

APPENDIX G-4
DRAFT BOUSS-2D MODELING REPORT

This page intentionally left blank.

**SOUTHERN PALM BEACH ISLAND COMPREHENSIVE
SHORELINE STABILIZATION PROJECT
BOUSS2D MODELING REPORT**

TABLE OF CONTENTS

1.0	INTRODUCTION.....	1
2.0	BACKGROUND	2
3.0	SURFING IMPACT ANALYSIS	7
3.1.	BOUSS-2D Model Description.....	7
3.2.	Model setup and simulated scenarios	9
3.2.1.	Model Grid.....	9
3.2.2.	Bathymetry.....	10
3.2.3.	Boundary Conditions	13
3.2.4.	Waves	14
3.2.5.	Model Parameters.....	16
4.0	RESULTS.....	17
4.1.	Lake Worth Pier.....	17
4.1.1.	Southeast Waves (Hs 6 feet, Tp 6.1 s from 105°).....	17
4.1.2.	Cold Front (Hs 7.4 feet, Tp 11 s from 65°).....	22
4.1.3.	Hurricane Pre-Landfall (Hs 8.1 feet, Tp 13.5 s from 103°)	27
4.2.	Lantana Park.....	31
4.2.1.	Southeast Waves (Hs 6 feet, Tp 6.1 s from 105°).....	31
4.2.2.	Cold Front (Hs 7.4 feet, Tp 11 s from 65°).....	36
4.2.3.	Hurricane Pre-Landfall (Hs 8.1 feet, Tp 13.5 s from 103°)	40
5.0	SUMMARY AND CONCLUSIONS.....	45
6.0	LITERATURE CITED.....	47

LIST OF FIGURES

Figure No.

2-1	Wave breaking type.	4
2-2	Peel angle terminology.	5
2-3	Classification of surfing skill rated against peel angle and wave height.	7
3-1	Bouss2D grid (red box – left) and zoom at areas of interest – Pier (right top) and Lantana (right bottom).	11
3-2	Existing bathymetry (left) and differences between alternatives and existing condition.	12
3-3	BOUSS-2D boundaries - wavemaker (green), sea sponge layer (blue) land sponge layer (orange)	14
4-1	Significant wave height for existing condition and differences between each alternative and the existing condition for southeast waves at Lake Worth Pier. .	18
4-2	Water surface elevation at Lake Worth Pier for southeast waves.....	20
4-3	Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for southeast waves at the Pier.	21
4-4	Significant wave height for existing condition and differences between each alternative and the existing condition for cold front scenario at Pier.....	24
4-5	Water surface elevation at Pier for cold front.....	25
4-6	Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for cold front at Pier.	26
4-7	Significant wave height for existing condition and differences between each alternative and the existing condition for pre-hurricane at Pier.....	28
4-8	Water surface elevation at Pier for hurricane pre-landfall.....	29
4-9	Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for hurricane pre-landfall at the Pier.....	30
4-10	Significant wave height for existing condition and differences between each alternative and the existing condition for southeast waves at Lantana Park.....	33
4-11	Water surface elevation at Lantana Park for southeast waves.....	34
4-12	Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for southeast waves at Lantana.....	35

4-13	Significant wave height for existing condition and differences between each alternative and the existing condition for cold front scenario at Lantana.	37
4-14	Water surface elevation at Lantana for cold front.	38
4-15	Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for cold front at Lantana.	39
4-16	Significant wave height for existing condition and differences between each alternative and the existing condition for pre-hurricane at Lantana Park.	42
4-17	Water surface elevation at Lantana for Hurricane Pre-Landfall.	43
4-18	Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for hurricane pre-landfall at Lantana.	44

LIST OF TABLES

Table No.

2-1	Rating of the skill of surfers. Ratings are independent of surf break quality or the degree of difficulty of waves.	6
3-1	Bouss2D simulated scenarios.	16
4-1	Comparison of existing conditions and alternatives for southeast waves at the Pier.	22
4-2	Comparison of existing and alternatives conditions for cold front at Pier.	23
4-3	Comparison of existing and alternatives conditions for hurricane pre-landfall at Pier.	31
4-4	Comparison of existing conditions and alternatives for southeast waves at Lantana.	32
4-5	Comparison of existing and alternatives conditions for cold front at Lantana.	40
4-6	Comparison of existing and alternatives conditions for hurricane pre-landfall at Lantana.	41

1.0 INTRODUCTION

Under direction of the U.S. Army Corps of Engineers (USACE), CB&I Coastal Planning & Engineering, Inc. (CB&I) assisted in the development of the Southern Palm Beach Island Comprehensive Shoreline Stabilization Project Environmental Impact Statement (EIS). The initial tasks associated with the effort included public scoping and agency coordination to determine what data was necessary to develop the EIS. After review of the data and previous work, the USACE has determined that numerical modeling of breaking waves is required to obtain necessary data that is not currently available.

Concern regarding potential impacts to surfing has previously been expressed in public scoping for projects within the Project Area. In order to evaluate project-related effects on surfing, the BOUSS-2D model was used in this study to simulate waves within the Project Area. BOUSS-2D model was developed by the U.S. Army Corps of Engineers (Nwogu and Demirbilek, 2001) and utilized through the Surface Water Modeling System (SMS) interface (Aquaveo, 2008).

To assess the potential impacts on surfability within the Study Area, a modeling approach was adopted. First, a morphological model (Delft3D) was run to develop the anticipated bathymetry from the coastline response to the alternatives. The bathymetry resulting from the alternatives along with the existing bathymetry were incorporated into the BOUSS-2D model to evaluate the impacts to surfability within the Project Area. In particular, the surfability was evaluated at two popular southern Palm Beach surf spots, Lantana Park and the Lake Worth Pier.

The alternatives that were considered in the analysis included:

- Alternative 1 – No Action Alternative (Status Quo) and referenced herein as the existing conditions.
- Alternative 2 – Applicants' Preferred Project (Proposed Action): Beach and Dune Fill with Shoreline Protection Structures Project

- Alternative 6 – The Town of Palm Beach Increased Sand Volume Project and County Increased Sand Volume without Shoreline Protection Structures Project
- Alternative 7a – Plan was presented by The Coalition to Save Our Shoreline, Inc. (SOS) consisting of beach fill and dune restoration between R-129-210 and R-134+135 with shoreline protection structures. The sand fill volumes required for the SOS plan are greater than the volumes for Alternative 6 over the same shoreline extents. For the purpose of modeling, Alternative 7a was defined as the SOS plan north of R-134+135 and Alternative 2 to the south.

The remainder of the alternatives (Alternatives 3, 4, and 5) did not need to be included in the analysis. They consisted of various combinations of the sand fill volumes and shoreline protection structures comprising Alternatives 2 and 6. Of Alternatives 2 through 6, Alternative 2 required the smallest fill volumes and Alternative 6 required the greatest.

2.0 BACKGROUND

According to Benedet *et al.* (2007), you can find surfers just about anywhere there is a large body of water with sufficient fetch to allow the generation of surfable waves. Surfing is practiced in the Pacific Nations, North America, South America, Central America, Europe and Asia. Surfing destinations range from Hawaii, Australia and Costa Rica to Ireland, Alaska, Dubai, and even at the North American Great Lakes and the Amazon River tidal bore. Surfing is currently the most popular sport in Australia, the second most popular sport in Brazil, and one of the most popular extreme sports in North America.

The population of surfers around the world has social and economic benefits. Recently, a number of studies are been conducted in terms of impacts of engineering works, creation of surf spots and relation between wave conditions and surfability (e.g. Black, 2001; Black and Mead, 2001; Hutt *et al.* 2001; Scarfe *et al.*, 2003 Benedet *et al.*, 2007).

