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Grand Cayman

Storm Surge Assessment

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Issue 1

   

Grand Cayman
Storm Surge Assessment

Prepared for

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Executive Summary

Orth-Rodgers & Associates, Inc. is carrying out the design of a vertical wall to protect a region located on the south coast of Grand Cayman Island from surge inundation during hurricane events. This region has been flooded in recent years during the passages of Hurricane Wilma in 2005 and Hurricane Ivan in 2004. The objective of the wall is to reduce overtopping and to direct the flood waters back into the sea.

Baird & Associates was retained by Orth-Rodgers to evaluate the storm surge and overtopping at the project site, and to estimate the loading on the wall. This was achieved through numerical modeling of storm surge and hurricane-generated waves, along with desktop analyses of wave overtopping and loading.

The site consists of a vertical bluff headland approximately 12 to 17 feet above sea level composed of a hard beach rock, as may be noted in Figure 1. Topographic and bathymetric surveys completed by Orth-Rodgers in 2007 showed that water depths in front of the bluff are in the order of 30 to 50 feet, and a shelf extends seaward approximately 1000 feet to depths in the order of 150 feet. At this point, the shelf drops dramatically to much greater depths (> 1000 feet). The proposed wall location is set back from the edge of the bluff by approximately 50 to 500 feet, depending on location.

Figure 1 Oblique Aerial Image of the Site

Detailed analyses of a historical hurricane database using specialized in-house software showed that hurricanes are a relatively frequent occurrence in the vicinity of Grand Cayman Island. For example, a hurricane occurs within 55 nautical miles of the site every five years, on average. An event of Category 4 intensity or greater passes every 35 years on average. Using the information contained in the historical database, synthetic design hurricane events were created for Category 2, 3 and 5 storms. These storms formed the basis of the analyses and design calculations carried out in the study.

A numerical model, MIKE21, was used to simulate storm surge at the project site due to the synthetic hurricane events, as well as due to Wilma 2005 and Ivan 2004. Storm surge is the increase in water level due to the direct action of wind and atmospheric pressure on the water's surface. The modeling showed that, due to the relatively deep water depths in front of the project site, the magnitude of the storm surge is limited and the project site cannot be directly inundated by such surge. Flooding is the result of wave overtopping of the bluff. Maximum storm surge estimates of 1.3 feet and 0.8 feet were developed for Hurricanes Ivan and Wilma, respectively. The largest estimated surge, 4.4 feet, was for a synthesized Category 5 hurricane in which the hurricane eye passed directly over the project site.

Numerical models of offshore wave generation and nearshore wave transformation were subsequently utilized to estimate the design wave conditions at the project site. This information was employed to estimate wave overtopping effects. Figure 2 shows a snapshot of wave heights during the passage of a Category 5 event. The colors scale with wave height, while the vectors show the wave direction.

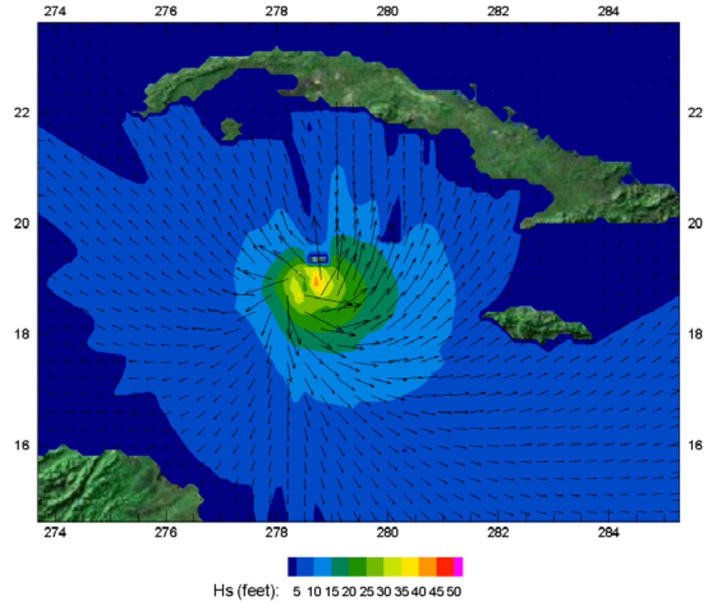

Figure 2 Simulated Wave Conditions for a Category 5 Hurricane

Wave overtopping of the bluff was estimated by means of various empirical equations, recently published in the technical literature. The greatest overtopping occurs in the central portion of the project site. A Category 5 hurricane will result in considerable overtopping, that may be an order of magnitude greater than was observed during Hurricane Wilma 2005 and, potentially, 2 to 5 times greater than that during Hurricane Ivan 2004.

The overtopping analysis showed that the presence of the proposed vertical wall will greatly reduce wave overtopping at the ends of the project where ground elevations are lower. In the central portion of the project site, the wall will serve to direct water that has overtopped the bluff back towards the sea. It is important to note that in this central area, the land slopes inland from the edge of the ocean bluff. Thus, water due to wave overtopping of the bluff flow will tend to flow inland.

The site bathymetry and topography will create highly complex and spatially variable loading conditions on the storm surge barrier. These loads cannot be readily estimated by means of desktop studies and/or numerical model investigations, as there is little guidance in the technical literature for such wall configurations. Estimates of wall loading were developed assuming ponding of water on top of the site bluff and the re-formation of waves on the bluff due to overtopping wave energy. Given the uncertainty associated with these calculations, it is recommended that a significant factor of safety be applied to the estimated loads.

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1.0 INTRODUCTION

Orth-Rodgers & Associates, Inc. is carrying out the design of a vertical wall to protect a region located on the south coast of Grand Cayman Island from surge inundation during hurricane events. This region has been flooded recently during the passages of Hurricane Wilma in 2005 and Hurricane Ivan in 2004. The objective of the wall is to reduce overtopping and to direct the flood waters back into the sea.

Specific design objectives for the wall include:

- To significantly reduce or eliminate flooding during lower intensity hurricane events, such as Wilma 2005.
- To remain structurally sound and withstand the effects of a direct hit by a Category 5 hurricane.

Baird & Associates was retained by Orth-Rodgers to evaluate the storm surge and overtopping at the project site, and to estimate the loading on the wall. This has been achieved through numerical modeling of storm surge and hurricane-generated waves, along with desktop analyses of wave overtopping and loading.

1.1 Definition of Hurricane Intensity

In this study, hurricane intensity is categorized according to the Saffir-Simpson scale, as summarized in Table 1.1.

Table 1.1 Saffir-Simpson Hurricane Intensity Scale

Category	Peak Wind Speed (knots)
1	64 - 82
2	83 - 95
3	96 - 113
4	114 - 135
5	> 135

2.0 THE PROJECT SITE AND WALL CONFIGURATION

The project site is located on the south shore of Grand Cayman Island, as shown in Figure 2.1, and is directly exposed to wave conditions on the Caribbean Sea. Figure 2.2 presents an aerial image of the region while Figures 2.3 presents an oblique aerial photograph of the site. Basically, the project site consists of a vertical bluff headland approximately 12 to 17 feet above sea level composed of a hard beach rock. Areas of slightly lower elevation are found east and west of the headland. The headland is devoid of any significant vegetation, an indication that this site may be subject to overtopping waves and sea spray on a relatively frequent basis.

Topographic and bathymetric surveys were conducted by Orth-Rodgers in 2007. Figure 2.4 presents contours of elevation as determined from the survey information, while Figure 2.5 gives a colour-shaded representation of the same data. The proposed wall location, which is set back from the edge of the bluff by approximately 50 to 500 feet, depending on location, is shown as a black line on the figures.

Water depths in front of the bluff are in the order of 30 to 50 feet, and a shelf extends seaward approximately 1000 feet to depths in the order of 150 feet. At this point, the shelf drops dramatically to much greater depths (> 1000 feet).

