available data.

Table 4.1, Gages and types of data available at FRF Duck, NC.

Station	**Lat**	**Long**	**Depth m**	**Distant offshore**	**Available Data**	**Comments**
Station 44014	36° 36.7 N	74°50'11" W	47.5	95 Km	1990 - 2008	Just Wave data
WMO ID 44100	36° 15.46 N	75° 35.48 W	26	18.5 Km	June 2008 - Present	Just Wave data
WMO ID 44056	36° 11.99 N	75° 42.84 W	17.4	3 Km	1997 - Present	Just Wave data
Senso-Metric 8m Array	36° 11.04 N	75° 44.70 W	8	1 Km	1987 - Present	Just Wave data
NOAA Tide Station at FRF ID 8651371	36° 11.04 N	75° 44.70 W	7.62	0.6 Km	1981-present	Just Tide Data

The location of the sensors field is shown in Figures 4.2, 4.3, 4.4, and 4.5.

There is just one tide gage which the tide data and water levels were obtained from at NOAA Tide Station at FRF (ID number of 865137). This tide gage is located at the end of the pier at depth of h= 7.62 m, (NGVD 29). Water wave characteristics (H_{mo}, T_p) were obtained from the 8 meter array located in water depths ranging from 7.44 to 8.08 m

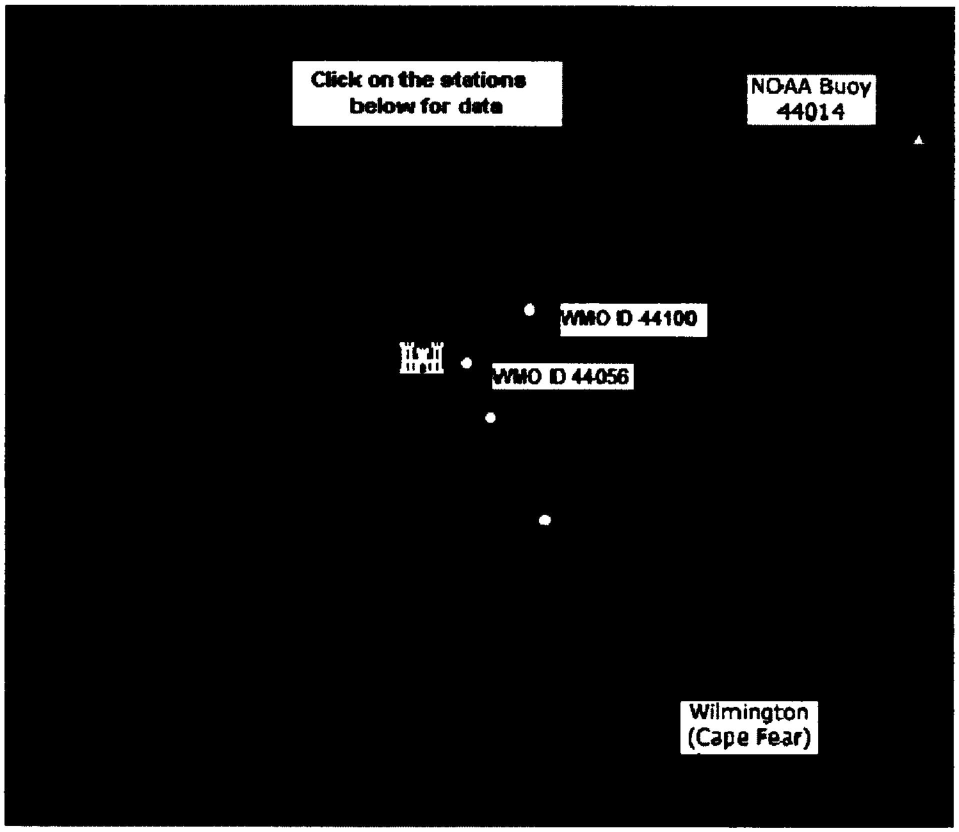

Figure 4.1. General map of FRF, Duck, NC, and available gages (Adapted from USACE FRF website www.frf.usace.army.mil)

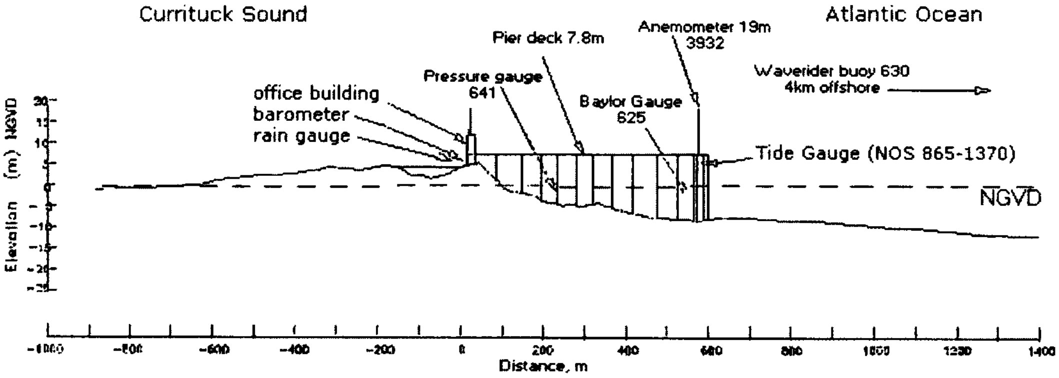

Figure4.2. Pier profile and tide gage location at FRF, Duck, NC. (Adapted from USACE FRF website www.frf.usace.army.mil)

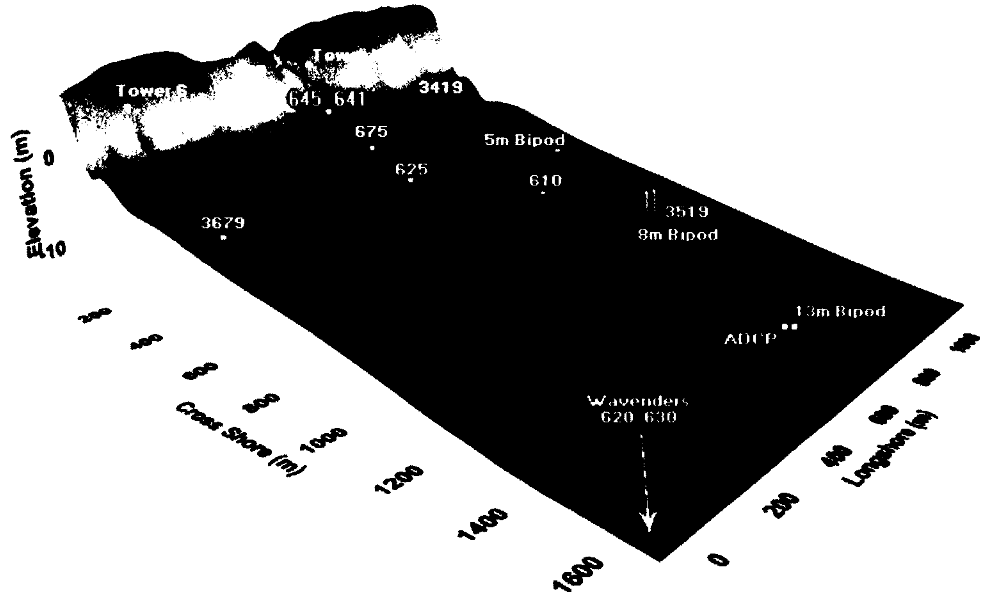

Figure 4.3. General sensor location map of FRF, Duck, NC (Adapted from USACE FRF website www.frf.usace.army.mil)

(NGVD). Here, H_{mo} is the spectral, significant wave height and T_p is the peak period. Hourly values are available over the internet.

4.2 Methodology

Storm definition is based on the wave height of more than 1.6 m at the 8 m water depth. The following methodology has been applied in calculating the modified COSI parameter:

1) For the years 1994 through 2003, the data were searched for any occurrences of wave heights at or greater than 1.6 meters at eight-meter water depth. These occurrences were then investigated to make sure they met the rest of the methodology described below.