Surfers are traditionally defensive about any activity in the vicinity of their favorite surfing breaks. This behavior may be justified because history shows that their rights have at times been ignored and many surfing breaks have been impacted by coastal modification (Scarfe *et al.*, 2003). Interestingly, some of the most popular surf spots on the east coast of Florida occur near these coastal modifications. For example, the New Smyrna Beach on the south side of Ponce Inlet, the north side of Sebastian Inlet, the north side of Ft. Pierce Inlet, Reef Road south of Palm Beach Inlet, and the south side of the Lake Worth Pier. In this way, the analysis of surfability has become an important issue where an engineering intervention is need.

The most important parameters to analyze surfability are the breaker type, peel angle, peel rate, wave velocity and surfer velocity. Battjes (1974) describes the breaker type as function of Iribarren number:

$$\xi_b = \frac{\tan \alpha}{\sqrt{H_b/L_0}}$$

where: $\tan \alpha$ is the beach slope, H_b is the significant wave height at break, L_0 is the deep water wavelength ($\sim 1.56 \cdot T^2$). According to the author:

Collapsing if $\xi_b > 2.0$

Plunging if $0.4 < \xi_b < 2.0$

Spilling if $\xi_b < 0.4$

Figure 2-1 presents examples of the wave breaker type.



Figure 2-1. Wave breaking type (Benedet, 2007).

In addition to the way wave breaks, it is important to understand the angle the wave breaks related to its crest. If this angle is too sharp, the wave will “close-out”. For optimal surfing conditions the wave has to break gradually along the wave crest. Figure 2-2 presents the peel angle, which is defined as the angle enclosed by the wave crest and the breaker lines (Dafferner and Klein, 2009; Walker, 1974). Knowing the peel angle and the wave velocity (in shallow water = \sqrt{gh}) it is possible to calculate the peel rate and surfer velocity.

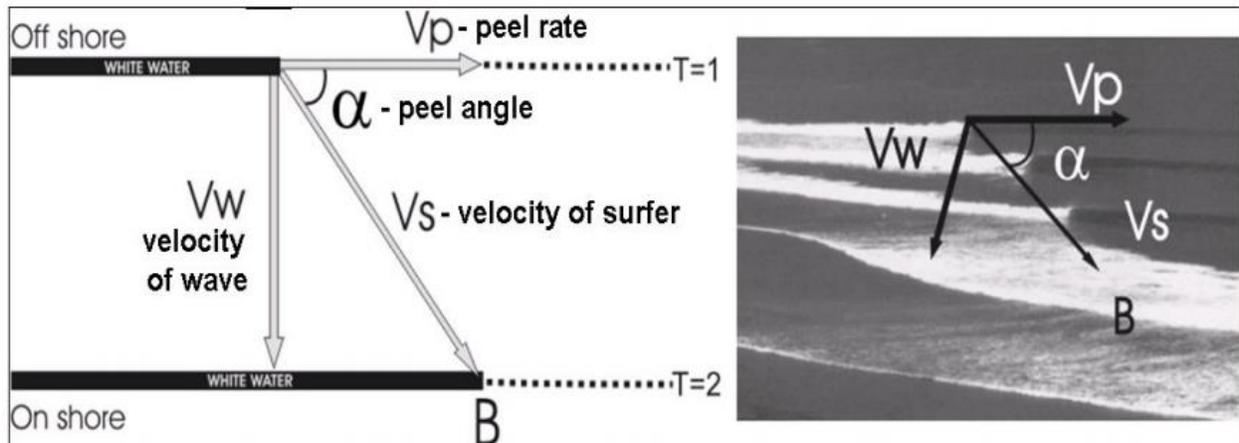


Figure 2-2. Peel angle terminology (Dafferner and Klein, 2009).

Hunt et al. 2001 rated the skill of surfers with respect to peel angle and wave height. Table 2-1 presents the rating matrix, while Figure 2-3 presents Hunt’s classification in graphical form. The larger peel angle and smaller the wave height, the easier the wave is to be ridden. Conversely, the smaller the peel angle and larger the wave height, the more difficult the wave becomes to ride.

Table 2-1. Rating of the skill of surfers. Ratings are independent of surf break quality or the degree of difficulty of waves (Hunt et al., 2001).

Rating	Description of Rating	Peel Angle Limit (°)	Min/Max Wave Height (m)	Min/Max Wave Height (ft)
1	Beginner surfers not yet able to ride the face of wave and simply moves forward as wave advances	90	0.70/1.00	2.3/3.3
2	Learner surfers able to successfully ride laterally along the crest of a wave	70	0.65/1.50	2.1/4.9
3	Surfers that have developed the skill to generate speed by “pumping” on the face of the wave	60	0.60/2.5	2/8.2
4	Surfers beginning to initiate and execute standard surfing maneuvers on occasion	55	0.55/4.0	1.8/13.1
5	Surfers able to execute standard surfing manoeuvres consecutively on a single wave	50	0.50/>4.0	1.6/>13.1
6	Surfers able to execute standard surfing manoeuvres consecutively. Executes advanced maneuvers on occasion	40	0.45/>4.0	1.5/>13.1
7	Top amateur surfers able to consecutively execute advanced maneuvers	29	0.40/>4.0	1.3/>13.1
8	Professional surfers able to consecutively execute advanced maneuvers	27	0.35/>4.0	1.1/>13.1
9	Top 44 professional surfers able to consecutively execute advanced maneuvers	Not reach	0.30/>4.0	1/>13.1
10	Surfers in the future	Not reach	0.30/>4.0	1/>13.1

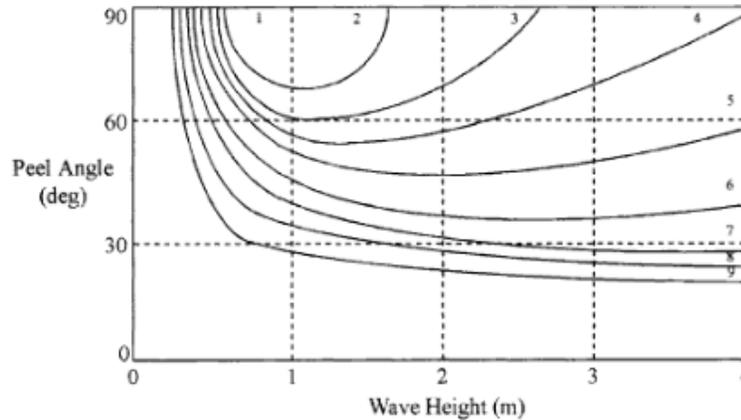


Figure 2-3. Classification of surfing skill rated against peel angle and wave height. (Hunt et al., 2001).

3.0 SURFING IMPACT ANALYSIS

3.1. BOUSS-2D Model Description

BOUSS-2D is a numerical model for simulating the propagation and transformation of waves in coastal regions and harbors based on a time-domain solution of Boussinesq-type equations (Nwogu and Demirbilek, 2001). The governing equations are uniformly valid from deep to shallow water and can simulate most of the phenomena of interest in the nearshore zone and harbor basins including shoaling/refraction over variable topography, reflection/diffraction near structures, energy dissipation due to wave breaking and bottom friction, cross-spectral energy transfer due to nonlinear wave-wave interactions, breaking-induced longshore and rip currents, wave-current interaction and wave interaction with porous structures.