Project Site

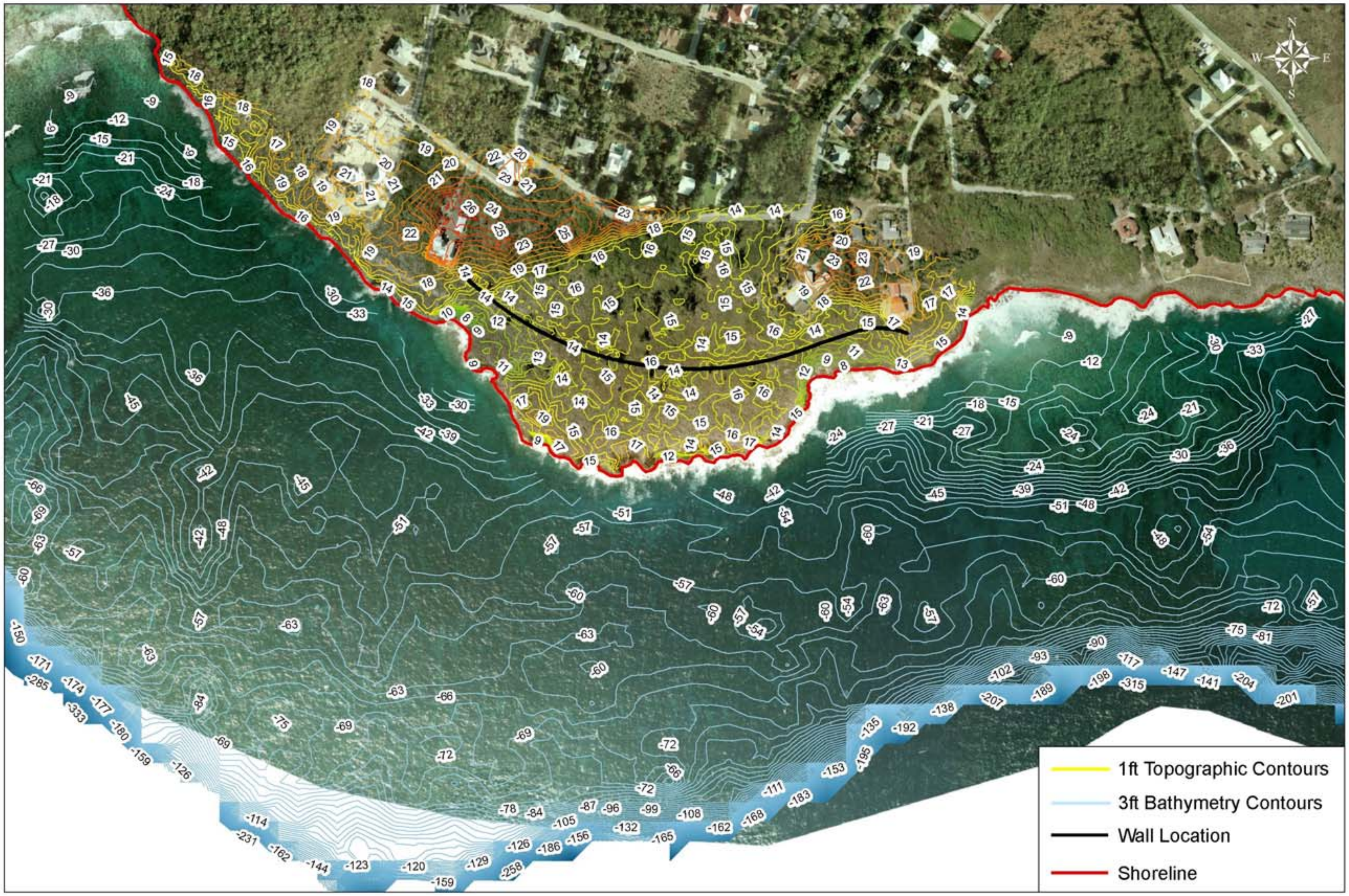
Grand Cayman Island

Spatial Reference: WGS 1984 UTM Zone 17N

Figure 2.1

Figure 2.2 Aerial Image of the Site

Figure 2.3 Oblique Aerial Photograph



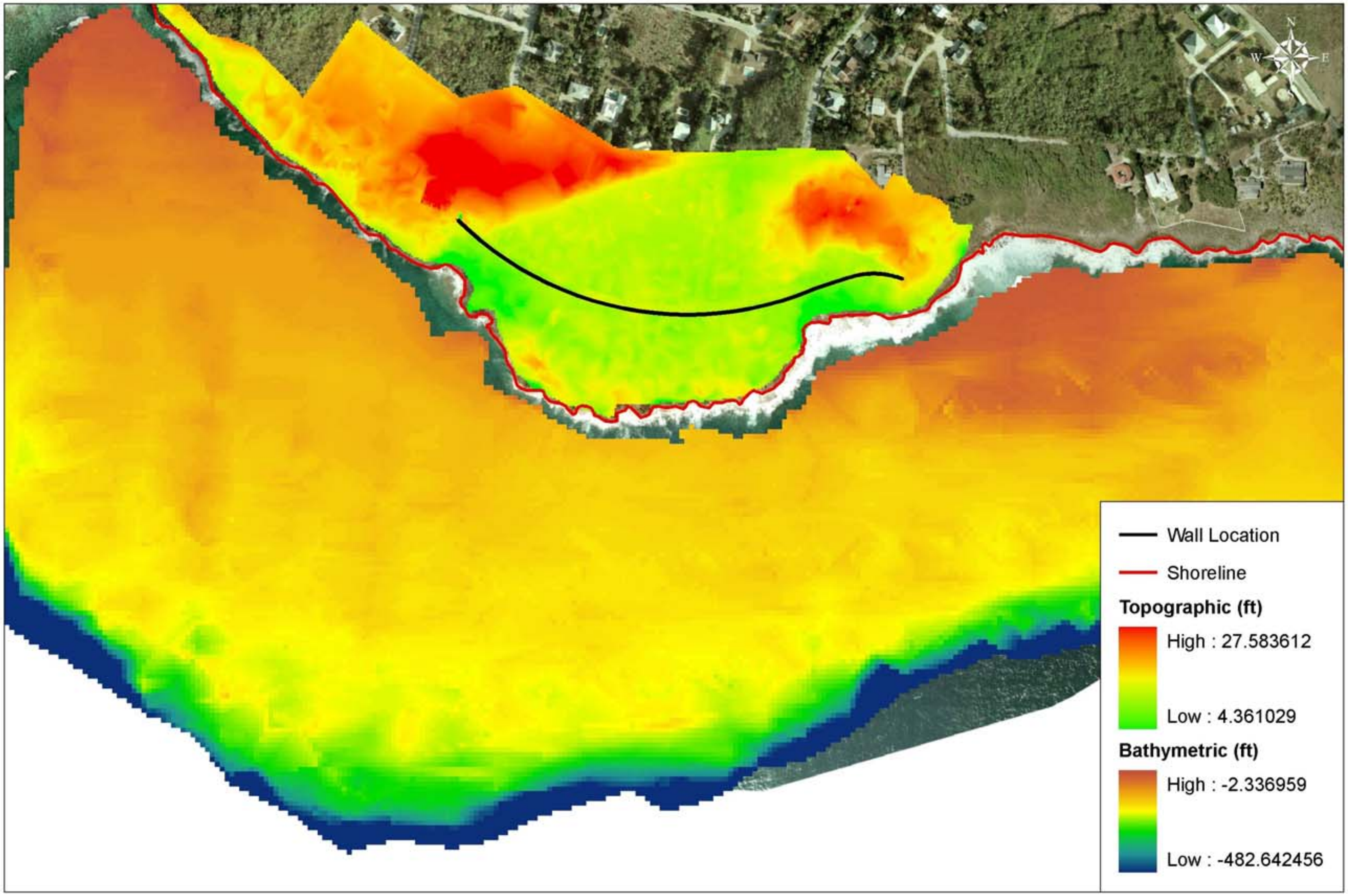
0 200 400 600 ft

Topographic and Bathymetry Data

Grand Cayman Islands

Spatial Reference: WGS1984 UTM Zone17N

Figure 2.4



ft
0 200 400 600

Topographic and Bathymetry Data

Grand Cayman Islands

Spatial Reference: WGS1984 UTM Zone17N

Figure 2.5

3.1 HISTORICAL HURRICANE EVENTS

3.1 Statistical Analyses of Historical Hurricanes

The HURDAT historical hurricane database of the US National Atmospheric and Oceanographic Administration (NOAA) Tropical Storm Center was analyzed using specialized in-house software in order to assess the frequency of occurrence of hurricanes within close proximity to the project site. The HURDAT database covered the period from 1850 to 2006; however, in this analysis, storms earlier than 1900 were not considered. Due to the limited meterological coverage in the 1800s, there is a possibility that certain significant storms may not be included in the database.

Table 3.1 gives the frequency of occurrence of the historical hurricane events passing within specific radial distances (55, 110, and 160 nautical miles) from the project site. In Table 3.2, the return period for hurricanes of various intensities passing within specified radial distances of the project site are given.

Table 3.1 Occurrence of Historical Hurricane Events

Numbers of Events (1900-2006)

	Distance from Site (nautical miles)		
	55	**110**	**160**
Number of Tropical Storms	40	83	121
Number of Hurricanes			
Category 1	12	17	23
Category 2	4	12	14
Category 3	3	7	13
Category 4	3	5	6
Category 5	0	2	5

Table 3.2 Return Period (Years) for Hurricane Events

Return Period (years)

	Distance from Site (nautical miles)		
	55	**110**	**160**
Tropical Storms	2.7	1.3	0.9
Hurricanes			
Category 1 or greater	4.9	2.5	1.8
Category 2 or greater	10.7	4.1	2.8
Category 3 or greater	17.8	7.6	4.5
Category 4 or greater	35.7	15.3	9.7
Category 5	n/a	53.5	21.4

The return period indicates the average time interval between passage of the hurricane events. For example, a hurricane with Category 2 wind intensity passes within 110 nautical miles of the project site, once every 4.1 years on average.

Figure 3.1 shows the tracks for historical storms of hurricane intensity (i.e. peak wind speeds greater than 63 knots) over the period from 1950 to 2006, and passing within 100 nautical miles of the project site.

In general, hurricanes are relatively frequent occurrence in the vicinity of Grand Cayman Island.

Further analyses were conducted on historical hurricanes passing within 160 nm (300 km) in order to assess the probability of exceedence for peak wind speed (Figure 3.2) and forward velocity (Figure 3.3).

3.2 Recent Hurricane Events of Note

Two recent hurricanes that resulted in flooding of the project area were:

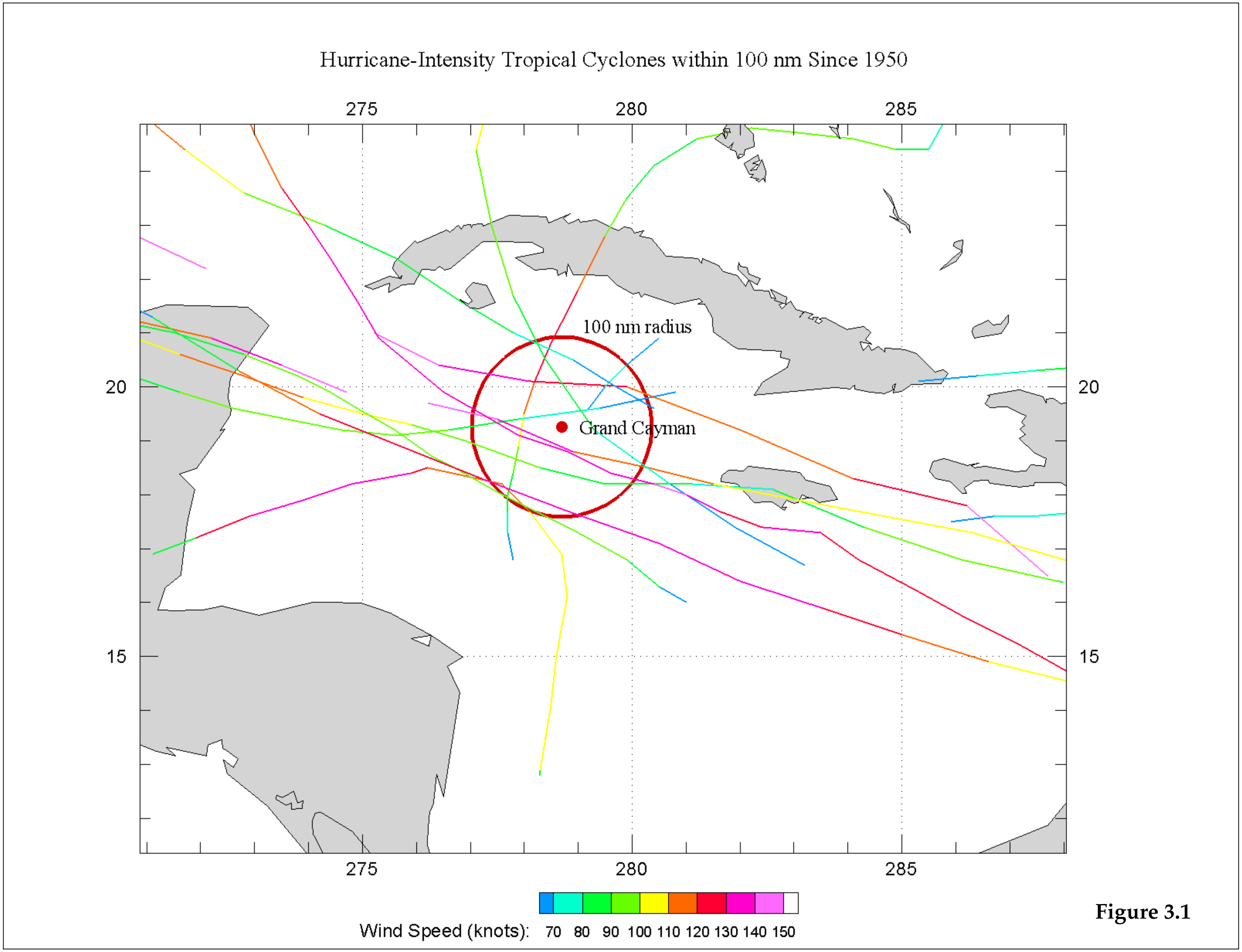
- *Hurricane Ivan*. This storm ran its course from September 2 to September 24, 2004, passing south of Grand Cayman by approximately 25 nautical miles between 9:00 and 11:00 am (local time) on September 12. Although nominally classified as a Category 5 event, the NOAA HURDAT hurricane database indicates that wind speeds dropped to a high Category 4 level (135 knots) in the immediate vicinity of Grand Cayman. The hurricane winds prior to and after departing the Grand Cayman region were of Category 5 intensity. Local wind measurements (Simon, 2004) on Grand Cayman support the Category 4 classification of the storm.

  Significant storm surge, in the order of 6 to 9 feet, occurred in North Sound and South Sound due to the high hurricane wind speeds and the shallow water depths in these regions. This surge resulted in extensive flooding. Wave damage also occurred in areas of the island not protected by coral reef. Anecdotal information (Simon, 2004) indicated that wave heights were in the order of 25 feet.

- *Hurricane Wilma*. This hurricane, a Category 5 event, occurred from September 15 to 26, 2005. At closest approach, this storm passed 145 nm south of Grand Cayman Island. Peak wind speeds reached almost 160 knots at that time which, in turn, generated large swell wave conditions that directly impacted the project site.

  A video tape of conditions at the project site occurring during Hurricane Wilma was provided by Orth-Rodgers. This tape showed extensive overtopping of the bluffs at the site, which led to flooding of nearby streets and homes.

Tracks for Hurricanes Ivan and Wilma are shown in Figure 3.4.



Hurricane-Intensity Tropical Cyclones within 100 nm Since 1950
275
280
285
20
15
100 nm radius
Grand Cayman
Wind Speed (knots):
70 80 90 100 110 120 130 140 150

Figure 3.1

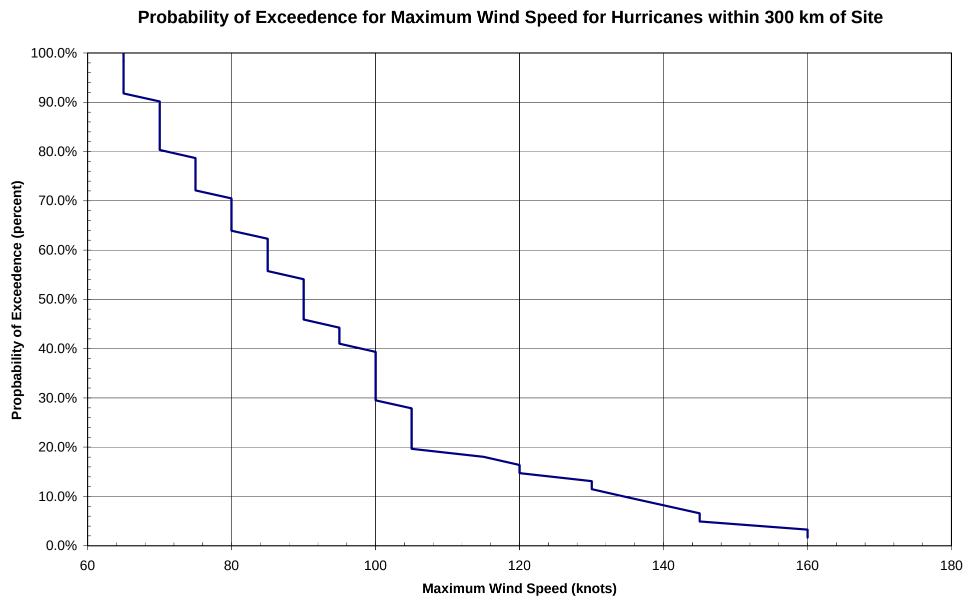


Figure 3.2 The Probability of Exceedence for Hurricane Peak Wind Speed

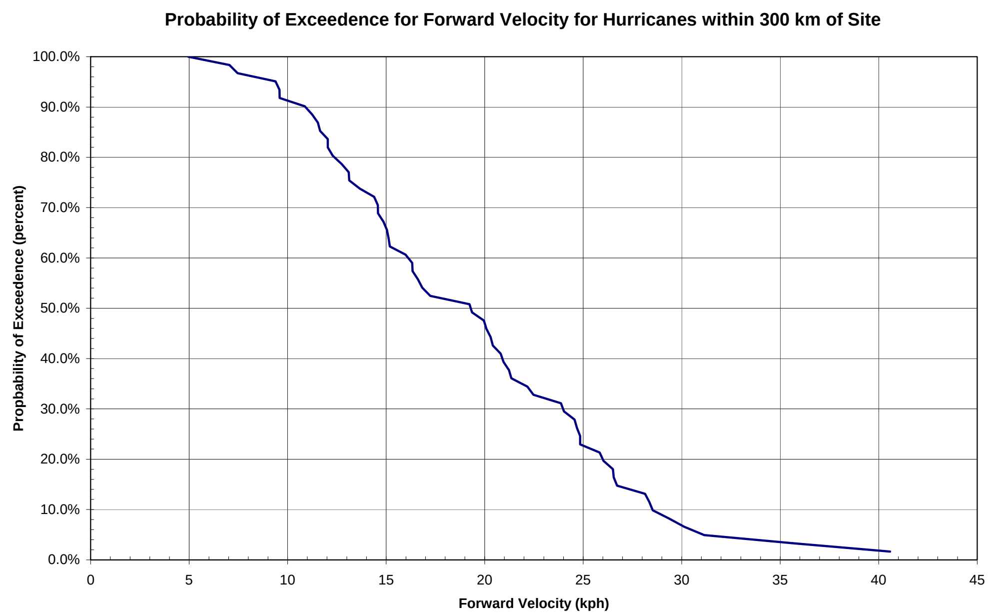
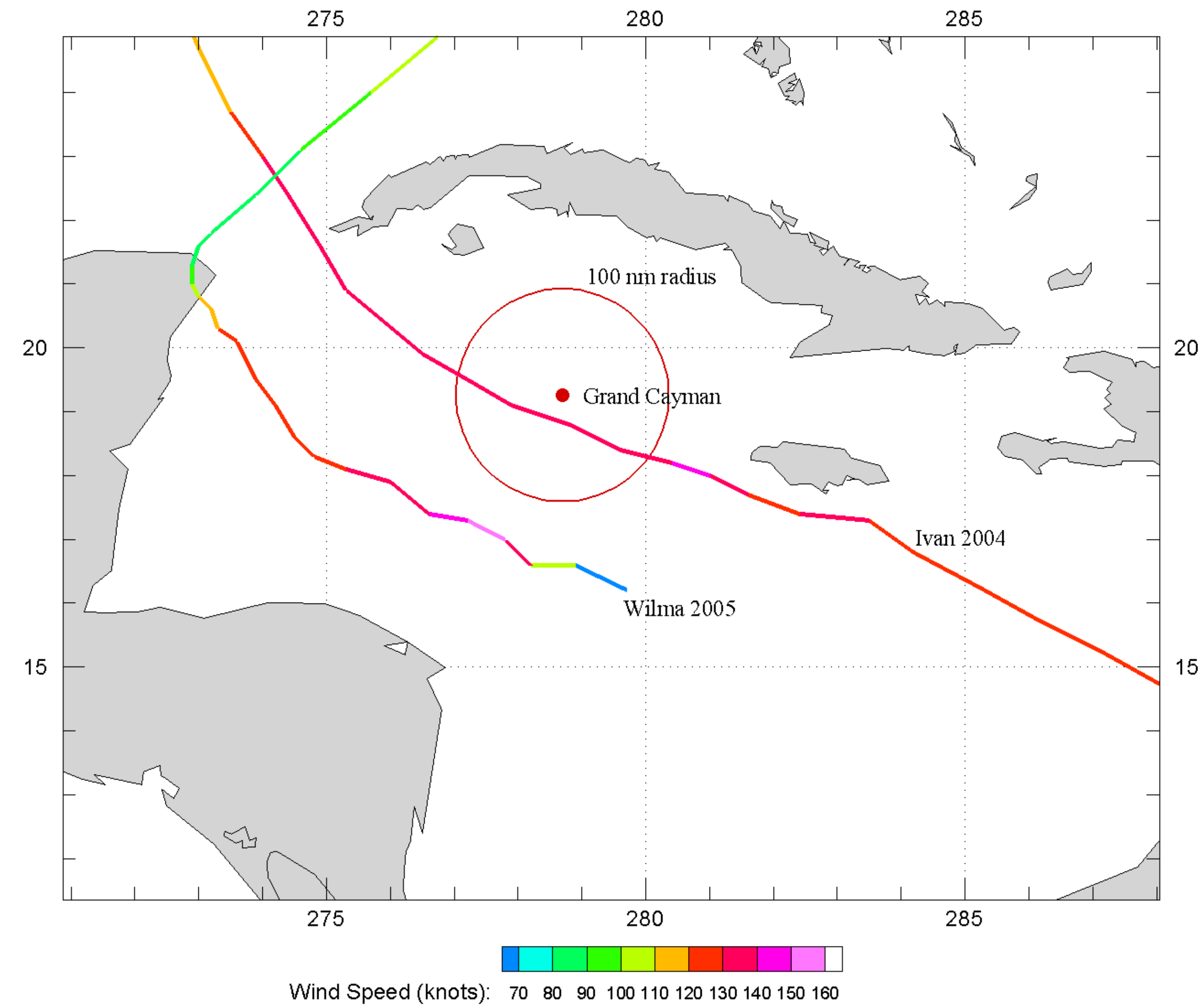


Figure 3.3 The Probability of Exceedence for Hurricane Forward Velocity

Figure 3.4 Hurricanes Ivan 2004 and Wilma 2005



3.3 Design Events

The surge barrier is to be designed to withstand a Category 5 hurricane event. Using the information developed from the HURDAT database, a synthetic design event was developed that had the following characteristics:

- Peak wind velocity of 145 knots.
- Central pressure of 920 mbar.
- Radius to maximum winds of 14 nm.
- A forward velocity of 11 miles per hour (18 kph).