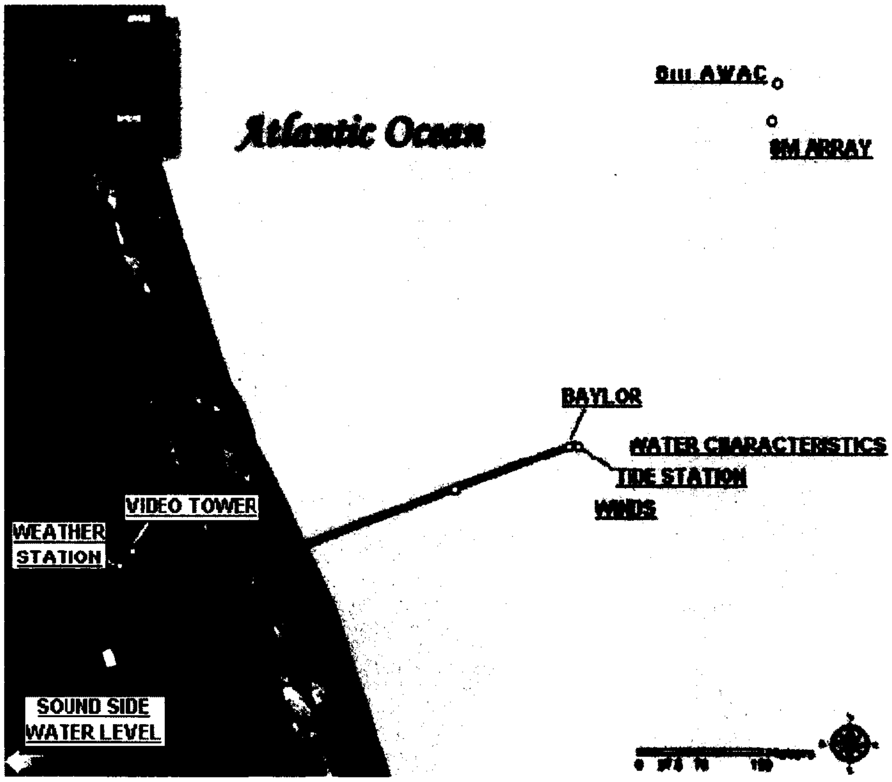

Figure 4.4. Map of pier at FRF, Duck, NC, tide gage and 8m array field sensor (Adapted from USACE FRF website www.frf.usace.army.mil)

2) For $f_{p(t)}$, the Storm Surge momentum, the difference of momentum between the actual measured water level and water level at MHW is computed. For the instances that actual measured water level was below MHW the surge momentum considered to be zero to avoid applying negative number. For the wave momentum, the newly introduced empirical formula is utilized with its coefficients, A_0 and A_1, and computed for each data point. Finally, the total modified COSI is calculated as Υ_s, the total of surge and wave momentum for each data point in the storm and integrated over the duration of the storm. The wave data is collected every three hours for the eight-meter water depth.

3) For a "storm event" it was assumed that the wave height will stay at or above 1.6 meter for 12 hours to have a chance to ride on the high tide and it is based on approximately of a tide cycle of 12 hours.

4) Forty-eight hours was chosen as the interval between storm events. That is, if another data point or points were above the storm definition line during a 48-hour period, it is assumed that this is a continuation of the same storm event. After forty-eight hours, it is classified as a new storm event. Forty-eight hours was chosen upon examination of the data from FRF. This tended to be a valid time-period between storm systems and matched the time periods between FRF defined storm events.

CHAPTER 5

ANALYSIS AND INTERPRETATION OF RESULTS

5.1 Description of Storm Events

Applying the methodology mentioned in Chapter 4, a summary of all the storm events, by year, is given in Tables 5.1 through 5.10. Using wave and storm surge data collected at the FRF and based on the previously discussed definition of a storm, 148 storms were identified over the study period (1994 to 2003). For each storm, the total impulse, or the Modified COSI Parameter, has been determined based on the wave height and elevated water level at each data point and integrated over the duration of the storm.

Table 5.1. Storms and their characteristics for year 1994 at 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 5.2. Storms and their characteristics for year 1995 at FRF, Duck, NC

Storm Type	Start	End	Duration (Hrs)	Max Surge (m)	Max Wave (m)	Max Period (sec)
	1/15/1995 1:00	1/19/1995 22:00	117	0.9	2.9	12.0
	3/1/1995 13:00	3/3/1995 10:00	45	0.9	2.6	10.7
	3/4/1995 22:00	3/5/1995 13:00	15	0.8	1.9	12.0
	3/9/1995 1:00	3/10/1995 7:00	30	0.6	2.0	8.2
	8/7/1995 4:00	8/9/1995 10:00	54	1.3	2.4	12.0
H/Felix	8/15/1995 10:00	8/21/1995 1:00	135	1.1	4.0	15.6
	8/28/1995 10:00	8/29/1995 19:00	33	1.1	2.5	8.9
	9/15/1995 10:00	9/16/1995 10:00	24	0.7	1.7	6.6
H/Luis	9/18/1995 19:00	9/20/1995 10:00	39	0.8	2.2	13.6
H/Marilyn	9/23/1995 1:00	9/24/1995 7:00	30	1.0	2.3	7.6
	9/29/1995 7:00	10/1/1995 7:00	48	1.0	2.3	10.7
	12/17/1995 7:00	12/17/1995 22:00	15	0.6	1.8	12.0

Table 5.3. Storms and their characteristics for year 1996 at FRF, Duck, NC

Storm Type	Start	End	Duration (Hrs)	Max Surge (m)	Max Wave (m)	Max Period (sec)
N	1/6/1996 22:00	1/7/1996 22:00	24	0.9	3.1	10.7
	1/19/1996 1:00	1/20/1996 10:00	33	1.0	1.9	10.7
N	2/2/1996 19:00	2/5/1996 7:00	60	1.1	2.9	12.0
N	2/16/1996 10:00	2/17/1996 10:00	24	1.1	2.8	10.7
	3/10/1996 19:00	3/13/1996 19:00	72	0.8	3.8	13.6
	3/29/1996 19:00	3/30/1996 16:00	21	0.7	2.5	13.6
H/Edouard	8/31/1996 10:00	9/2/1996 10:00	48	1.1	3.5	15.6
H/Fran	9/5/1996 7:00	9/6/1996 10:00	27	0.8	3.1	13.6
TS/Josephine	10/3/1996 16:00	10/8/1996 19:00	123	1.0	3.1	12.0
	10/22/1996 13:00	10/24/1996 16:00	51	0.9	2.7	15.6
	11/15/1996 1:00	11/19/1996 4:00	99	1.2	3.3	18.4
	11/22/1996 1:00	11/22/1996 13:00	12	1.2	2.5	8.2
	11/26/1996 22:00	11/27/1996 10:00	12	0.9	2.2	8.2
	12/14/1996 7:00	12/17/1996 19:00	84	1.4	2.8	13.6

Table 5.4. Storms and their characteristics for year 1997 at FRF, Duck, NC

Storm Type	Start	End	Duration (Hrs)	Max Surge (m)	Max Wave (m)	Max Period (sec)
N	2/8/1997 7:00	2/10/1997 7:00	48	1.2	2.6	12.0
	3/19/1997 13:00	3/20/1997 1:00	12	0.7	1.8	8.2
	4/1/1997 4:00	4/2/1997 16:00	36	0.9	2.7	12.0
	4/23/1997 16:00	4/25/1997 10:00	42	1.3	2.3	10.7
	5/27/1997 7:00	5/29/1997 13:00	54	0.9	2.5	12.0
	6/3/1997 19:00	6/8/1997 16:00	117	1.3	3.1	12.0
	9/3/1997 22:00	9/4/1997 10:00	12	0.9	2.5	7.0
	10/16/1997 13:00	10/17/1997 7:00	18	1.3	1.8	12.0
	10/18/1997 10:00	10/21/1997 16:00	78	1.5	3.5	13.6
	11/6/1997 10:00	11/8/1997 1:00	39	1.1	2.5	12.0
N	11/13/1997 10:00	11/14/1997 7:00	21	1.3	3.0	8.9
	12/27/1997 16:00	12/28/1997 16:00	24	1.1	2.4	9.7