The governing equations in BOUSS-2D are solved in a time domain with a finite-difference method where the water-surface elevation and horizontal velocities are calculated at the grid nodes in a staggered manner. The area of interest is discretized as a rectangular grid. Time-histories of the velocities and fluxes corresponding to incident storm conditions are specified along wave generation boundaries of the grid. The input wave conditions may be periodic (regular) or non-periodic (irregular). Unidirectional or multidirectional sea states can be simulated. Waves propagating out of the computational domain are either absorbed in damping layers placed around the perimeter of the domain or allowed to leave the domain freely. Damping and porosity

layers are used to simulate the reflection and transmission characteristics of jetties, breakwaters, and other structures existing in the modeling domain (Demirbilek *et al.*, 2005). Details about BOUSS-2D model are provided in the model theory and examples report (Nwogu and Demirbilek, 2001).

The classical form of the Boussinesq equations for wave propagation over water of variable depth was derived by Peregrine (1967). The equations were restricted to relatively shallow water depths, i.e., the water depth, h , had to be less than one-fifth of the wavelength, L , in order to keep errors in the phase velocity to less than 5%. Nwogu (1993) extended the range of applicability of Boussinesq-type equations to deeper water by recasting the equations in terms of the velocity at an arbitrary distance, z , from the still-water elevation, instead of the depth-averaged velocity. The distance from the still-water elevation of the velocity variable becomes a free parameter, which is chosen to optimize the linear dispersion characteristics of the equations.

The optimized form of the equations results in an error of less than 2% for the phase velocity from shallow-water depths up to the deepwater limit ($h/L= 0.5$). Despite the improvement in the frequency dispersion characteristics, Nwogu's (1993) equations are based on the assumption that the wave heights were much smaller than the water depth. This limits the ability of the equations to describe highly nonlinear waves in shallow water, which led Wei *et al.* (1995) to derive a fully nonlinear form of the equations. The fully nonlinear equations are particularly useful for simulating highly asymmetric waves in shallow water, wave-induced currents, wave setup close to the shoreline, and wave-current interaction. As ocean waves approach the shoreline, they steepen and ultimately break.

The turbulence and currents generated by breaking waves are important driving mechanisms for the transport of sediments and pollutants. Nwogu (1996) extended the fully nonlinear form of the Boussinesq equations to the surf zone, by coupling the mass and momentum equations with a one-equation model for the temporal and spatial evolution of the turbulent kinetic energy produced by wave breaking. The equations

have since been modified to include the effects of bottom friction and flow through porous structures (Nwogu and Demirbilek, 2001).

The modified equations can simulate most of the hydrodynamic phenomena of interest in coastal regions and harbor basins including:

- Shoaling
- Refraction
- Diffraction
- Full/partial reflection and transmission
- Bottom friction
- Nonlinear wave-wave interactions
- Wave breaking and runup
- Wave-induced currents
- Wave-current interaction

The BOUSS-2D was used to analyze the potential impacts to surfability due to the alternatives as compared to the existing conditions. Surfability was assessed in terms of peel angle, peel rate, wave velocity, and the velocity of the surfer.

3.2. Model setup and simulated scenarios

3.2.1. Model Grid

The potential impacts of the alternatives were analyzed at two important southern Palm Beach surf spots, Lantana Park (hereafter called “Lantana”) and Lake Worth Pier (hereafter called “Pier”). A grid with 4 meter resolution was developed as shown by the red box in Figure 3-1. The grid is 1732 meter (X direction) x 5720 meter (Y direction) with a total of 433 x 1730 grid cells.

3.2.2. Bathymetry

Bathymetries for the BOUSS-2D model were developed to represent the beach conditions after the coastal system's natural processes had responded to construction of the alternatives to achieve equilibrium. The temporal evolution of the bathymetries after equilibration was simulated by running the Delft3D morphological model for 3 years after construction for each alternative. The relative changes (greater than 0.2 feet) are shown by the three graphics on the right in Figure 3-2. The relative changes represent the differences between each bathymetry alternative and the existing condition bathymetry (left graphic in Figure 3-2). Within the area of interest at the Pier, Alternatives 2 and 6 did not show differences greater than 0.2 feet, while Alternative 7a showed sedimentation between 2 and 4 feet extending offshore from the shoreline approximately half the length of the Pier. Within the area of interest at Lantana, the differences were more evident for all of the alternatives considered with sedimentation up to 1 foot within the surf zone.

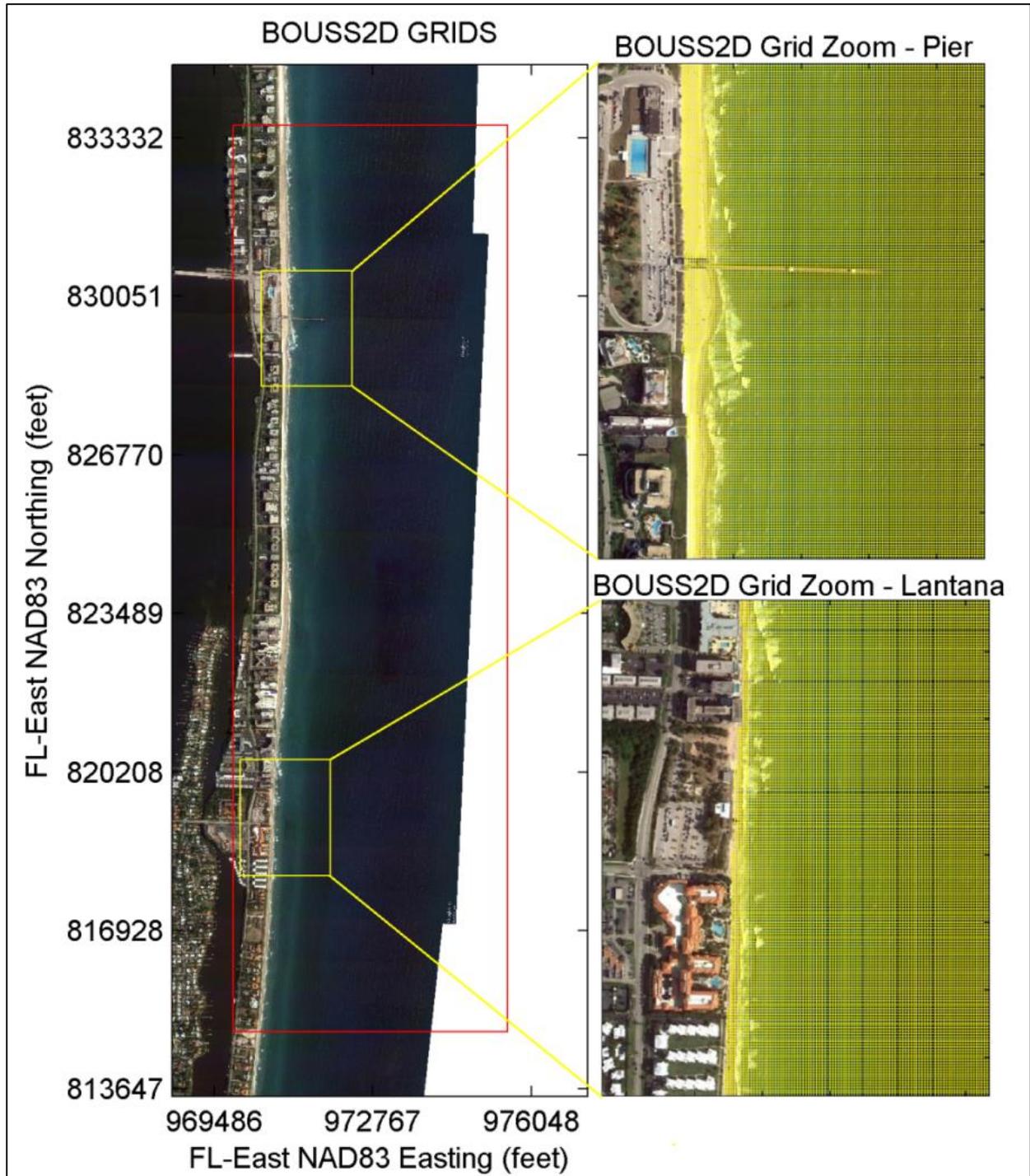


Figure 3-1. Bouss2D grid (red box – left) and zoom at areas of interest – Pier (right top) and Lantana (right bottom).