Two different tracks for this cyclone were created:

- A south to north path located to the west of the project site such that the maximum winds occurred at the site.
- A south to north path such that the eye of the hurricane passed directly over the site.

Similar events were also created for Category 2 and 3 hurricanes for assessment of wall overtopping performance.

4.0 STORM SURGE MODELING

4.1 Model Selection and Configuration

Storm surge simulations were carried out using the MIKE21 hydrodynamic model developed by Danish Hydraulic Institute. The basic two-dimensional hydrodynamic model simulates water level variations and unsteady flows on a regularly spaced finite difference grid in response to a variety of forcing functions, such as tides, wind and atmospheric pressure. The model is typically applied to solve hydraulic and environmental problems in lakes, islands, coastal areas, bays and open seas, and includes such effects as Coriolis, bottom friction, and flooding and drying.

An essential input to the model are grids defining the bathymetric and topographic elevations throughout the model domain. For this study, these elevations were developed from the available British Admiralty hydrographic charts, ETOP02 data from National Geodetic Data Centre (NGDC) and higher resolution project site survey data provided by Orth-Rodgers. Due to the requirement for the model to cover a large geographic domain in order to include much of the hurricane track, and the need for detailed results at the project site itself, a "nested" grid approach was employed. That is, a large "outer" grid of relatively coarse resolution (7972 ft) was initially created, and subsequent nested grids of higher resolution were embedded in successive fashion to define the south shore of Grand Cayman Island. The bathymetry of the outer grid, which extended from 77° W to 84° W and 16° N to 22.4° N, and outlines of the five nested grids are shown in Figure 4.1, while the resolution for the various grids is summarized in Table 4.1 Figure 4.2 presents contours of elevation for the grid of highest resolution (33 feet).

Table 4.1 Nested Model Grid Resolution

Grid	Grid Resolution (ft)
Outer	7972
Nested 1	2657
Nested 2	885
Nested 3	295
Nested 4	98
Nested 5	33

The surge model is driven, or "forced", by wind speed and direction as well as atmospheric pressure deficit. The temporal variation of specific hurricane parameters, such as maximum wind speed, radius to maximum winds, and central pressure were input to a specialized tropical cyclone wind/pressure generation found within the MIKE21 system. The resulting wind fields were compared to available overflight and hurricane analysis data obtained from NOAA.

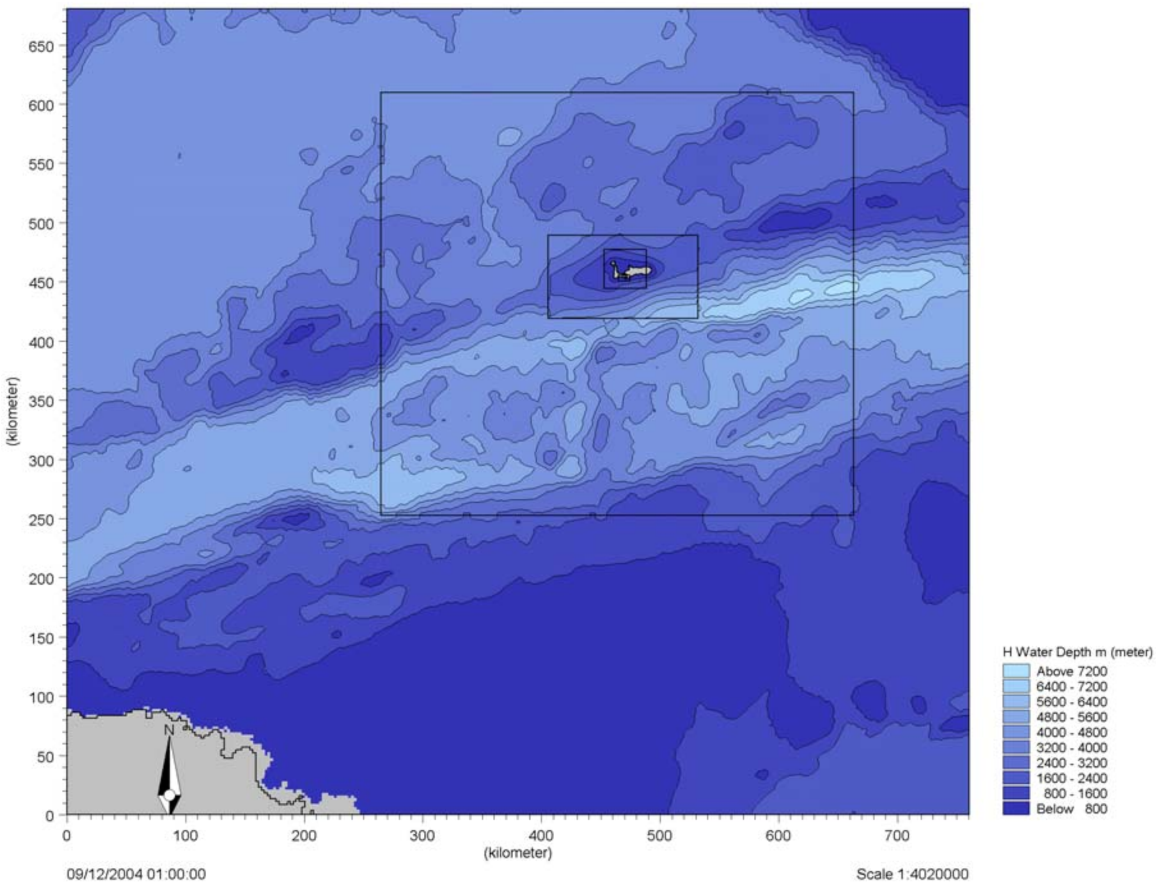


Figure 4.1 Bathymetry of Outer Model Grid Showing Outline of the Nested Grids

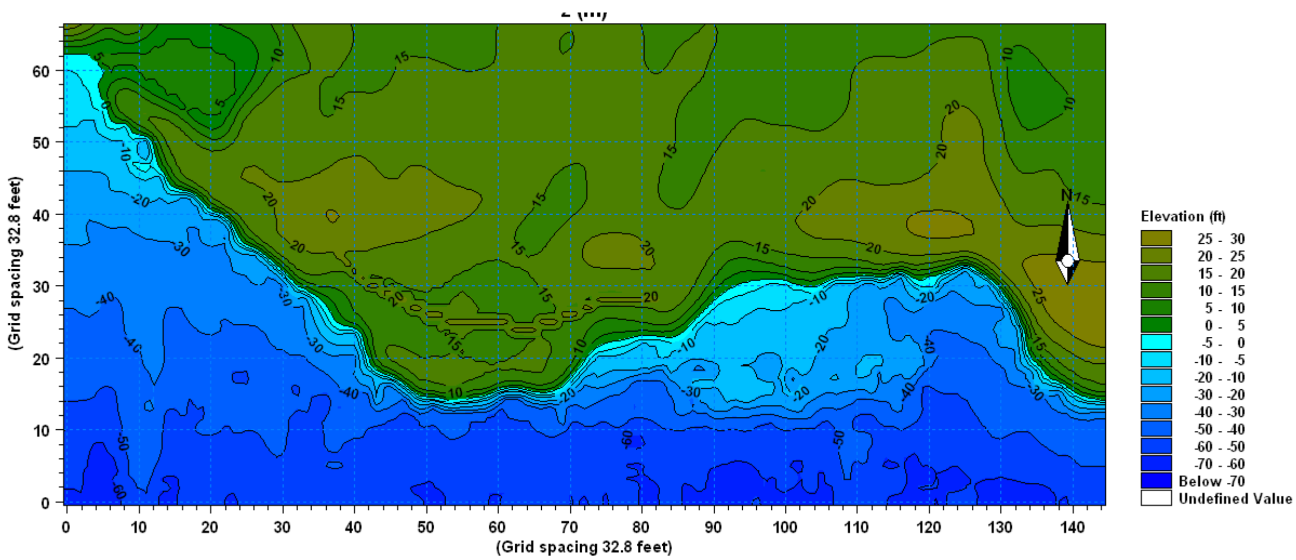


Figure 4.2 Bathymetry of the Highest Resolution Grid (33 ft grid spacing)

4.2 Model Results

Storm surge simulations were carried out for Hurricanes Ivan 2004, Wilma 2005 and the hypothetical Category 2, 3 and 5 design events (as previously discussed). Figures 4.3 to 4.5 show contours of the maximum estimated surge computed in the model for Ivan, Wilma and the Category 5 hurricane, respectively. The maximum surge values at a grid point directly in front of middle of the project site is summarized in Table 4.2. Typically, surge was slightly larger in the shallower bay located to the east of the site, as may be noted in the Figures.