Table 5.5. Storms and their characteristics for year 1998 at FRF, Duck, NC

Storm Type	Start	End	Duration (Hrs)	Max Surge (m)	Max Wave (m)	Max Period (sec)
	1/16/1998 19:00	1/24/1998 19:00	192	1.0	2.1	15.6
N	1/27/1998 16:00	1/29/1998 22:00	54	1.7	4.6	13.6
N	2/3/1998 19:00	2/10/1998 19:00	168	1.7	3.8	13.6
	2/16/1998 22:00	2/18/1998 4:00	30	0.7	3.0	10.7
	2/23/1998 4:00	2/23/1998 16:00	12	0.9	2.2	8.9
	4/4/1998 13:00	4/5/1998 22:00	33	1.0	3.1	13.6
	4/12/1998 19:00	4/14/1998 19:00	48	0.8	2.5	13.6
	4/22/1998 16:00	4/23/1998 13:00	21	1.0	2.5	9.7
	5/12/1998 16:00	5/15/1998 10:00	66	1.3	3.3	13.6
H/Earl	8/1/1998 19:00	8/4/1998 4:00	57	0.9	2.3	8.2
H/Bonnie	8/25/1998 22:00	8/28/1998 19:00	69	0.8	3.5	15.6
	9/23/1998 1:00	9/23/1998 19:00	18	1.1	2.5	13.6
	10/22/1998 10:00	10/23/1998 4:00	18	0.7	2.2	7.0
	12/13/1998 22:00	12/16/1998 19:00	69	1.0	3.5	10.7

Table 5.6. Storms and their characteristics for year 1999 at FRF, Duck, NC

Storm Type	Start	End	Duration (Hrs)	Max Surge (m)	Max Wave (m)	Max Period (sec)
	1/2/1999 13:00	1/3/1999 19:00	30	0.8	3.0	10.7
	1/9/1999 22:00	1/10/1999 10:00	12	0.9	2.5	7.0
	1/31/1999 1:00	2/2/1999 16:00	63	1.2	2.7	13.6
N	2/19/1999 16:00	2/20/1999 13:00	21	1.1	2.0	8.2
	2/21/1999 19:00	2/26/1999 16:00	117	1.0	2.5	13.6
N	3/7/1999 7:00	3/8/1999 13:00	30	0.6	2.2	8.2
	3/26/1999 10:00	3/28/1999 1:00	39	0.9	3.0	12.0
N	4/28/1999 13:00	5/4/1999 4:00	135	1.2	3.6	10.7
	5/14/1999 7:00	5/17/1999 19:00	84	1.4	3.6	10.7
	6/11/1999 22:00	6/12/1999 13:00	15	1.8	2.1	12.0
H/Dennis	8/30/1999 1:00	9/5/1999 10:00	153	1.8	5.1	15.6
H/Floyd	9/15/1999 19:00	9/16/1999 10:00	15	1.2	4.2	13.6
	9/21/1999 10:00	9/23/1999 1:00	39	1.0	3.3	15.6
H/Irene	10/17/1999 22:00	10/18/1999 16:00	18	0.9	2.7	8.9
	11/11/1999 19:00	11/12/1999 10:00	15	0.9	2.6	9.7
	11/30/1999 7:00	12/2/1999 16:00	57	1.2	2.7	15.6
	12/19/1999 16:00	12/20/1999 16:00	24	1.8	2.4	10.7

Table 5.7. Storms and their characteristics for year 2000 at FRF, Duck, NC

Storm Type	Start	End	Duration (Hrs)	Max Surge (m)	Max Wave (m)	Max Period (sec)
	1/13/2000 19:00	1/14/2000 16:00	21	0.6	2.6	8.2
	1/17/2000 1:00	1/18/2000 1:00	24	0.8	2.2	9.7
N	1/24/2000 13:00	1/25/2000 22:00	33	1.2	4.5	10.7
N	3/17/2000 16:00	3/24/2000 19:00	171	1.1	3.2	15.6
	4/12/2000 22:00	4/14/2000 13:00	39	0.7	2.2	7.6
	4/18/2000 10:00	4/20/2000 13:00	51	1.3	2.8	10.7
	4/25/2000 13:00	4/27/2000 1:00	36	1.0	3.2	12.0
	5/29/2000 4:00	5/31/2000 13:00	57	1.6	4.5	12.0
	8/30/2000 10:00	8/30/2000 22:00	12	0.9	2.0	8.9
	9/5/2000 7:00	9/7/2000 19:00	60	1.2	3.1	10.7
	9/29/2000 7:00	10/3/2000 1:00	90	1.0	2.5	18.5
	10/9/2000 4:00	10/9/2000 16:00	12	0.9	2.0	8.9
Subtropical	10/27/2000 4:00	10/29/2000 7:00	51	1.1	2.5	10.7
	11/11/2000 16:00	11/12/2000 13:00	21	1.3	1.9	10.7
	11/25/2000 16:00	11/26/2000 13:00	21	0.8	3.1	10.7
	12/2/2000 16:00	12/5/2000 4:00	60	0.8	3.5	12.0

Table 5.8. Storms and their characteristics for year 2001 at FRF, Duck, NC

Storm Type	Start	End	Duration (Hrs)	Max Surge (m)	Max Wave (m)	Max Period (sec)
	2/17/2001 16:00	2/18/2001 4:00	12	0.7	1.8	7.0
	2/21/2001 22:00	2/22/2001 19:00	21	0.8	2.3	7.6
N	3/7/2001 1:00	3/9/2001 4:00	51	1.1	2.4	13.6
	3/20/2001 16:00	3/22/2001 7:00	39	0.8	4.2	12.0
	7/19/2001 22:00	7/20/2001 19:00	21	1.2	1.8	8.2
	7/27/2001 7:00	7/27/2001 19:00	12	1.1	2.0	8.9
H/Gabrielle	9/11/2001 1:00	9/12/2001 1:00	24	0.9	1.9	13.6
	9/14/2001 7:00	9/18/2001 7:00	96	1.4	2.9	13.6
	9/29/2001 19:00	10/1/2001 22:00	51	1.0	3.4	13.6
H/Karen	10/12/2001 19:00	10/13/2001 16:00	21	1.0	2.3	15.6
	10/28/2001 4:00	10/28/2001 16:00	12	0.8	2.0	7.6
	11/5/2001 10:00	11/6/2001 13:00	27	1.0	2.3	13.6
	11/17/2001 16:00	11/18/2001 7:00	15	0.9	2.1	8.9
	11/26/2001 22:00	11/27/2001 13:00	15	0.8	2.0	13.6

Table 5.9. Storms and their characteristics for year 2002 at FRF, Duck, NC

Storm Type	Start	End	Duration (Hrs)	Max Surge (m)	Max Wave (m)	Max Period (sec)
	1/3/2002 1:00	1/4/2002 22:00	45	1.2	3.9	12.0
	2/2/2002 1:00	2/2/2002 13:00	12	0.9	2.3	7.6
	2/4/2002 19:00	2/5/2002 10:00	15	0.9	1.9	7.6
	2/19/2002 13:00	2/20/2002 1:00	12	0.6	2.0	13.6
	2/24/2002 7:00	2/25/2002 7:00	24	0.7	1.8	10.7
	3/2/2002 19:00	3/3/2002 13:00	18	0.7	2.5	10.7
	3/17/2002 4:00	3/19/2002 16:00	60	0.8	2.6	10.7
	4/3/2002 22:00	4/4/2002 10:00	12	0.7	2.4	7.0
	4/11/2002 13:00	4/12/2002 4:00	15	0.6	2.0	10.7
	6/7/2002 16:00	6/8/2002 16:00	24	1.0	2.5	10.7
H/Gustav	9/9/2002 4:00	9/11/2002 1:00	45	1.2	3.1	10.7
	10/8/2002 1:00	10/8/2002 19:00	18	1.2	2.0	7.6
H/Kyle	10/14/2002 1:00	10/16/2002 10:00	57	1.0	3.3	13.6
	10/24/2002 16:00	10/26/2002 7:00	39	0.8	2.1	8.9
	10/28/2002 22:00	10/31/2002 16:00	66	1.0	2.2	12.0
	12/10/2002 16:00	12/11/2002 13:00	21	0.7	2.3	9.7

Table 5.10. Storms and their characteristics for year 2003 at FRF, Duck, NC

Storm Type	Start	End	Duration (Hrs)	Max Surge (m)	Max Wave (m)	Max Period (sec)
N	2/15/2003 19:00	2/18/2003 10:00	63	1.0	3.9	13.6
	2/26/2003 16:00	3/1/2003 10:00	66	0.9	2.5	12.0
	3/6/2003 22:00	3/8/2003 1:00	27	0.8	2.1	8.9
	3/14/2003 1:00	3/14/2003 19:00	18	0.7	2.7	8.9
	3/19/2003 4:00	3/21/2003 7:00	51	1.1	2.5	10.7
	3/30/2003 7:00	3/31/2003 4:00	21	0.9	2.1	8.2
	4/6/2003 22:00	4/11/2003 19:00	117	1.1	4.3	10.7
	4/17/2003 16:00	4/21/2003 4:00	84	1.2	3.2	13.6
	5/3/2003 7:00	5/3/2003 19:00	12	0.8	1.9	6.6
	5/17/2003 1:00	5/20/2003 1:00	72	1.2	2.1	10.7
TS/Henri	9/8/2003 16:00	9/13/2003 10:00	114	1.3	3.1	15.6
H/Isabel	9/15/2003 19:00	9/19/2003 7:00	84	2.0	6.0	15.6
	10/9/2003 22:00	10/12/2003 1:00	51	1.2	3.0	12.0
	11/8/2003 22:00	11/10/2003 10:00	36	1.0	1.9	7.0
	11/25/2003 1:00	11/25/2003 16:00	15	1.4	2.4	12.0
N	12/6/2003 13:00	12/7/2003 1:00	12	0.8	2.0	10.7
	12/13/2003 22:00	12/14/2003 22:00	24	0.8	2.8	9.7

5.2 Analysis of Surge and Wave Momentum

The Modified COSI Parameter has been computed for the available data for the year of 1994 to 2003, and chronological display is shown in Figure 5.1.