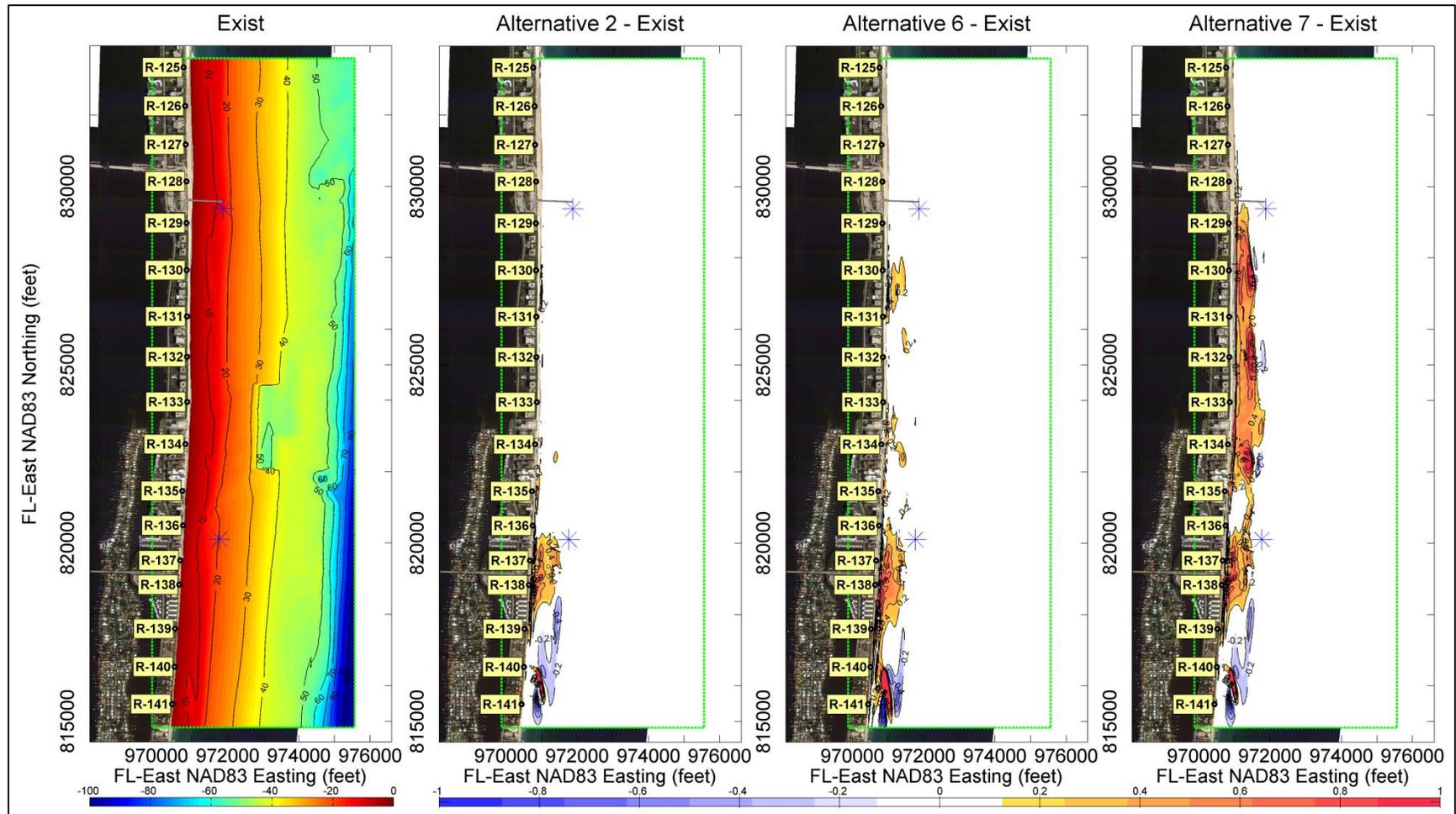


Figure 3-2. Existing bathymetry (left) and differences between alternatives and existing condition. The * represent the points where probes were placed to analyse wave timeseries of Lantana and the Pier. The green line represents the BOUSS2D grid limits.

3.2.3. Boundary Conditions

According to Nwogu and Demirbilek (2001), to solve the governing equations, appropriate boundary conditions have to be imposed at the boundaries of the computational domain. This requires specification of waves propagating into the domain and the absorption of waves propagating out of the domain. The equations have also been modified to simulate wave interaction with fully/partially reflecting structures within the computational domain. The types of boundaries considered in BOUSS-2D include:

- Fully reflecting or solid wall boundaries
- External wave generation boundaries
- Internal wave generation boundaries
- Wave absorption or damping regions
- Porous structures

For the present study, two types of boundary conditions were defined: wave makers and sponge/damp layers (Figure 3-3). According to Nwogu and Demirbilek (2001), waves propagating out of the computational domain should be absorbed in damping regions placed around the perimeter of the computational domain.

The “sponge layers” were set by adjusting the width and reflection coefficient values (Table 3-1). At the north and south boundaries, the layers were defined to minimize reflection (approximately 2.5%) in order to absorb wave energy exiting the grid (Goda, 1985). At the landward boundary, the layer was set to simulate the reflection of the incident wave energy (approximately 20%) as waves interact within the coastline (Goda, 1985).



Figure 3-3. BOUSS-2D boundaries - wavemaker (green), sea sponge layer (blue) land sponge layer (orange).

3.2.4. Waves

The wave scenarios modeled were selected to be representative of conditions conducive for surfing for which the surfing community might expect to experience during a given year. Three wave events were considered to capture the various points of origination.

- Southeast Waves
- Cold Fronts
- Hurricanes

Southeast waves were assumed to represent the typical surfing conditions experienced within the modeling domain. These conditions are characterized as closely spaced, short period waves that provide a minimal ride for surfing. Wave data used in the model to represent the southeast wave event was obtained from CPE-ADCP measurements collected at the Pier between 02/10/2008 to 04/21/2008 (CPE, 2009). The event had a significant wave height (H_s) of 6 feet, period (T_p) of 6.1 seconds, and direction (D_p) of 105° .

Cold fronts, commonly as known as Nor'easters, frequently occur during winter months (October to April) as low pressure systems move offshore of North Carolina and New England. These systems can produce large waves originating from the northeast that propagate south impacting the Study Area. The wave events experienced at the Study Area typically results in longer period swells accompanied by short period wind waves. Depending upon the wind direction and severity of the wind waves, the wave event can provide a relatively long ride as compared to southeast wave events. Wave data used in the model to represent the cold front wave event was obtained from CPE-ADCP measurements collected at the Pier between 02/10/2008 to 04/21/2008 (CPE, 2009). The event had a significant wave height (H_s) of 7.4 feet, period (T_p) of 11 seconds, and direction (D_p) of 64.5° .

Hurricanes generally occur during the summer months (June to November). Depending on the storm track in relation to the Study Area, the systems can produce swells from any direction radiating outward from its center. The wave events experienced can result in long period, high energy swells immediately preceding and/or following the passage of the storm. These ground swells can produce the longest rides experienced within the Study Area. Wave data obtained approximately 12 miles offshore of the Study Area at USACE WIS station ST 63461 over a 30 year period was reviewed (Hubertz, 1992). The highest significant wave height within the record was associated with Hurricane Frances occurring in September 2004. When considering the wind (direction and speed) and swell (direction, height, and period), the best surf conditions were assumed to occur approximately 12 hours prior to landfall of the storm. The conditions characterizing this event were simulated in Delft3D-WAVES in order to determine the wave parameters at

Bouss2D offshore boundary. A summary of simulated wave scenarios are presented in Table 3-1.