Table 4.2 Summary of Maximum Surge (ft) at the Project Site

Hurricane	**Surge (ft)**
Ivan 2004	1.3
Wilma 2005	0.8
Category 2	1.3
Category 3	1.6
Category 5	2.3
Category 5 (eye over project site)	4.4

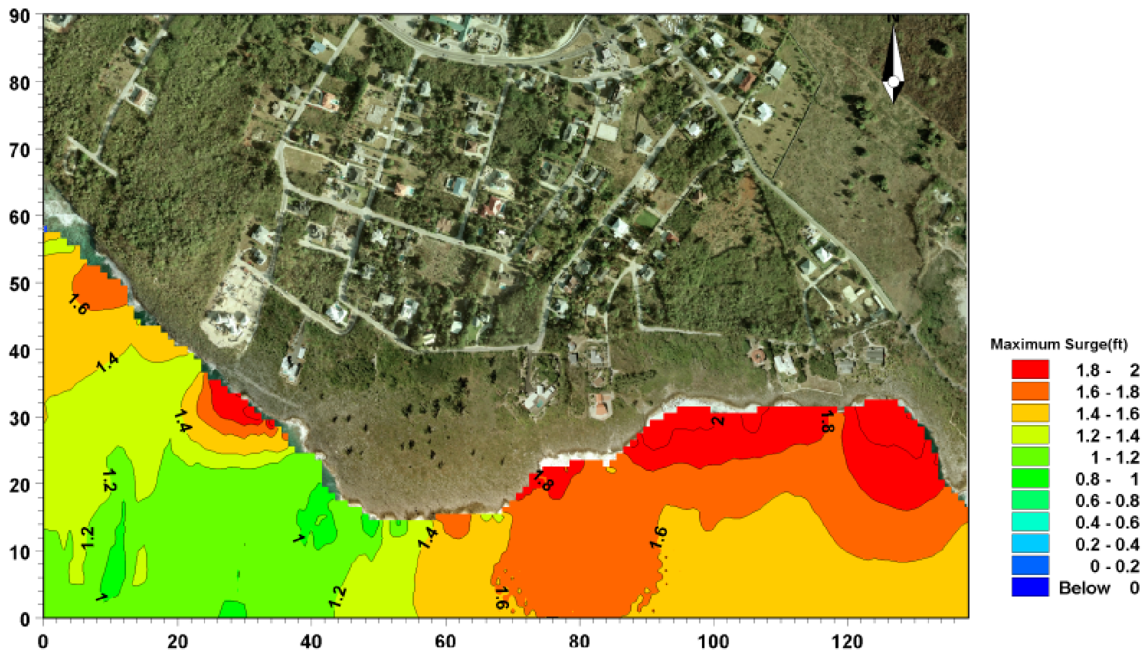


Figure 4.3 Maximum Surge (ft) Associated with Ivan 2004

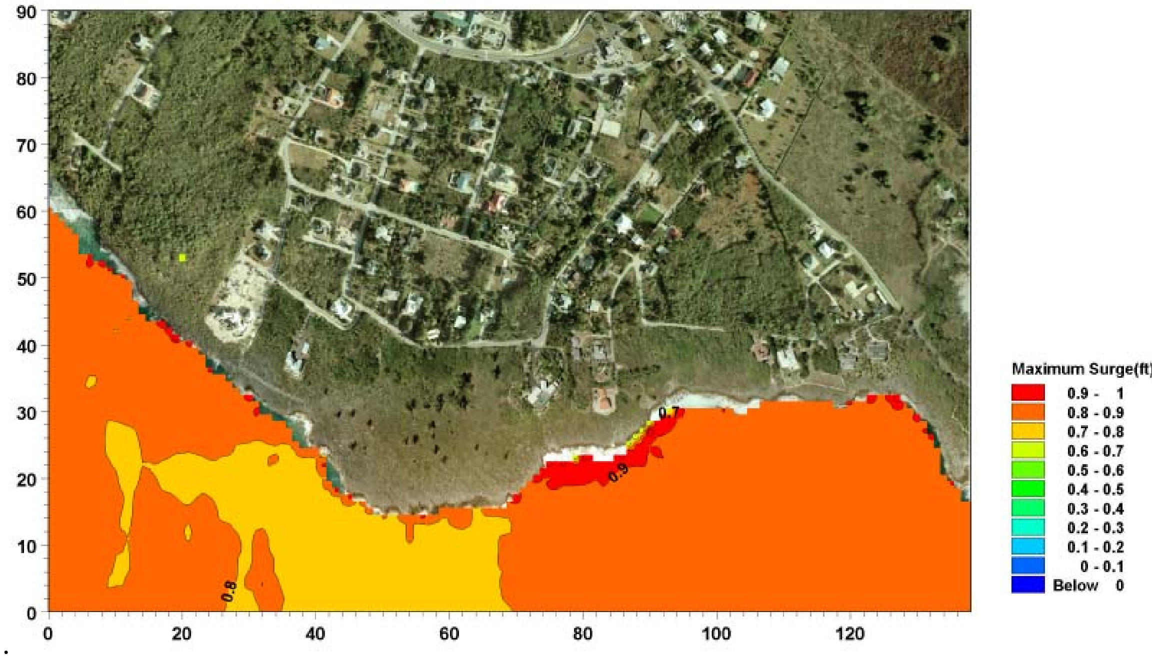


Figure 4.4 Maximum Surge (ft) Associated with Wilma 2005

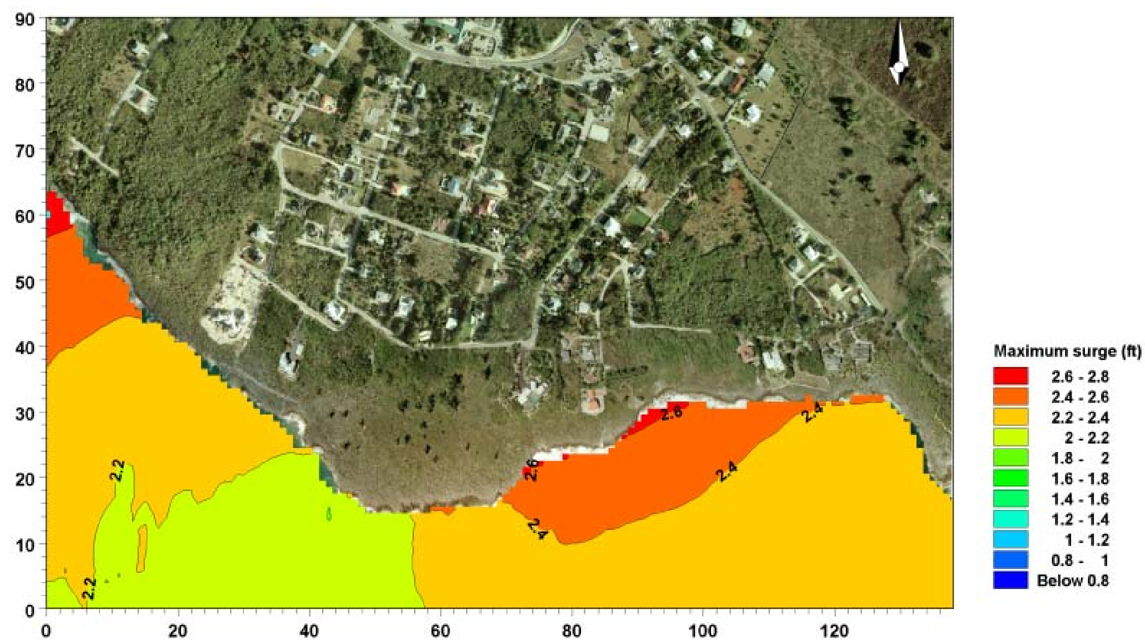


Figure 4.5 Maximum Surge (ft) Associated with Category 5 Hurricane

5.0 WAVE MODELING

5.1 Offshore Hindcast

The WAVAD model, as summarized in Resio (1981) and Resio and Perrie (1989), was used for the tropical cyclone wave simulations carried out in this study. WAVAD is a second generation (2G) spectral wave model that maintains an equilibrium between the wind source and non-linear wave energy flux with an assumed f^{-4} shape for the wave spectrum. The non-linear wave interactions are represented as a momentum flux to the forward face (frequencies less than spectral peak) of the spectrum based on a constant proportion of the energy transferred out of the mid-range frequencies. Wave-wave interactions also transfer energy to the high frequency region of the spectrum where it is assumed that energy is lost due to breaking processes. Wave propagation is handled in WAVAD by means of a first order upwinding scheme. The model can simulate both deep and shallow water physics (refraction); however, only deep water processes were considered in this investigation. The model has also been extensively tested and verified at a range of sites throughout the world by Baird and others.

Inputs to the WAVAD model consisted of a regular grid defining the shoreline and bathymetry in the region of interest as well as a spatially and temporally varying wind field defined at the grid points. Output from the model included the spectral wave energy densities at all grid locations, from which standard parameters such as significant wave height (Hs), peak wave period (Tp), peak wave direction and wave directional spreading were derived. The model bathymetry for the grid was derived from the ETOPO30 database.

The model grid had 161 longitudinal grid points and 200 latitude grid points at an equal resolution of 0.10°. A time step of 15 minutes was used in all of the simulations. A total of 23 frequencies were employed in conjunction with a directional resolution of 15.0° (24 directional bins).

The cyclone wind field model that was used to drive the WAVAD wave model was based on the work of Holland (1980). Input data to the wind field generation model included the cyclone path, and the peak wind speed, cyclone central pressure, distance to the maximum wind speeds (Rmax) and an empirical shape factor ("B"), all defined on a 6-hourly basis. Estimates of Rmax and B were derived from recent work by Willoughby et al. (2004) for Atlantic Ocean hurricanes. The output wind fields were defined on an hourly basis.