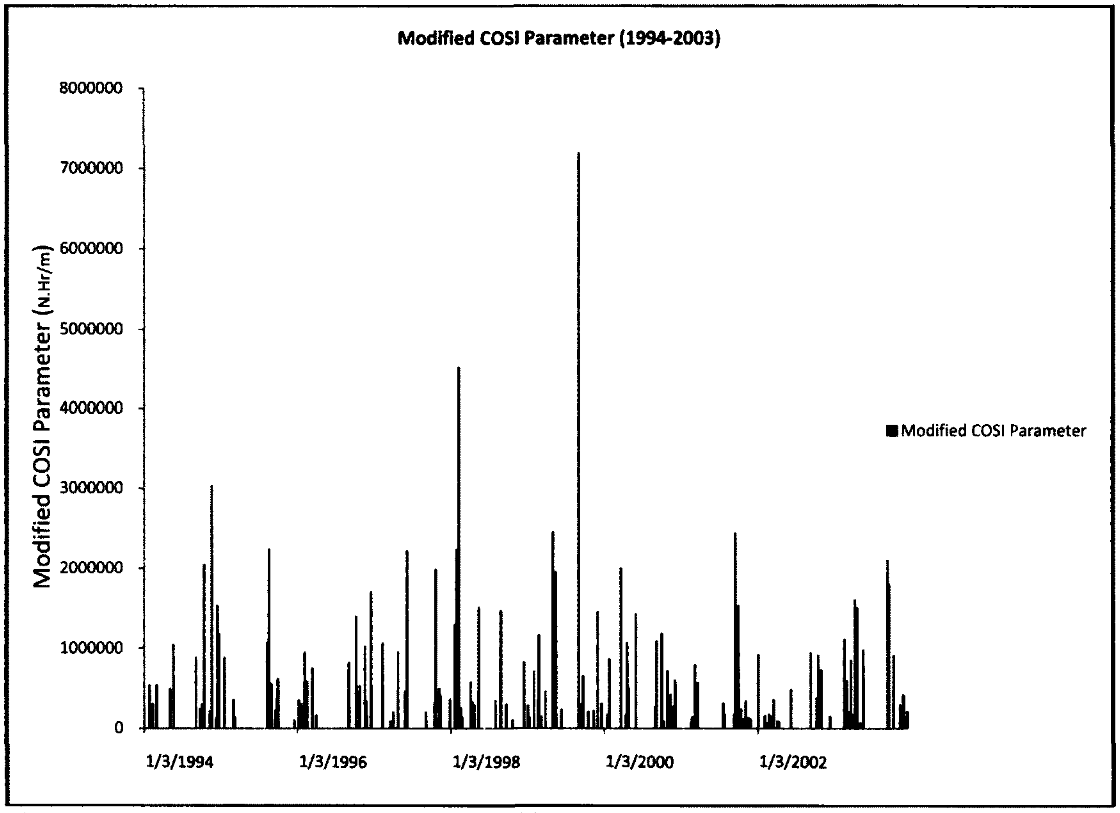

Figure 5.1. Chronological display of Modified COSI Parameter for 157 storms over the 10-yr period, Jan 1994-Dec 2003

Also, the chronological display of the duration for each storm is shown in Figure 5.2.

Storms have been identified based on criteria set forth in Chapter 4 and analysis of these storms show the ratio of the wave and surge momentum to total momentum. Tables showing the results of the analysis are from Table 5.1 to Table 5.10.

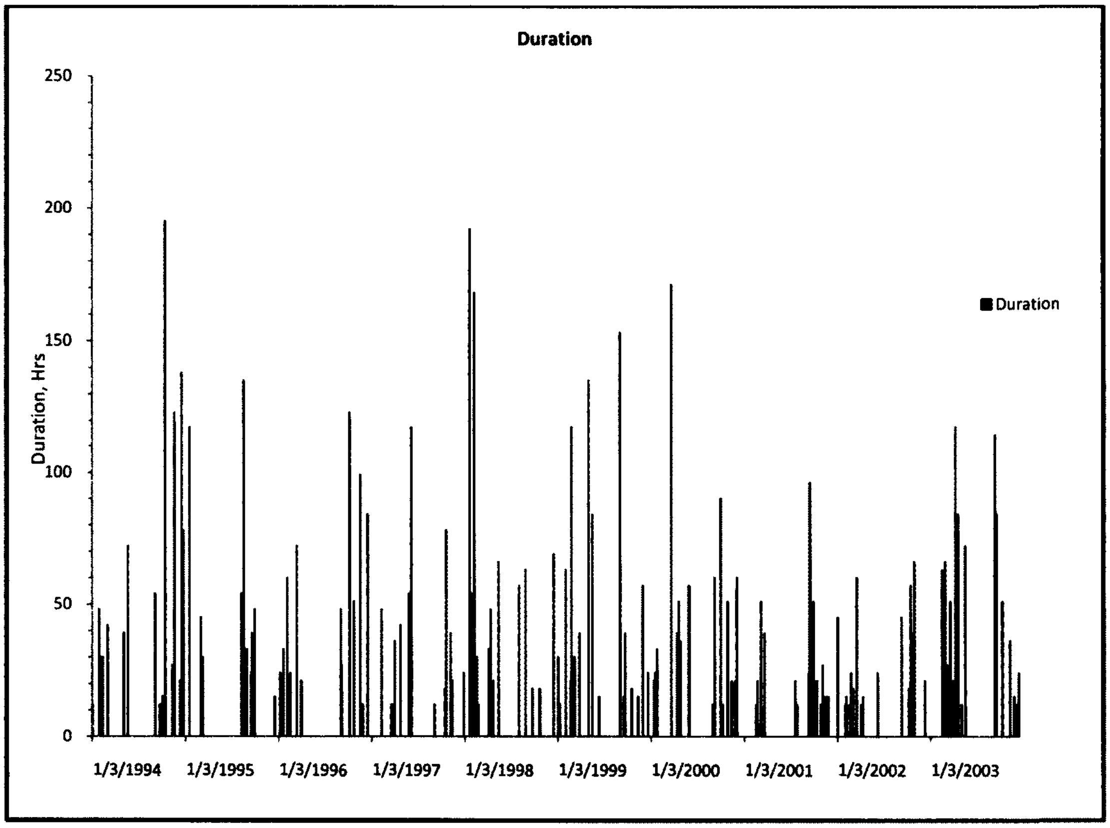

Figure 5.2. Chronological display of the duration for Modified COSI Parameter for 157 storms over the 10-yr period, Jan 1994-Dec 2003

The results from the Modified COSI parameter over the 1994-2003 data set show the proportion of the wave momentum and the surge momentum are in average at 60% and 40% respectively. It is interesting to note that some storms are wave dominated meaning surge momentum share is small and some storms are surge dominated which means wave momentum share is small. This is a good indication that there is a key difference in type of storms and the impact they might have on the shoreline which can be more investigated. The storms related wave and surge momentum along with the Modified COSI parameter and types of the storms are mentioned in Tables 5.11 to 5.20, if they have been categorized by National Hurricane Center or there were information available from online sources.

The resulting storm set consisted of both tropical (hurricanes) and extra-tropical (northeasters) with resulting the Modified COSI Parameter ranging from 66594 N-Hrs/m to 7183579 N-Hrs/m.