Table 3-1. BOUSS-2D simulated scenarios.

Condition	Wave	Wave Maker				Sponge Beach		Sponge North/South	
		Hs (ft)	Tp (s)	Dir (°)	Spreading (cosine power)	Value	Width (m)	Value	Width (m)
Existing	Southeast	6.0	6.1	105	9	30	0.15	17.0	0.30
	Cold Front	7.4	11.0	65	55	30	0.15	44.1	0.30
	Hurricane Pre Landfall	8.1	13.5	103	14	29	0.15	29.0	0.30
Alt. 2	Southeast	6.0	6.1	105	9	30	0.15	17.0	0.30
	Cold Front	7.4	11.0	65	55	30	0.15	44.1	0.30
	Hurricane Pre Landfall	8.1	13.5	103	14	29	0.15	29.0	0.30
Alt. 6	Southeast	6.0	6.1	105	9	30	0.15	17.0	0.30
	Cold Front	7.4	11.0	65	55	30	0.15	44.1	0.30
	Hurricane Pre Landfall	8.1	13.5	103	14	29	0.15	29.0	0.30
Alt. 7	Southeast	6.0	6.1	105	9	30	0.15	17.0	0.30
	Cold Front	7.4	11.0	65	55	30	0.15	44.1	0.30
	Hurricane Pre Landfall	8.1	13.5	103	14	29	0.15	29.0	0.30

3.2.5. Model Parameters

The model was run for 850 seconds with a timestep of 0.1 s and used the same calibration parameters presented by CPE (2009). The bottom roughness and the Chezy coefficient used in this study are the same as used by the authors at CPE (2009). The Chezy coefficient values used ranged from 30 to 1,000. A Chezy coefficient of 30 is the model default and represents high wave energy dissipation due to bottom friction. A Chezy coefficient of 1,000 is the maximum value allowed by the model, represents small bottom roughness and shows little to no wave energy dissipation. The specific Chezy values utilized during calibration were 30, 350, 650 and 1000. Wave breaking was enabled, and the rest of the parameters were set at the model default values. The

authors found that the best value for Chezy coefficient is 1,000. According to Nwogu and Demirbilek (2001), the Smagorinsky number should be kept between 0 and 0.5, with a default value of 0. CPE (2009) found the best value of 0 and this value was used in this study.

4.0 RESULTS

The results of the potential impacts to surfing are divided in two main sections, one section for each surf spot: Lake Worth Pier and Lantana Park. Within each main section, results for the three wave events (southeast waves, cold front and hurricanes) were included. For each wave event, the significant wave height and wave direction for existing condition were presented followed by the percentage difference of H_s between each alternative and existing condition. Additionally, water surface elevation timeseries were presented followed by the breaker type, water surface elevation and wave breaking for each condition. The peel angle, peel rate, wave velocity and surfer velocity were calculated from BOUSS-2D wave simulations screenshots. The Iribarren number (ξ_b) was calculated from significant wave height at breaking, deep water wave length and beach slope.

4.1. Lake Worth Pier

4.1.1. Southeast Waves (H_s 6 feet, T_p 6.1 s from 105°)

The significant wave height (H_s) for existing conditions and the differences between each alternative and the existing conditions at the Pier are presented in Figure 4-1. Analysis of the wave propagation for existing conditions revealed the reduction of H_s until certain point where the waves start the shoaling process, thereby increasing H_s . The effect of the borrow area on the wave propagation is also observed. For this wave case, two wave energy focalization areas are noticed: one between R134 and R135 and another at R132. Two lobes of wave height reduction at each side of the borrow area are observed as a result of refraction/diffraction.

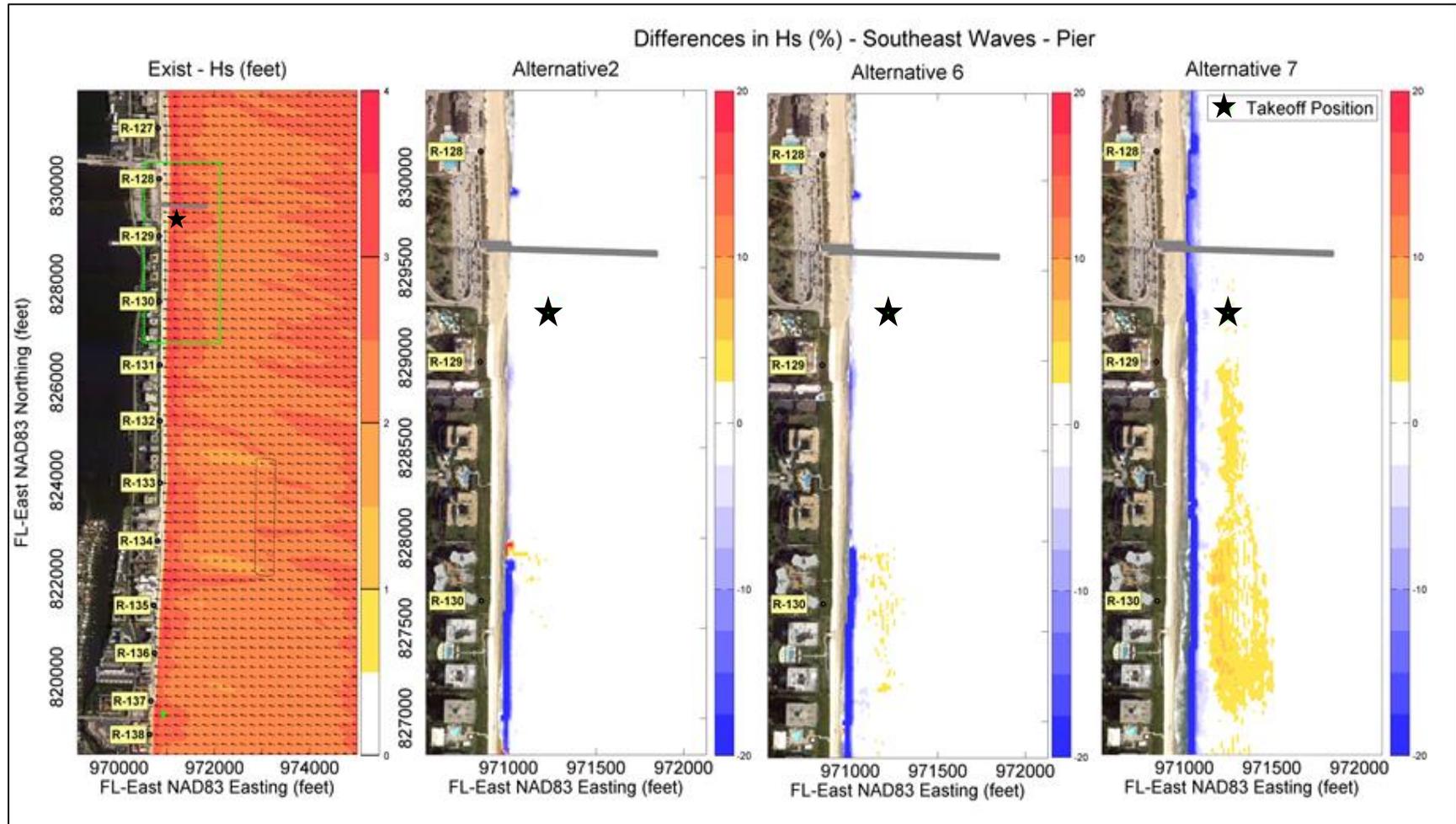


Figure 4-1. Significant wave height for existing condition and differences between each alternative and the existing condition for southeast waves at the Pier.