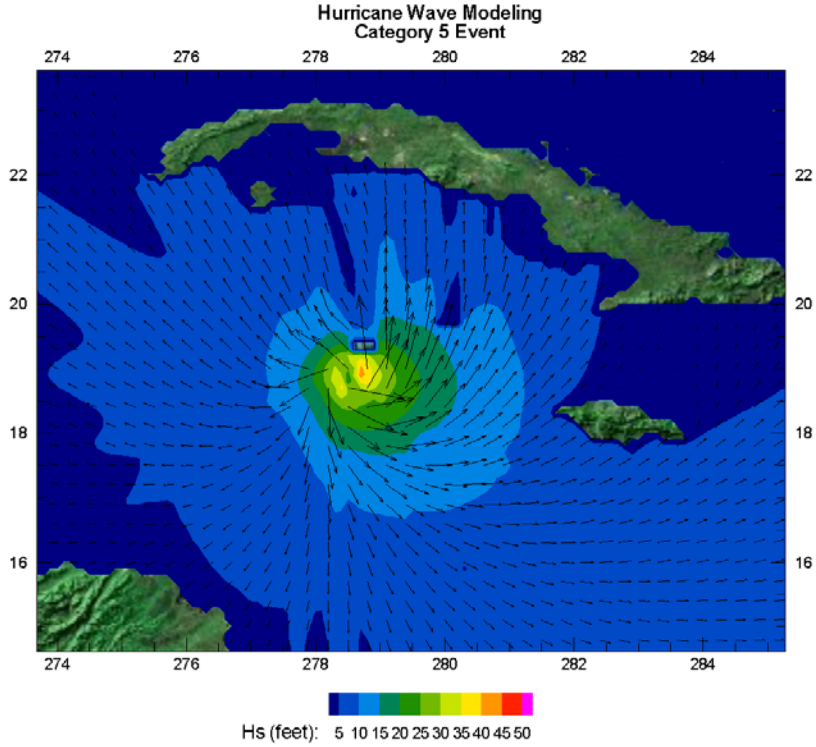


Figure 5.1 Simulated Wave Conditions for a Category 5 Hurricane

Table 5.1 Estimated Offshore Wave Conditions from the Model Simulations

Case	Hs (ft)	Tp (s)	Direction (deg TN)
Ivan 2004	35.8	11.6	124.
Wilma 2005	20.0	14.4	186.
Category 2	30.5	11.0	170.
Category 3	34.8	11.0	170.
Category 5	43.0	12.0	185.
Category 5 (Eye Over the Island)	34.1	11.0	170.

5.2 Nearshore Wave Model

Nearshore wave conditions at the project site arising from hurricane waves were simulated using the MIKE21 Nearshore Wave Module (M21NSW). M21NSW is a spectral nearshore wave model developed by the Danish Hydraulic Institute, which is applied to simulate multi-directional irregular wave spectra. The various nearshore process included in the model are refraction, shoaling, breaking, wind-induced growth and seabed frictional dissipation. The model bathymetry and offshore wave conditions at the boundary are given as input to the model.

A bathymetric grid of north-south orientation was defined with resolutions of 16.4 ft and 82 ft in the onshore and alongshore directions, respectively. Figure 5.2 provides a plot of bathymetric contours for the model domain.

A total of six different input wave conditions were simulated, as summarized in Table 5.2.

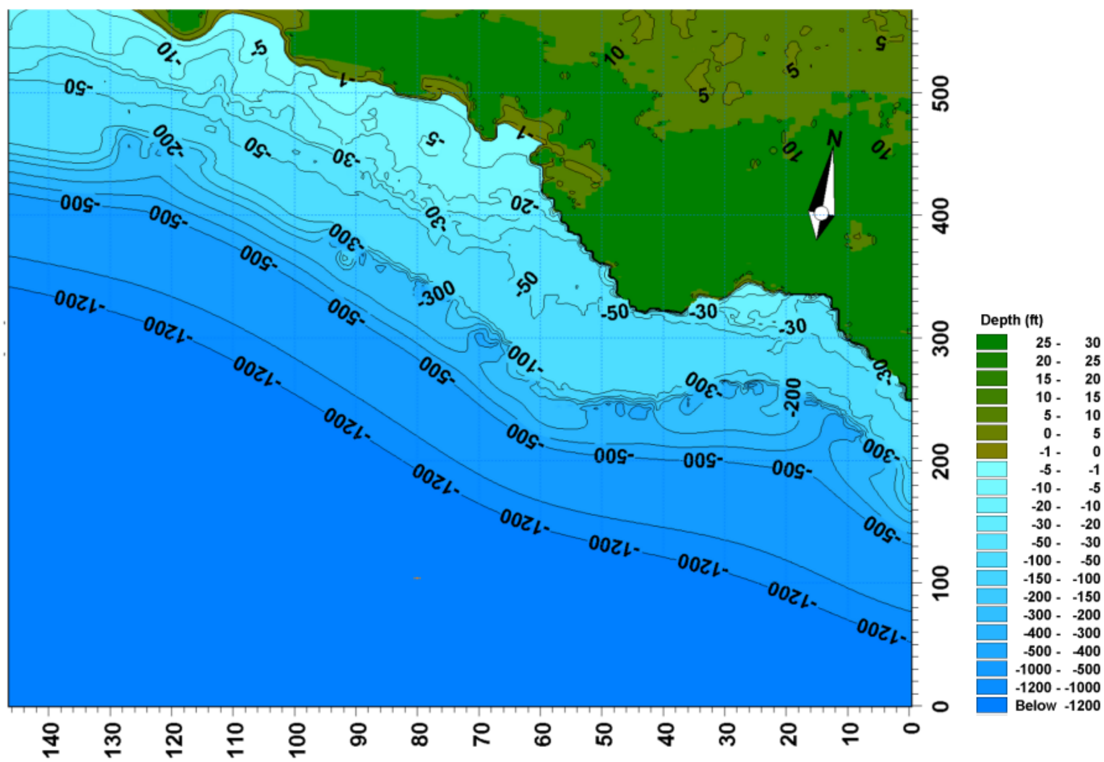


Figure 5.2 Bathymetry Represented in the NSW Model

Table 5.2 Input Conditions used for NSW runs

Case	Hs (ft)	Tp (s)	Direction (deg TN)	Tide (ft)	Estimated Surge (ft)	Total Water Level (ft)
Ivan 2004	35.8	11.6	124.	0.66	1.31	0.46
Wilma 2005	20.0	14.4	186.	0.66	0.85	1.51
Category 2	30.5	11.0	170.	0.66	1.35	2.00
Category 3	34.8	11.0	170.	0.66	1.57	2.23
Category 5	43.0	12.0	170.	0.66	2.13	2.79
Category 5 (Eye Over the Island)	34.1	11.0	170.	0.66	3.61	4.27

Figures 5.3 and 5.4 give sample results for Hurricane Wilma and for the design Category 5 event. It may be noted that with the large offshore waves (Hs of 43 ft) associated with the Category 5 hurricane, that considerable nearshore wave breaking occurs as the waves propagate across the coastal shelf in front of the project site.

Results were extracted from the wave model at approximately the 50 foot depth contour for five different locations in front of the project site, as shown in Figure 5.5. The wave height and direction at these five locations is summarized in Table 5.3 for each of the model simulations.