Table 5.11. The 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

Table 5.12. The Modified COSI Parameter for storms in year 1995

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
	1/15/1995 1:00	1/19/1995 22:00	117	192933.8	684278.0	877211.8	0.8	0.2
	3/1/1995 13:00	3/3/1995 10:00	45	99885.4	250349.4	350234.8	0.7	0.3
	3/4/1995 22:00	3/5/1995 13:00	15	41007.2	84491.2	125498.4	0.7	0.3
	3/9/1995 1:00	3/10/1995 7:00	30	0.0	133833.6	133833.6	1.0	0.0
	8/7/1995 4:00	8/9/1995 10:00	54	682040.5	378762.3	1060802.9	0.4	0.6
H/Felix	8/15/1995 10:00	8/21/1995 1:00	135	936321.0	1296770.2	2233091.2	0.6	0.4
	8/28/1995 10:00	8/29/1995 19:00	33	391694.2	163525.1	555219.3	0.3	0.7
	9/15/1995 10:00	9/16/1995 10:00	24	2872.8	83970.1	86842.8	1.0	0.0
H/Luis	9/18/1995 19:00	9/20/1995 10:00	39	31388.9	189654.0	221042.9	0.9	0.1
H/Marilyn	9/23/1995 1:00	9/24/1995 7:00	30	206936.2	148963.7	355899.9	0.4	0.6
	9/29/1995 7:00	10/1/1995 7:00	48	354434.5	261204.6	615639.0	0.4	0.6
	12/17/1995 7:00	12/17/1995 22:00	15	8645.7	86313.7	94959.3	0.9	0.1

Table 5.13. The Modified COSI Parameter for storms in year 1996

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	1/6/1996 22:00	1/7/1996 22:00	24	135239.1	214669.3	349908.4	0.6	0.4
	1/19/1996 1:00	1/20/1996 10:00	33	144473.5	155088.0	299561.5	0.5	0.5
N	2/2/1996 19:00	2/5/1996 7:00	60	422196.8	521746.9	943943.7	0.6	0.4
N	2/16/1996 10:00	2/17/1996 10:00	24	389541.2	190529.4	580070.6	0.3	0.7
	3/10/1996 19:00	3/13/1996 19:00	72	56698.6	692049.1	748747.7	0.9	0.1
	3/29/1996 19:00	3/30/1996 16:00	21	9153.3	153277.8	162431.1	0.9	0.1
H/Eduard	8/31/1996 10:00	9/2/1996 10:00	48	406039.7	410926.5	816966.2	0.5	0.5
H/Fran	9/5/1996 7:00	9/6/1996 10:00	27	44968.3	199602.1	244570.4	0.8	0.2
TS/Josephine	10/3/1996 16:00	10/8/1996 19:00	123	609204.0	784896.1	1394100.1	0.6	0.4
	10/22/1996 13:00	10/24/1996 16:00	51	179095.2	348362.9	527458.1	0.7	0.3
	11/15/1996 1:00	11/19/1996 4:00	99	344732.2	675684.9	1020417.1	0.7	0.3
	11/22/1996 1:00	11/22/1996 13:00	12	254007.7	83683.7	337691.4	0.2	0.8
	11/26/1996 22:00	11/27/1996 10:00	12	84438.0	61061.7	145499.7	0.4	0.6
	12/14/1996 7:00	12/17/1996 19:00	84	1058078.9	640247.2	1698326.1	0.4	0.6

Table 5.14. The Modified COSI Parameter for storms in year 1997

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	2/8/1997 7:00	2/10/1997 7:00	48	718866.8	339456.5	1058323.3	0.3	0.7
	3/19/1997 13:00	3/20/1997 1:00	12	23875.4	64418.9	88294.3	0.7	0.3
	4/1/1997 4:00	4/2/1997 16:00	36	97578.4	102514.0	200092.4	0.5	0.5
	4/23/1997 16:00	4/25/1997 10:00	42	702794.0	244194.7	946988.7	0.3	0.7
	5/27/1997 7:00	5/29/1997 13:00	54	122964.1	337563.2	460527.4	0.7	0.3
	6/3/1997 19:00	6/8/1997 16:00	117	1326557.7	888076.7	2214634.4	0.4	0.6
	9/3/1997 22:00	9/4/1997 10:00	12	123994.8	76367.6	200362.4	0.4	0.6
	10/16/1997 13:00	10/17/1997 7:00	18	229790.9	83308.3	313099.1	0.3	0.7
	10/18/1997 10:00	10/21/1997 16:00	78	1428597.6	555297.3	1983894.8	0.3	0.7
	11/6/1997 10:00	11/8/1997 1:00	39	276567.9	219428.9	495996.8	0.4	0.6
N	11/13/1997 10:00	11/14/1997 7:00	21	259320.8	149342.0	408662.7	0.4	0.6
	12/27/1997 16:00	12/28/1997 16:00	24	201364.7	153128.3	354493.0	0.4	0.6

Table 5.15. The Modified COSI Parameter for storms in year 1998

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
	1/16/1998 19:00	1/24/1998 19:00	192	511675.0	785113.5	1296788.6	0.6	0.4
N	1/27/1998 16:00	1/29/1998 22:00	54	1511447.0	718292.3	2229739.3	0.3	0.7
N	2/3/1998 19:00	2/10/1998 19:00	168	2780157.9	1743641.0	4523798.9	0.4	0.6
	2/16/1998 22:00	2/18/1998 4:00	30	32502.9	216105.3	248608.2	0.9	0.1
	2/23/1998 4:00	2/23/1998 16:00	12	76114.9	63547.6	139662.5	0.5	0.5
	4/4/1998 13:00	4/5/1998 22:00	33	283183.4	288424.4	571607.9	0.5	0.5
	4/12/1998 19:00	4/14/1998 19:00	48	33654.4	291295.5	324949.8	0.9	0.1
	4/22/1998 16:00	4/23/1998 13:00	21	132153.1	157141.0	289294.0	0.5	0.5
	5/12/1998 16:00	5/15/1998 10:00	66	852977.2	656182.4	1509159.6	0.4	0.6
H/Earl	8/1/1998 19:00	8/4/1998 4:00	57	85329.0	258048.8	343377.8	0.8	0.2
H/Bonnie	8/25/1998 22:00	8/28/1998 13:00	69	139205.2	519453.7	658658.9	0.8	0.2
	9/23/1998 1:00	9/23/1998 19:00	18	195840.9	105182.1	301023.0	0.3	0.7
	10/22/1998 10:00	10/23/1998 4:00	18	25656.6	81485.5	107142.2	0.8	0.2
	12/13/1998 22:00	12/16/1998 19:00	69	351620.2	467871.2	819491.4	0.6	0.4

Table 5.16. The Modified COSI Parameter for storms in year 1999

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
	1/2/1999 13:00	1/3/1999 19:00	30	56431.7	221052.1	277483.8	0.8	0.2
	1/9/1999 22:00	1/10/1999 10:00	12	56276.0	79768.4	136044.4	0.6	0.4
	1/31/1999 1:00	2/2/1999 16:00	63	322405.4	387284.6	709690.0	0.5	0.5
N	2/19/1999 16:00	2/20/1999 13:00	21	244883.5	96319.8	341203.3	0.3	0.7
	2/21/1999 19:00	2/26/1999 16:00	117	569281.1	593340.4	1162621.6	0.5	0.5
N	3/7/1999 7:00	3/8/1999 13:00	30	0.0	140481.6	140481.6	1.0	0.0
	3/26/1999 10:00	3/28/1999 1:00	39	119400.8	335143.0	454543.8	0.7	0.3
N	4/28/1999 13:00	5/4/1999 4:00	135	1200876.8	1247216.6	2448093.4	0.5	0.5
	5/14/1999 7:00	5/17/1999 19:00	84	1109029.3	838997.2	1948026.5	0.4	0.6
	6/11/1999 22:00	6/12/1999 13:00	15	129640.2	96260.5	225900.7	0.4	0.6
H/Dennis	8/30/1999 1:00	9/5/1999 10:00	153	4724883.0	2458695.7	7183578.7	0.3	0.7
H/Floyd	9/15/1999 19:00	9/16/1999 10:00	15	96812.0	200269.9	297082.0	0.7	0.3
	9/21/1999 10:00	9/23/1999 1:00	39	314678.4	337210.1	651888.6	0.5	0.5
H/Irene	10/17/1999 22:00	10/18/1999 16:00	18	85747.8	119393.1	205140.9	0.6	0.4
	11/11/1999 19:00	11/12/1999 10:00	15	84697.2	127577.3	212274.6	0.6	0.4
	11/30/1999 7:00	12/2/1999 16:00	57	1052771.5	397483.6	1450255.1	0.3	0.7
	12/19/1999 16:00	12/20/1999 16:00	24	126635.4	178141.8	304777.2	0.6	0.4