Analyzing the results at the Pier takeoff position (point where the wave starts to break and the surfer would start to surf), it can be observed that for all alternatives there are virtually no changes in H_s . Alternative 7a shows a little variation (~2.5%) south of the Pier's takeoff position. Alternative 7a presented the higher H_s increase at this Study Area since this alternative has the higher nourishment volume. A reduction in significant wave height is observed in very shallow water, close to the beach. This reduction should not be an issue for surfing since it happens landward of the surfing area.

Figure 4-2 presents the water surface elevation at the Pier for existing and alternatives conditions. The analysis points are presented in Figure 3-2. All alternatives presented very similar timeseries with very small variations, indicating that at the analyzed points, there will not be significant changes in wave propagation.

BOUSS-2D screenshots of wave simulation results are presented for the Pier in Figure 4-3. The parameters calculated from these screenshots are presented in Table 4-1. At the Pier, the breaker type did not change between existing conditions and the alternatives. This breaker was classified as a spilling breaker type. The peel angle was 46° (rating of 6) for existing conditions. A faster wave section was observed for all alternatives, as evident by the increased peel angle. These peel angles were anticipated to result in "close-out" waves. For the same wave velocity, the peel rate increased and consequently, the surfer velocity increased between existing conditions and the alternatives.

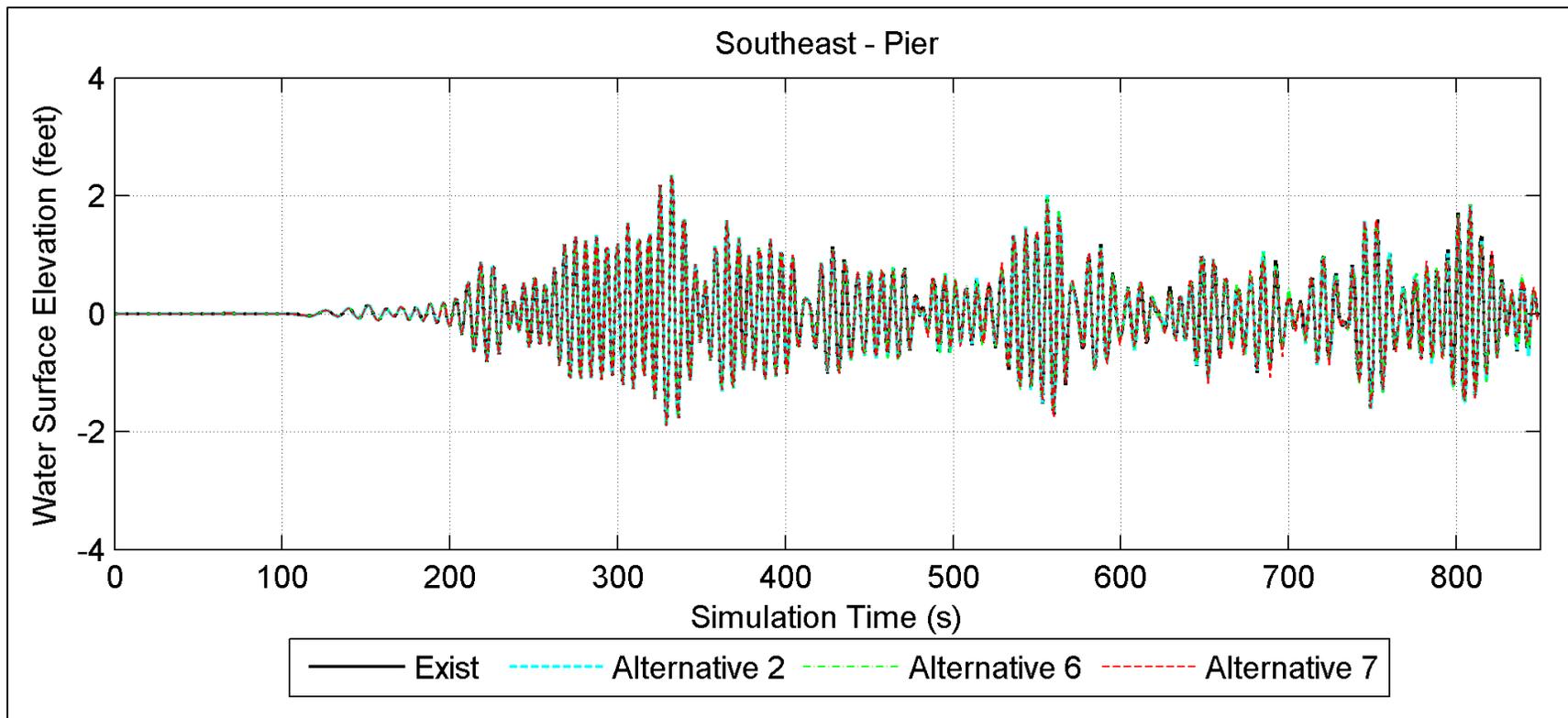


Figure 4-2. Water surface elevation at the Pier for southeast waves.