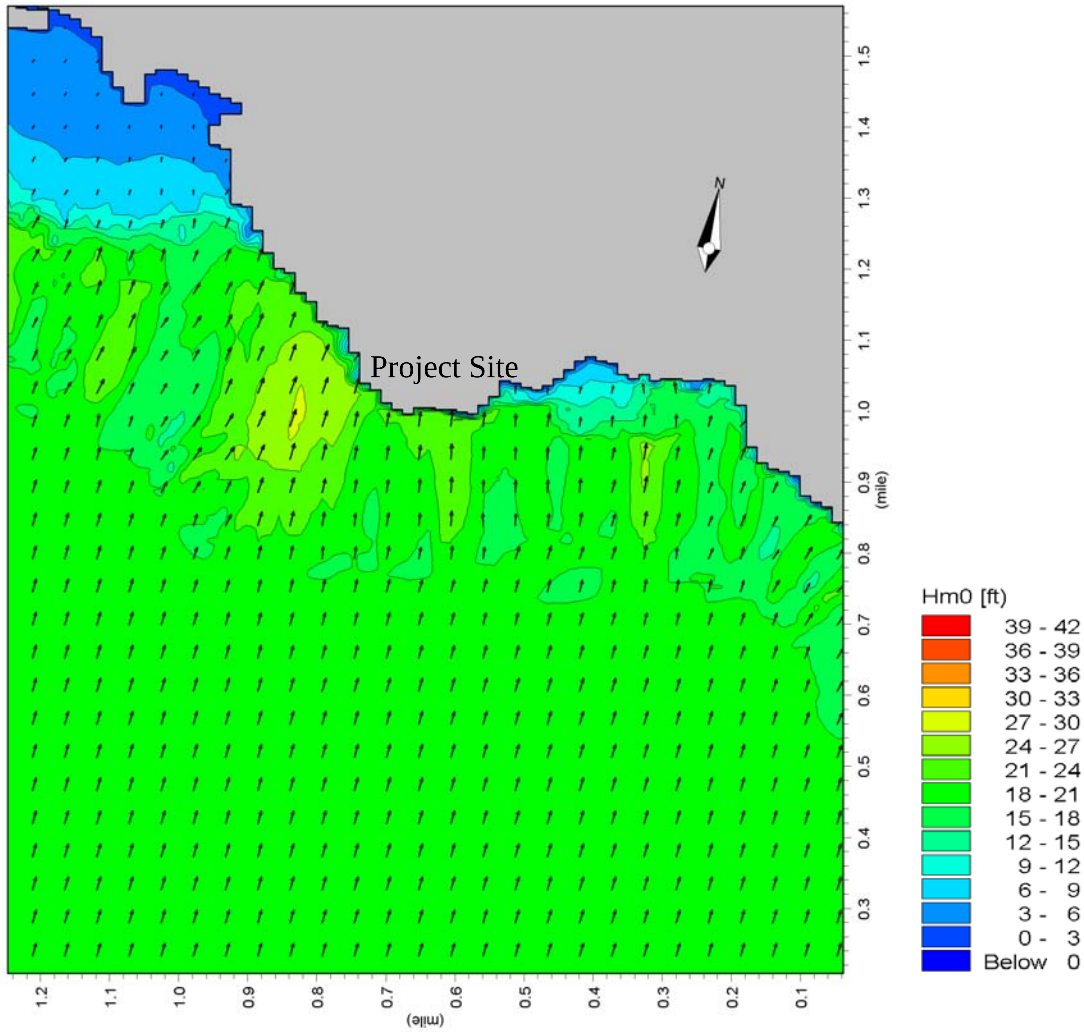


Figure 5.3 Nearshore Wave Conditions from Hurricane Wilma

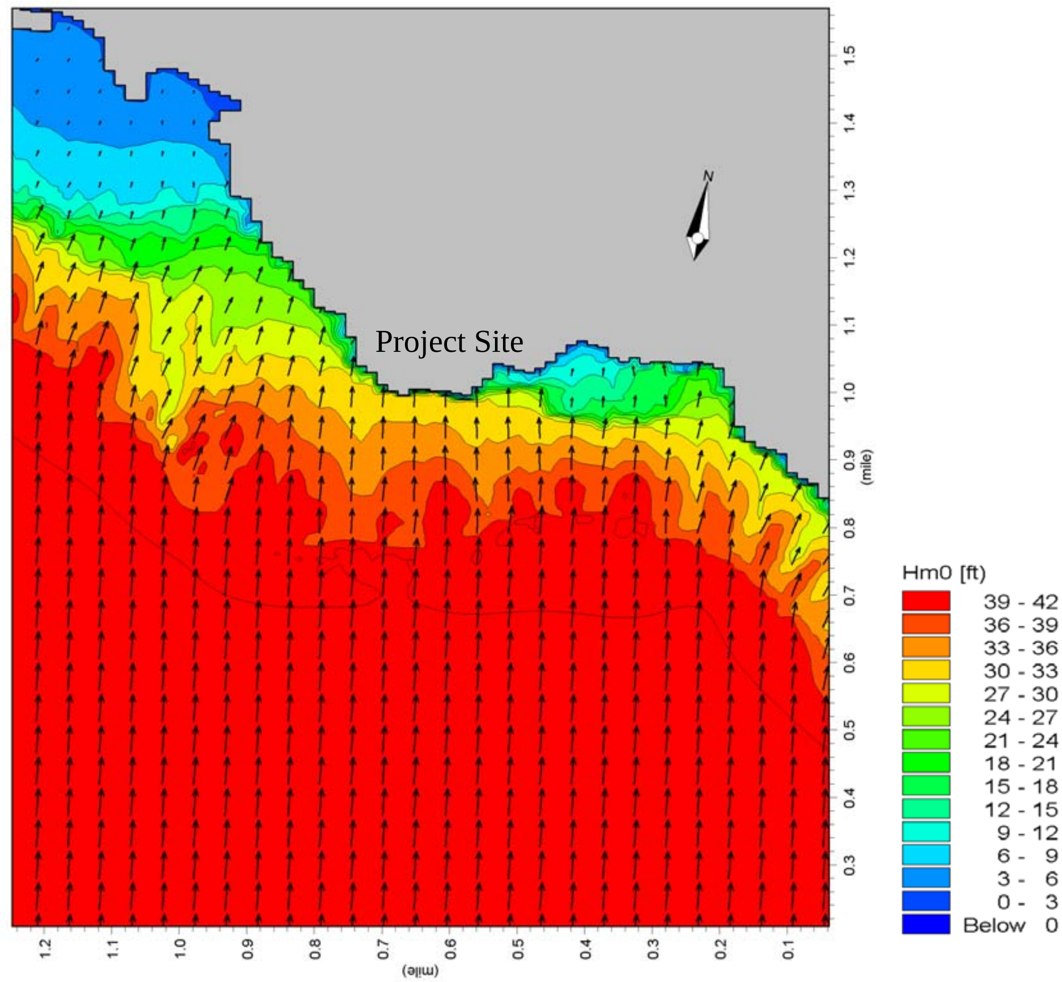


Figure 5.4 Nearshore Wave Conditions due to a Category 5 Event

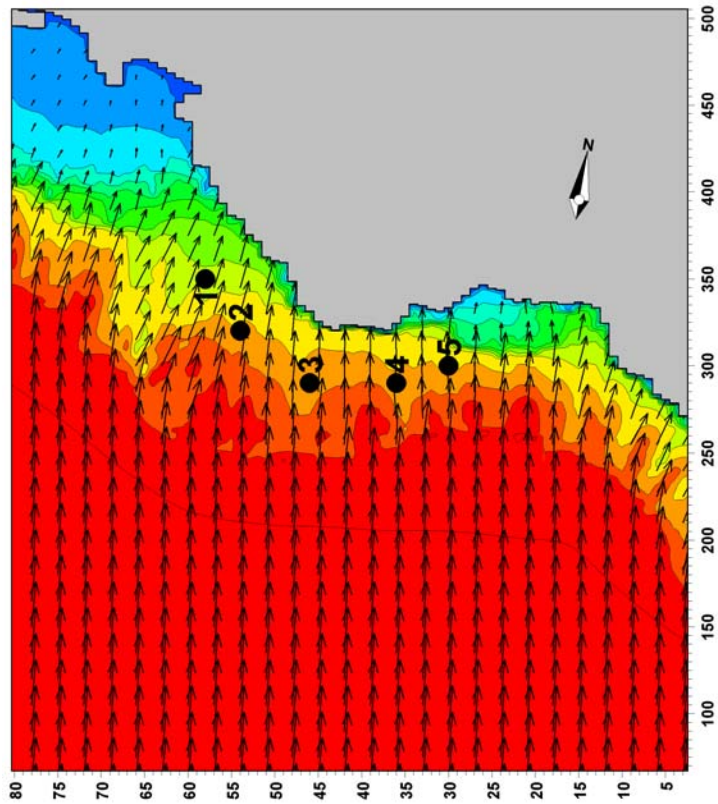


Figure 5.5 Output Extraction Locations

Table 5.3 Wave Conditions at Selected Locations from the NSW Simulations

Case	**Location 1**		**Location 2**		**Location 3**		**Location 4**		**Location 5**	
	Hm0 (ft)	**Dir (deg)**	**Hm0 (ft)**	**Dir (deg)**	**Hm0 (ft)**	**Dir (deg)**	**Hm0 (ft)**	**Dir (deg)**	**Hm0 (ft)**	**Dir (deg)**
Ivan 2004	26.8	159	26.9	150	30.3	146	26.6	146	23.8	149
Wilma 2005	20.6	192	26.9	192	18.2	181	18.3	174	18.0	171
Category 2	24.8	182	29.4	179	27.4	171	26.2	167	26.1	165
Category 3	25.5	182	30.6	179	29.9	171	28.9	167	28.4	165
Category 5	27.1	187	34.2	184	34.1	174	33.7	169	32.6	167
Category 5 (Eye Over the Island)	26.2	182	31.0	179	29.8	171	28.7	167	28.4	166

5.3 Wave Setup

Wave setup is the mean increase in water level due to the effect of breaking wave conditions. The setup over the coastal shelf to the south of the project site was evaluated using empirical procedures outlined in the Coastal Engineering Manual (USACE, 2002), and found to be of fairly small magnitude due to the relatively deep water that is present on the shelf.

6.0 WAVE OVERTOPPING ESTIMATES

6.1 Methodology

When waves run up a shoreline to a height that is potentially higher than the shoreline crest, wave overtopping occurs. *Green water overtopping* occurs when waves break on or over the shoreline such that the overtopping rate is fairly continuous. *Splash overtopping* occurs when the shoreline is high relative to the wave height, but droplets of water are carried over the crest of the shoreline due to their own momentum. *Spray overtopping* is due to the action of wind driving droplets of water over the top of the shoreline crest. Spray overtopping does not generally contribute significantly to overall overtopping volumes and is not considered in the analyses presented in this document.

Overtopping analyses were carried out for four different shoreline profiles that represent the range of conditions at the project site, as shown in Figures 6.1 and 6.2.

Average overtopping rates were calculated for each of the hurricane storms of interest based primarily on the methodology presented in TAW (2002), assuming rough impermeable slopes, with estimates for Profiles 2 and 3 (which have near vertical slopes at the water line) also developed using the methodology of Besley (1999). Inputs to the overtopping calculations included:

- The local shoreline slope.
- The crest elevation for the bluff. Three of the profiles (1 to 3) have a definite crest elevation. For the fourth profile, the crest was assumed to be the elevation at the toe of the wall.
- The water depth at the toe of the shoreline slope (between –50 to –60 feet).
- The design still water level (surge + tide).
- The wave height and period at the toe of the shoreline slope.

6.2 Results

Table 6.1 summarizes the results of the overtopping rate estimates for the four profiles given existing conditions. The largest overtopping is estimated to occur for the central portion of the project site where the bluff has a near-vertical face. A Category 5 hurricane event will result in considerable overtopping, that may be an order of magnitude larger than was observed during Hurricane Wilma and potentially 2 to 5 times larger (depending on location) than that during Hurricane Ivan.

An estimate of overtopping for more typical sea states and water levels was also carried out. Little to no overtopping would occur at the edge of the bluff under such day-to-day conditions.

Overtopping rate estimates are given in Table 6.2 for future conditions with the wall in place. Note that these estimates could only be derived for those profiles (1 and 4) that did not have a near-vertical slope. A comparison of the two tables indicates an almost order of magnitude reduction in overtopping.

The presence of the wall will not affect overtopping volumes at the middle portion of the project site characterized by near-vertical slopes but will serve to direct water that has overtopped the bluff back towards the sea, preventing inland flow.

It is important to recognize that the overtopping estimates are based on empirical equations assuming more simplified conditions (planar slopes, etc.) and are subject to uncertainty. In particular, such equations do not take into account horizontal planform variations that might induce funneling of wave energy.