Table 5.17. The Modified COSI Parameter for storms in year 2000

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
	1/13/2000 19:00	1/14/2000 16:00	21	0.0	126693.8	126693.8	1.0	0.0
	1/17/2000 1:00	1/18/2000 1:00	24	44804.9	122336.7	167141.5	0.7	0.3
N	1/24/2000 13:00	1/25/2000 22:00	33	388289.8	472211.0	860500.7	0.5	0.5
N	3/17/2000 16:00	3/24/2000 19:00	171	862055.4	1133763.2	1995818.6	0.6	0.4
	4/12/2000 22:00	4/14/2000 13:00	39	8629.2	154248.7	162877.9	0.9	0.1
	4/18/2000 10:00	4/20/2000 13:00	51	697205.0	366970.5	1064175.5	0.3	0.7
	4/25/2000 13:00	4/27/2000 1:00	36	190631.9	314930.4	505562.3	0.6	0.4
	5/29/2000 4:00	5/31/2000 13:00	57	699095.4	728492.7	1427588.1	0.5	0.5
	8/30/2000 10:00	8/30/2000 22:00	12	182188.5	79571.8	261760.4	0.3	0.7
	9/5/2000 7:00	9/7/2000 19:00	60	507715.1	575987.8	1083703.0	0.5	0.5
	9/29/2000 7:00	10/3/2000 1:00	90	670557.9	511979.5	1182537.4	0.4	0.6
	10/9/2000 4:00	10/9/2000 16:00	12	34783.9	53471.7	88255.6	0.6	0.4
Subtropical	10/27/2000 4:00	10/29/2000 7:00	51	430555.4	290404.1	720959.5	0.4	0.6
	11/11/2000 16:00	11/12/2000 13:00	21	318305.9	100622.0	418927.9	0.2	0.8
	11/25/2000 16:00	11/26/2000 13:00	21	46135.9	221272.4	267408.2	0.8	0.2
	12/2/2000 16:00	12/5/2000 4:00	60	54984.0	544993.1	599977.1	0.9	0.1

Table 5.18. The Modified COSI Parameter for storms in year 2001

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
	2/17/2001 16:00	2/18/2001 4:00	12	12069.6	54524.5	66594.1	0.8	0.2
	2/21/2001 22:00	2/22/2001 19:00	21	49333.3	93000.1	142333.4	0.7	0.3
N	3/7/2001 1:00	3/9/2001 4:00	51	483280.4	305810.2	789090.6	0.4	0.6
	3/20/2001 16:00	3/22/2001 7:00	39	109332.7	460024.3	569356.9	0.8	0.2
	7/19/2001 22:00	7/20/2001 19:00	21	228005.5	83394.9	311400.4	0.3	0.7
	7/27/2001 7:00	7/27/2001 19:00	12	115290.3	59016.5	174306.7	0.3	0.7
H/Gabrielle	9/11/2001 1:00	9/12/2001 1:00	24	56276.0	118538.0	174814.1	0.7	0.3
	9/14/2001 7:00	9/18/2001 7:00	96	1815448.9	622256.0	2437704.9	0.3	0.7
	9/29/2001 19:00	10/1/2001 22:00	51	1014092.3	517529.8	1531622.1	0.3	0.7
H/Karen	10/12/2001 19:00	10/13/2001 16:00	21	110553.7	124663.8	235217.5	0.5	0.5
	10/28/2001 4:00	10/28/2001 16:00	12	55427.4	62968.6	118396.0	0.5	0.5
	11/5/2001 10:00	11/6/2001 13:00	27	193443.6	142343.7	335787.4	0.4	0.6
	11/17/2001 16:00	11/18/2001 7:00	15	39540.0	89308.1	128848.1	0.7	0.3
	11/26/2001 22:00	11/27/2001 13:00	15	30478.3	87056.2	117534.5	0.7	0.3

Table 5.19. The Modified COSI Parameter for storms in year 2002

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
	1/3/2002 1:00	1/4/2002 22:00	45	374178.3	543207.3	917385.7	0.6	0.4
	2/2/2002 1:00	2/2/2002 13:00	12	74425.9	62049.2	136475.1	0.5	0.5
	2/4/2002 19:00	2/5/2002 10:00	15	87610.8	63817.5	151428.3	0.4	0.6
	2/19/2002 13:00	2/20/2002 1:00	12	0.0	71834.9	71834.9	1.0	0.0
	2/24/2002 7:00	2/25/2002 7:00	24	60411.2	108502.4	168913.6	0.6	0.4
	3/2/2002 19:00	3/3/2002 13:00	18	19132.9	132506.2	151639.1	0.9	0.1
	3/17/2002 4:00	3/19/2002 16:00	60	68642.4	284001.2	352643.6	0.8	0.2
	4/3/2002 22:00	4/4/2002 10:00	12	23611.6	68189.6	91801.2	0.7	0.3
	4/11/2002 13:00	4/12/2002 4:00	15	0.0	82888.6	82888.6	1.0	0.0
	6/7/2002 16:00	6/8/2002 16:00	24	308734.3	172088.2	480822.5	0.4	0.6
H/Gustav	9/9/2002 4:00	9/11/2002 1:00	45	560995.4	377594.0	938589.4	0.4	0.6
	10/8/2002 1:00	10/8/2002 19:00	18	296150.6	80585.8	376736.4	0.2	0.8
H/Kyle	10/14/2002 1:00	10/16/2002 10:00	57	476944.9	430639.4	907584.3	0.5	0.5
	10/24/2002 16:00	10/26/2002 7:00	39	47201.2	180614.0	227815.2	0.8	0.2
	10/28/2002 22:00	10/31/2002 16:00	66	424334.4	302873.9	727208.4	0.4	0.6
	12/10/2002 16:00	12/11/2002 13:00	21	23084.3	124461.0	147545.3	0.8	0.2

Table 5.20. The Modified COSI Parameter for storms in year 2003

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	2/15/2003 19:00	2/18/2003 10:00	63	391556.9	714058.3	1105615.2	0.6	0.4
	2/26/2003 16:00	3/1/2003 10:00	66	218794.8	369712.2	588507.0	0.6	0.4
	3/6/2003 22:00	3/8/2003 1:00	27	72881.6	126311.7	199193.3	0.6	0.4
	3/14/2003 1:00	3/14/2003 19:00	18	22293.5	117573.2	139866.7	0.8	0.2
	3/19/2003 4:00	3/21/2003 7:00	51	503002.8	344391.4	847394.2	0.4	0.6
	3/30/2003 7:00	3/31/2003 4:00	21	68071.7	96056.9	164128.6	0.6	0.4
	4/6/2003 22:00	4/11/2003 19:00	117	707144.1	897184.2	1604328.3	0.6	0.4
	4/17/2003 16:00	4/21/2003 4:00	84	862013.6	641830.5	1503844.1	0.4	0.6
	5/3/2003 7:00	5/3/2003 19:00	12	17887.1	48866.7	66753.8	0.7	0.3
	5/17/2003 1:00	5/20/2003 1:00	72	608036.7	366765.8	974802.5	0.4	0.6
TS/Henri	9/8/2003 16:00	9/13/2003 10:00	114	1176356.0	923737.9	2100093.9	0.4	0.6
H/Isabel	9/15/2003 19:00	9/19/2003 7:00	84	907005.6	895869.1	1802874.8	0.5	0.5
	10/9/2003 22:00	10/12/2003 1:00	51	500810.7	405421.4	906232.1	0.4	0.6
	11/8/2003 22:00	11/10/2003 10:00	36	148583.7	139169.1	287752.8	0.5	0.5
	11/25/2003 1:00	11/25/2003 16:00	15	316099.5	97206.4	413305.8	0.2	0.8
N	12/6/2003 13:00	12/7/2003 1:00	12	47271.5	74580.6	121852.1	0.6	0.4
	12/13/2003 22:00	12/14/2003 22:00	24	43740.6	166319.0	210059.6	0.8	0.2

A statistical analysis of Modified COSI Parameter has been done and statistics of the data is summarized in Table 5.21.