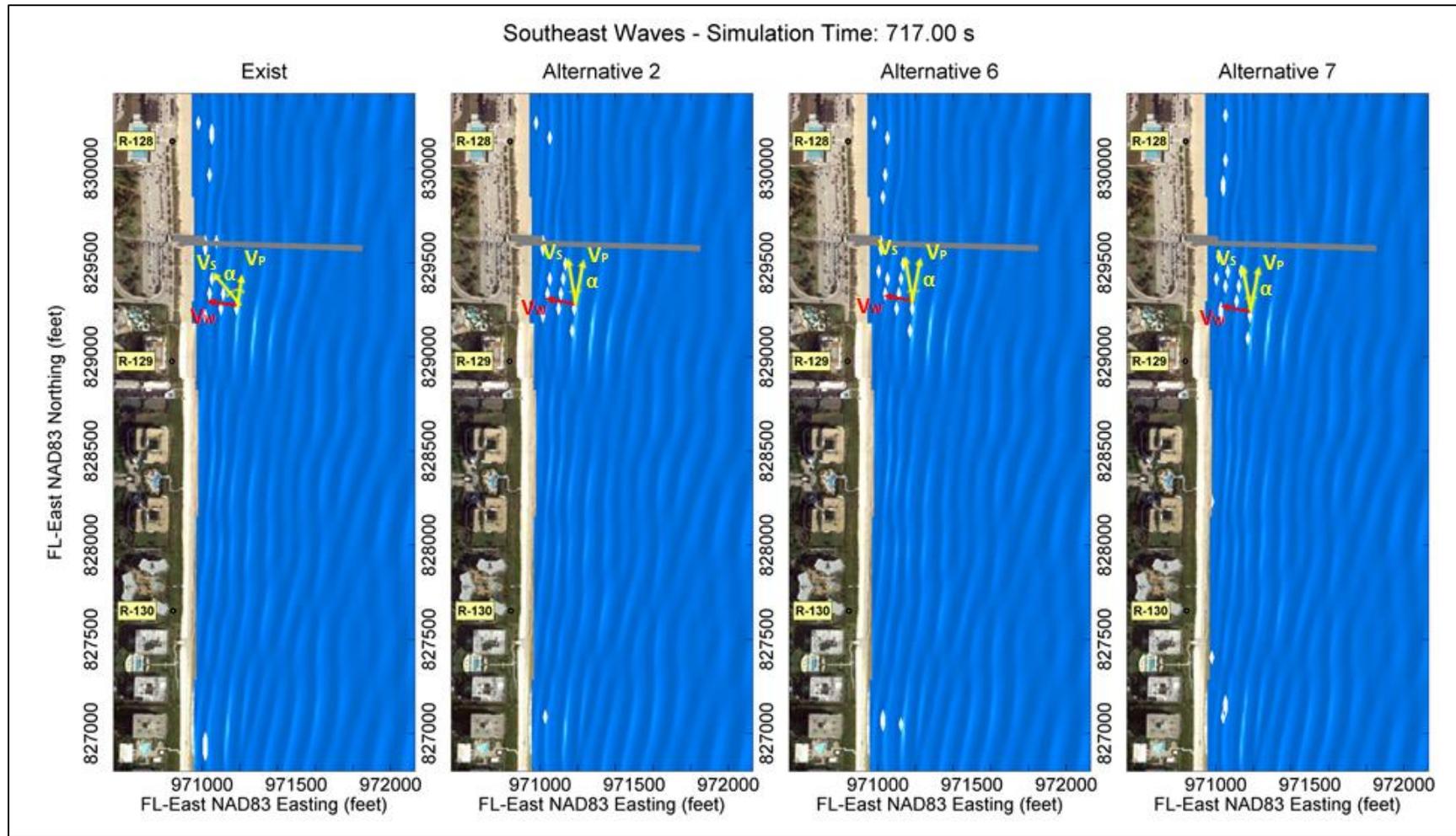


Figure 4-3. Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for southeast waves at the Pier.

Table 4-1. Comparison of existing conditions and alternatives for southeast waves at the Pier.

Condition	ξ_b	Peel angle (°)	Velocity of wave (mph)	Peel rate (mph)	Velocity of surfer (mph)
Existing	0.3	46	9.1	8.7	12.6
Alternative 2	0.2	17	9.3	30.5	31.9
Alternative 6	0.2	16	9.3	32.4	33.7
Alternative 7a	0.2	19	9.3	27.0	28.5

4.1.2. Cold Front (Hs 7.4 feet, Tp 11 s from 65°)

For cold front scenarios at the Pier, the significant wave height (Hs) for existing conditions and the differences between alternatives are presented in Figure 4-4. The wave propagation for existing conditions shows shoaling at approximately 1,200 feet from the beach shoreline and it also shows a reduction of Hs, related to wave breaking, at approximately 1,000 feet from the dry beach. Two points of wave focalization are observed, these points are caused by wave refraction/diffraction over the borrow area. One point is located between R132 and R133, and the other at R135. The differences in Hs between alternatives and existing conditions occur only shoreward of wave breaking. This event indicates that the bathymetric changes generated by alternatives do not impact the wave heights at surfing area. Figure 4-4 presents the takeoff position of analyzed waves where it is clear that no changes higher than 2.5% in wave height occur at the takeoff position.

Figure 4-5 presents the water surface elevation at the Pier for existing and alternatives conditions at the analysis points presented in Figure 3-2. All alternatives presented very similar timeseries with very small variations, indicating that at the analyzed points, there will not be significant changes in wave propagation.

BOUSS-2D wave simulations screenshots at the Pier are presented in Figure 4-6. The parameters calculated from these screenshots are presented in Table -2. The breaker type for the Pier surfing spot for all simulated scenarios and alternatives leads to a spilling break with ξ_b of 0.3. Existing conditions presented the same peel angle and peel rate as Alternatives 2 and 6.

Table 4-2. Comparison of existing and alternative conditions for a cold front at the Pier.

Condition	ξ_b	Peel angle (°)	Velocity of wave (mph)	Peel rate (mph)	Velocity of surfer (mph)
Existing	0.3	60	14.2	8.2	16.5
Alternative 2	0.3	60	14.3	8.2	16.5
Alternative 6	0.3	60	14.2	8.2	16.4
Alternative 7a	0.3	70	14.2	5.2	15.1

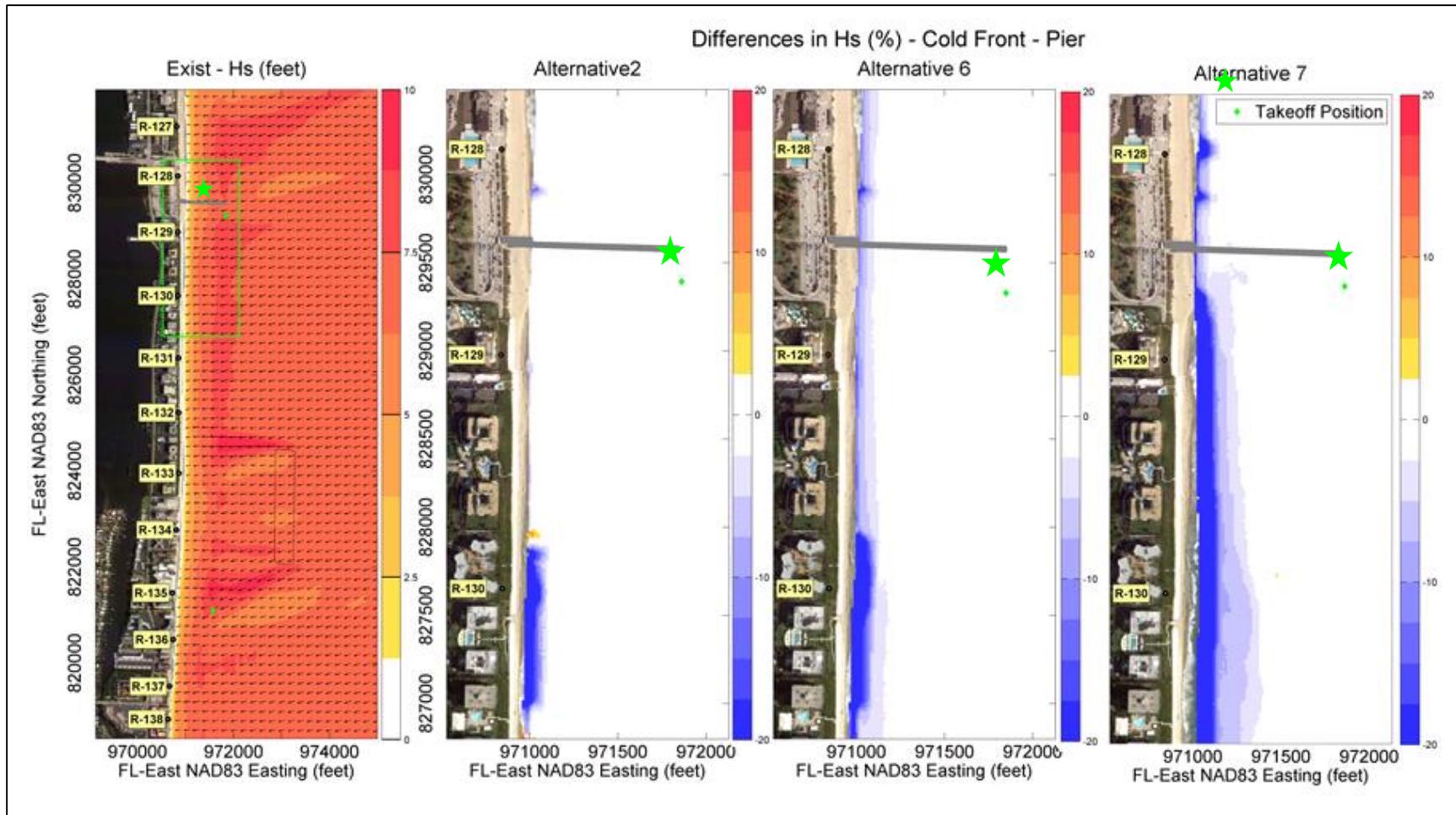


Figure 4-4. Significant wave height for existing condition and differences between each alternative and the existing condition for cold front scenario at Pier.