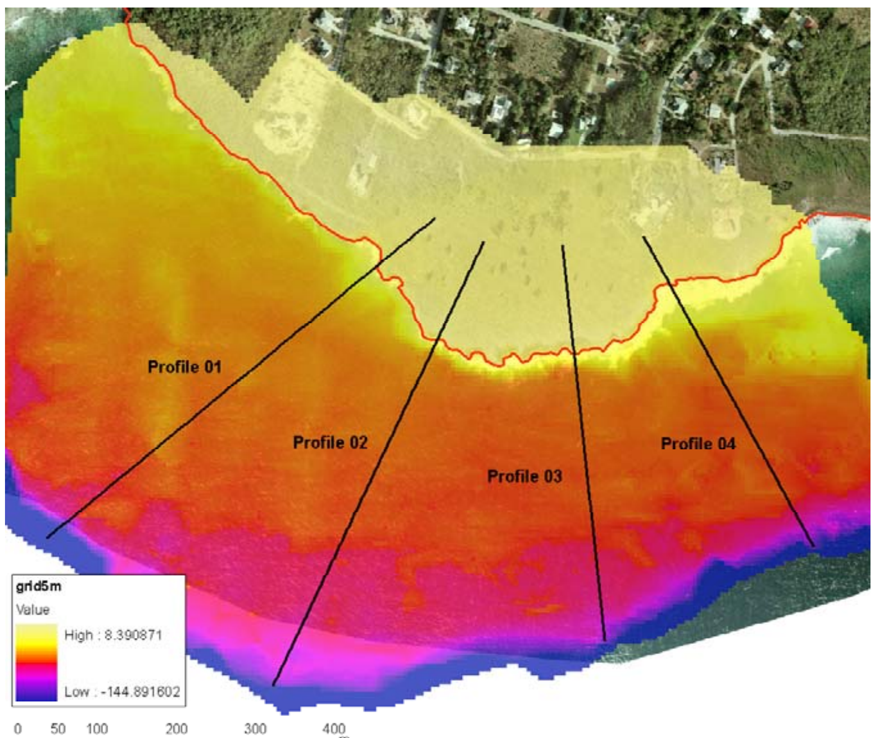


Figure 6.1 Location of Profiles Selected for Overtopping Analysis

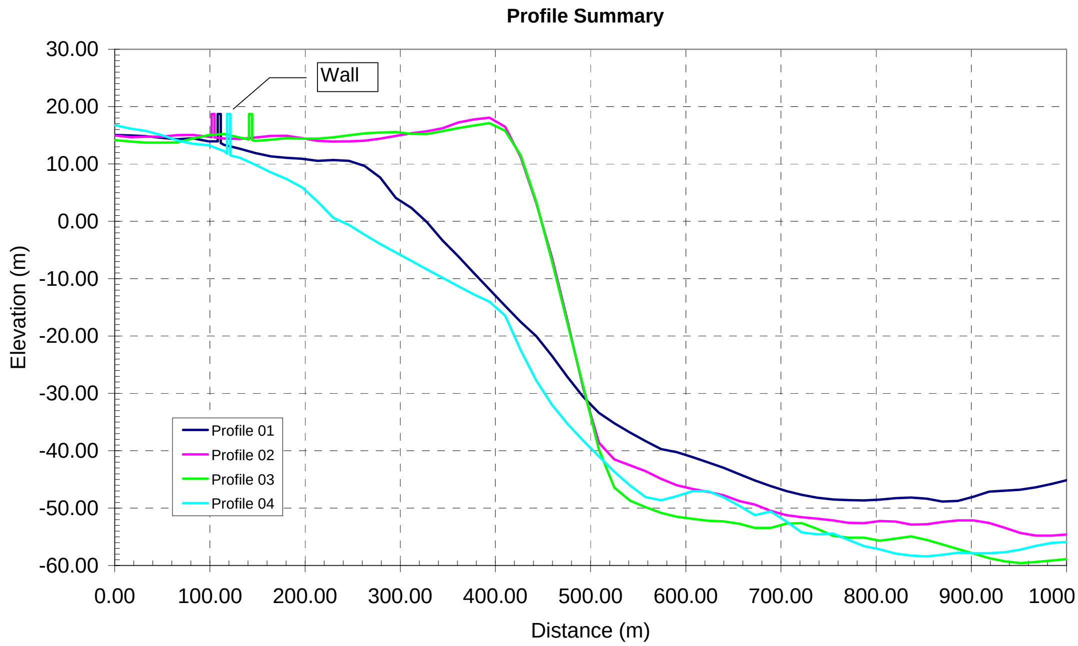


Figure 6.2 Cross-sectional Profiles Selected for Overtopping Analysis

Table 6.1 Estimated Bluff Overtopping Rate ($ft^3/s/ft$) for Existing Conditions

Hurricane Event	Profile			
	1	2	3	4
Category 5	8.5	57.2	55.6	5.4
Category 5 (eye over site)	10.0	50.3	45.0	4.8
Category 2	3.7	33.5	23.0	1.5
Wilma 2005	5.6	23.6	5.5	1.5
Ivan 2004	5.4	25.2	23.9	1.4
Typical Conditions (1.5 m/12s)	0.0	0.0	0.0	0.0

Table 6.2 Estimated Bluff Overtopping Rate ($ft^3/s/ft$) with Wall

Hurricane Event	Profile			
	1	2	3	4
Category 5	0.4	n/a	n/a	0.4
Category 5 (eye over site)	0.3	n/a	n/a	0.3
Category 2	0.1	n/a	n/a	0.1
Wilma 2005	0.3	n/a	n/a	0.1
Ivan 2004	0.2	n/a	n/a	0.1

7.0 WAVE FORCES ON THE WALL

The proposed wall is to be designed to resist the hydrodynamic loading associated a Category 5 hurricane. A key aspect with respect to estimating the wall loading is the fact that the structure is located well above the surge level associated with such a hurricane event. It is not directly exposed to wave impact, but would experience the indirect effects of wave overtopping and wave re-formation.

As noted previously, there will be considerable wave overtopping at this site during a Category 5 hurricane. The site grades are such that waves overtopping the central portion of the project area will result in water flowing towards the wall and towards the eastern and western extremities of the project site. Due to these flow patterns and the impermeability of the soils, it may be expected that some degree of water ponding on top of the bluff will occur.

In general, the site bathymetry and topography will create highly complex and spatially variable loading conditions that cannot be readily estimated by means of desktop studies and/or numerical model investigations. In particular, there is little guidance in the technical literature for the evaluation of loading conditions on walls set back from the waterline.

For this study, various approaches to estimating the wall loads were carried out:

- Initially, the methodology of USACE (1990) was applied, which considers the interaction between a vertical wall and a surge of water created by a wave running up a planar slope. This methodology could be applied at those locations where the wall is situated within the wave runup zone (generally locations with a more gradual slope), but does not include the possible effects of water ponding or flowing through the area of interest. The calculations provided estimated wall loadings of 83 lb/ft and 4080 lb/ft for Profiles 1 and 4, respectively. The loads were considerably lower for Profile 1 due to the steeper slope at this location, limiting the estimated height of the surge impacting the wall.

- An approach outlined FEMA (2005) was applied to the profiles (2 and 3) that have near-vertical slope. This approach, derived from work by Cox and Machemahl (1986), considers the propagation of a bore of water created by a wave overtopping the crest of a coastal structure. These calculations indicated that such a bore would dissipate prior to reaching the wall. We note, however, that the calculation procedure does not consider the possibility that significant quantities of water may pond on top of the bluff area.

- Assuming that significant ponding of water might occur on top of the bluff, the load due to re-formed waves was calculated as a function of wall height. It was assumed that the still water depth was equivalent to the wall height, and that overtopping wave energy would induce a wave to be created that was of sufficient height to break directly on the wall. The wave period was assumed to be equivalent to that of the incoming wave (note: this is conservative – generally re-formed waves will have shorter period). The wave loads were calculated as per Goda (2000), as summarized in Table 7.1 as a function of local wall height.

Table 7.1 Estimated Wave Loading on the Proposed Wall as a Function of Wall Height
[Re-formed Waves]

Wall Height[1] (ft)	Total Load (lb/ft)	Total Moment (lb-ft/ft)	Resultant Pt. Of Load Application[4] (ft)
4	1600	2800	1.8
5	2400	5300	2.2
6	3400	8900	2.7
7	4500	13900	3.1
8	5800	20400	3.5
9	7200	28700	4.0

Notes:

1. Wall height is from top of wall to ground level in front of wall.
2. Estimates based on Goda (2000), assuming re-formed waves on top of bluff.
3. All loads per running foot of wall.
4. Resultant point of load application is relative to ground level in front of structure.
5. **No** factors of safety have been applied to the loads.

Given the simplifications and uncertainties associated with the load estimation, it is our recommendation that the loads provided in Table 7.1 be utilized in the wall design process. It is strongly recommended that appropriate factors of safety be applied to the loads given in Table 7.1.

8.0 CONCLUSIONS AND RECOMMENDATIONS

An analysis of storm surge, wave conditions and wave overtopping has been carried out for a vertical wall proposed as a surge barrier for a location on the south shore of Grand Cayman Island. This analysis included numerical modeling of storm surge, wave generation and wave transformation for specific hurricane events. The following conclusions and recommendations were derived on the basis of this study.

- Hurricanes pass in the vicinity of the project site on a relatively frequent basis. For example, a hurricane of Category 1 intensity or greater passes within 55 nautical miles of the site approximately once every 4.9 years on average. Two recent hurricanes that resulted in flooding at the project site were Hurricane Ivan in 2004 and Hurricane Wilma 2005.

- Numerical modeling of storm surge was conducted using the MIKE21 hydrodynamic model for Hurricanes Ivan and Wilma, as well as various synthetic "design" events that had Category 2, 3 and 5 intensities. The design events were developed such that the hurricanes had a south to north track resulting in a direct hit on the project site. The surge modeling showed that, due to the relatively deep water depths in front of the project site, the magnitude of the storm surge is limited and the project site cannot be directly inundated by such surge. Flooding is likely the result of wave overtopping of the bluff. Maximum storm surge estimates of 1.3 feet and 0.8 feet were developed for Hurricanes Ivan and Wilma, respectively. The largest estimated surge, 4.4 feet, was for a synthesized Category 5 hurricane in which the hurricane eye passed directly over the project site.

- Numerical modeling of hurricane wave generation indicated that significant wave heights of up to 43 feet (for a synthetic Category 5 event) can occur offshore of the project site. Wave heights of 20 feet were estimated for Hurricane Wilma; this height appeared consistent with site observations.

- Desktop estimates of overtopping indicated very high rates of overtopping at the project site due to hurricane-generated waves. The presence of a wall with a top elevation of +19.0 feet will reduce overtopping volumes by an order of magnitude for the two areas of lower ground elevations on the east and west sides of the project site.

- The site bathymetry and topography will create highly complex and spatially variable loading conditions on the storm surge barrier. These loads cannot be readily estimated by means of desktop studies and/or numerical model investigations, as there is little guidance in the technical literature for such wall configurations. Estimates of wall loading were developed assuming ponding of water on top of the site bluff and the re-formation of waves on the bluff due to overtopping wave energy. Given the uncertainty associated with these calculations, it is recommended that a significant factor of safety be applied to the estimated loads.

9.0 REFERENCES

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