Table 5.21. Modified COSI Parameter statistics analysis

Statistics	Duration (hrs)	Surge Momentum	Wave Momentum	Modified COSI	Surge (m)	Wave (m)	Period (sec)	Wave Ratio	Surge Ratio
Average	47.0	367879	349353	717232	1.0	2.7	11.2	0.6	0.4
Max	195	4724883	2458696	7183579	2.0	6.0	18.5	1.0	0.8
Min	12	0	48867	66594	0.6	1.7	6.6	0.2	0.0
STDEV	38.9	554246	360713	876558	0.3	0.8	2.6	0.2	0.2
Median	34.5	186410	215387	366318	1.0	2.5	10.7	0.6	0.4

The histogram of the Modified COSI parameter has been prepared with its cumulative distribution and both are shown in Figure 5.3.

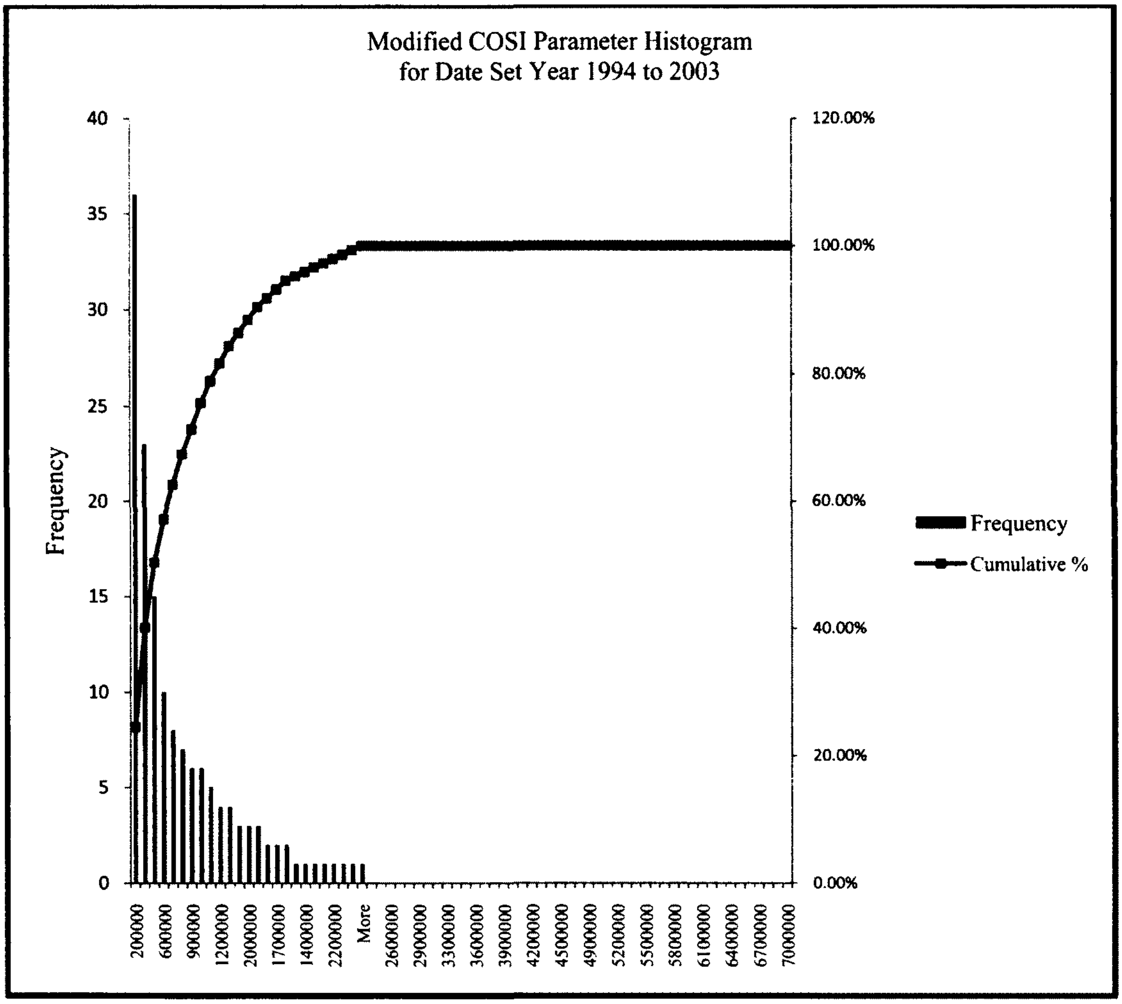

Figure 5.3. Modified COSI parameter Histogram and Cumulative Distribution

Also, a Lognormal distribution function has been developed that fits the distribution and its probability density function for the Modified COSI parameter data set is shown in Figure 5.4.

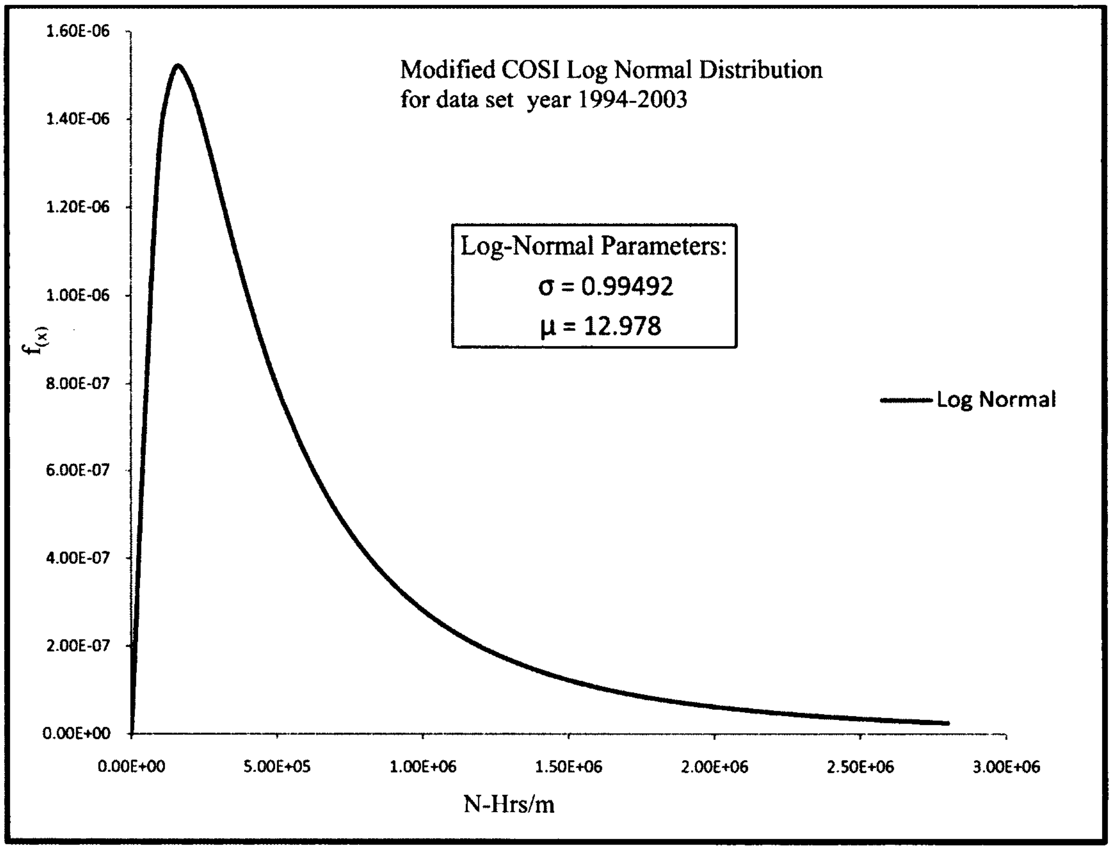

Figure 5.4. Modified COSI parameter Lognormal Probability Density Function

5.3 Comparison of Saffir-Simpson Scale to the Modified COSI Parameter

Since the Saffir-Simpson scale is used for hurricanes, a comparison of this scale and the Modified COSI parameter has been tabulated in Table 5.22.

Table 5.22, Comparison of the Modified COSI parameters to Saffir-Simpson Scale

Hurricane	Date	Duration (Hrs)	Original COSI Scale*	The Modified COSI Parameter	Saffir-Simpson Scale	Remarks
Dennis	August 29-Sep 5, 1999	153	10.4	7.18 x 10^6 N-Hr/m Ranked 1st	1	Approached from south, reaching 200km east of Cape Hatteras where it remain until 2 September, having been downgraded to a Tropical Storm. Made landfall as a Tropical Storm on 5 September, Because of duration offshore, significant beach erosion occurred (Baron et al., August 1999).
Isabel	Sept 7-19, 2003	84	10.1	1.80 x 10^6 N-Hr/m Ranked 14th	5 2 at landfall	Reached maximum intensity on 11 September, well out into the Atlantic. Gradually weakened until landfall as a Category 2 on 18 September. Considered one of the most significant tropical cyclones to effect North Carolina since Hurricane Hazel in 1954. (Beven and Cob, December 2003).
Gordon	Nov. 16-21, 1994	123	5.8	3.03 x 10^6 N-Hr/m Ranked 3th	1	Gordon never made landfall, following an erratic path until dissipating off of South Carolina on 20 Nov. Significant coastal erosion (Pasch, January 1995).
Felix	August 12-21, 1995	135	7.6	2.23 x 10^6 N-Hr/m Ranked 6th	3	Reached maximum value on 15 August. Approached closest to North Carolina coast on 17 August as a Category 1. Never made landfall. Considerable beach erosion (Baron, et.al., August 1995).
Irene	August 26, 2011	24	NA	0.63 x 10^6 N-Hr/m Rank would be 55 (not included in the data set)	3 2 at landfall	Irene hit Crooked, Acklins and Long Island in the Bahamas as a category 3 hurricane but gradually weakened after crossing the Bahamas. It made landfall in North Carolina as a category 1 hurricane and caused widespread damage across a large portion of the eastern United States as it moved north-northeastward, bringing significant effects from the mid-Atlantic states through New England. The most severe impact of Irene in the northeastern United States was catastrophic inland flooding in New Jersey, Massachusetts and Vermont (Avila and Cangialosi, 2011)

* From Klentzman, 2007.

As it is clear from the Table 5.22, the Saffir-Simpson scale not necessarily correlates with the damages to the coast while the Modified COSI parameter is well correlates to the damages and the morphological changes on the coast.

One of the recent hurricanes that brought significant rain and impacted the entire east coast of the U.S. was hurricane Irene, August 2011. As an example, the data for hurricane Irene has been processed based on the criteria set forth in this dissertation and results are tabulated in Table 5.23.

Table 5.23. Modified COSI Parameter and its characteristics for Hurricane Irene 2011

Storm	Start	End	Dur. (Hr)	Surge Mom (N-Hrs/m)	Wave Mom (N-Hrs/m)	Modified COSI (N-Hrs/m)	Wave Ratio	Surge Ratio	Max. Wave (m)	Max Surge (m)
Irene	8/26/11 19:00	8/27/11 19:00	24	322860	307371	630231	0.51	0.49	4.38	0.58

Table 5.23 shows the wave and surge momentum and their share in the Modified COSI parameter with the hydrodynamic parameters of storm such as maximum wave height and maximum storm surge.

Also, the graphics of wave, surge and total momentum has been prepared for Hurricane Irene. Figure 5.5 shows a graphical momentum changes of the wave, surge and total (the Modified COSI Parameter) at 8 meter gage, FRF, Duck, NC.

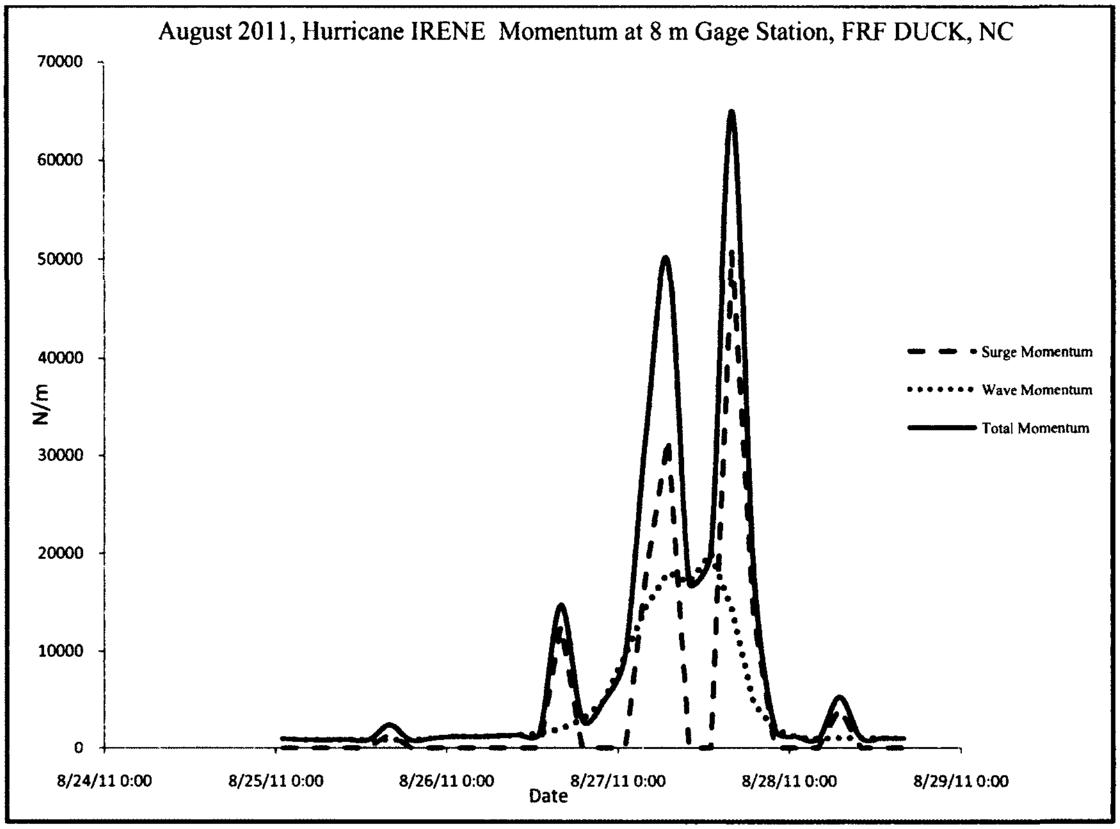

Figure 5.5. Hurricane Irene 2011, wave and surge momentum and total Momentum (the Modified COSI Parameter)

SUMMARY, CONCLUSION AND RECOMMENDATIONS

The objectives of this dissertation to study, to improve and to introduce a new approach to compute the COSI parameter in order to produce more realistic results is met and it is named the Modified Coastal Storm Impulse (COSI) Parameter. The Modified COSI Parameter physically combines storm surge, waves and storm duration to determine one unique number to serve as a coastal storm-strength index.

The data set of a ten year period (1994-2003) at FRF, Duck, has been reanalyzed based on the new approach introduced for the wave momentum and the storm surge momentum. It has produced 148 storms which includes both hurricanes and northeasters. The hydrodynamic parameters of storms such as wave height, wave period, storm surge and the duration of the storm have been considered in developing the Modified COSI parameter for each storm and obtained from the same data set. In average, the results show a reasonable proportionality of the wave momentum (60%) and the surge momentum (40%) over the duration of the storm in the total momentum.

Now the Modified COSI parameter is based on more robust approach, it can be studied to find a correlation between the morphological changes of the cost and the type of the storms and learn for example if surge dominant storms are more erosive for the shoreline and wave dominant storms are more accreting the beaches. Since the data set that has been utilized in this dissertation is limited to one location, FRF, Duck, more investigation is needed to examine the influence of the different depth in the Modified COSI parameter. Since the tide elevations are variable and different for different locations and regions, it is recommended to investigate different regions with different tide characteristics and apply the methodology represented here to compare the results. Since the Modified COSI parameter can be applied to both northeasters and hurricanes, this methodology can be investigated for different regions with different climates to study the results.

The results of the Modified COSI parameter are for a 1 meter slice of the beach during the storm and more investigation is needed to apply this methodology in time and space. The Modified COSI parameter is incorporating all three storm intensity parameters (water levels, waves and storm duration) and can be used in design, quantifying risk and wherever these parameters are utilized for design or analysis purposes. For example, in rubble-mound structures design, "damage" curves can be modified as a function of the Modified COSI parameter and not just wave heights above the design wave height. Another example for application of the Modified COSI parameter might be when calculating the wave run up and overtopping rates on seawall structures by developing fragility curves for design. A very useful application of the Modified COSI parameter can be 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. Another application of the Modified COSI Parameter is to develop numerical models to calculate the Modified COSI parameter for storm intensity in time as the storm moves toward the coast and forecast the damages.

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