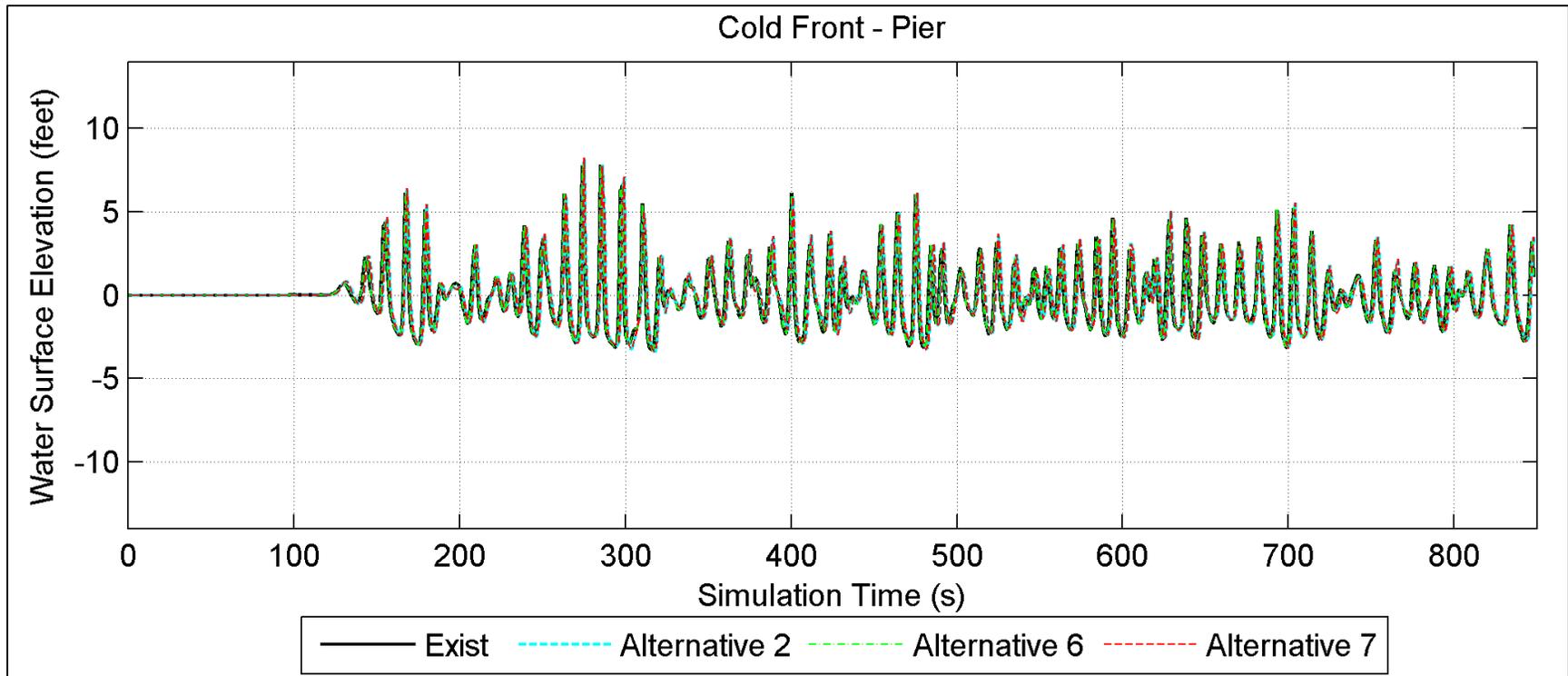


Figure 4-5. Water surface elevation at Pier for cold front.

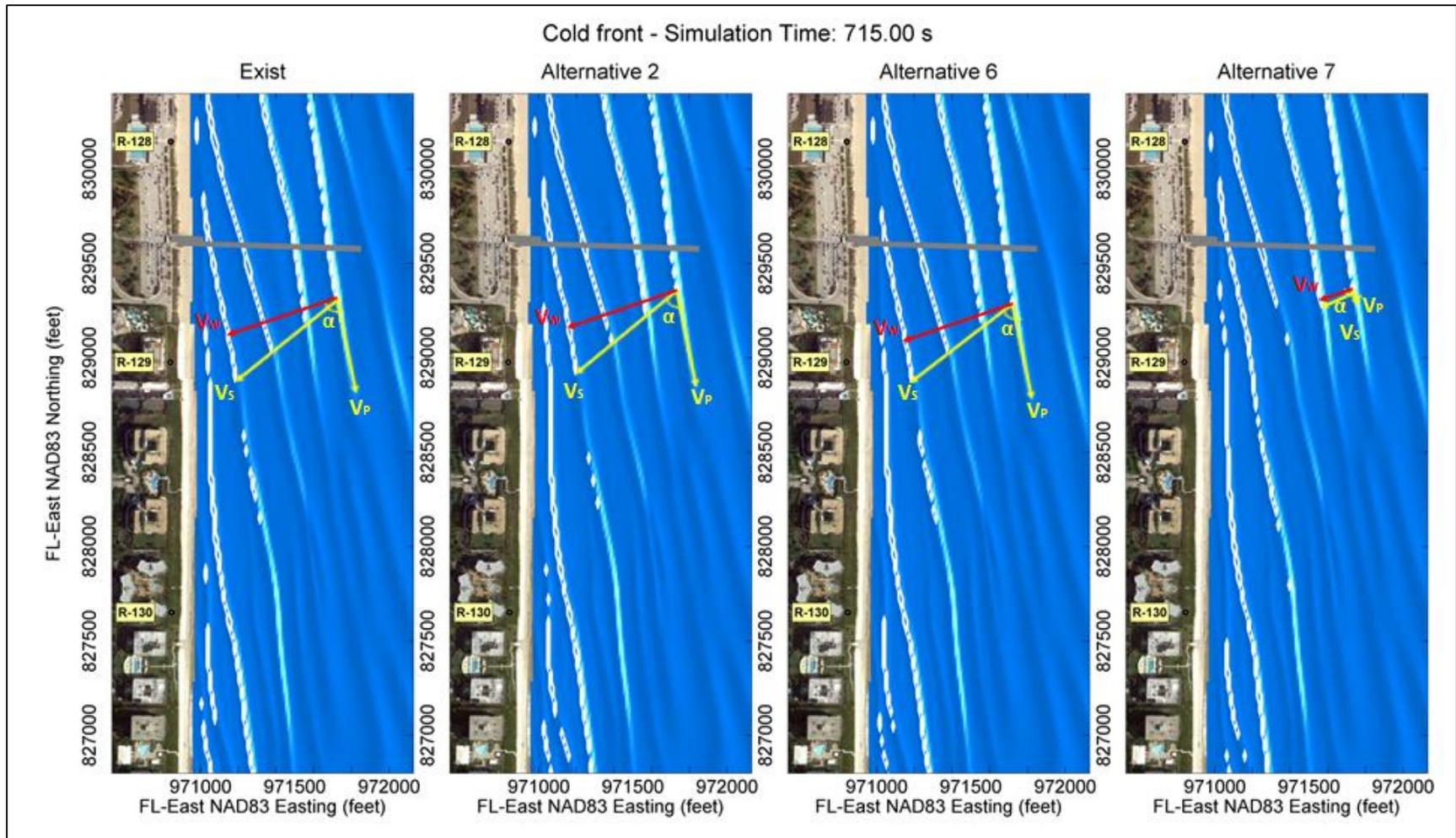


Figure 4-6. Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for cold front at Pier.

4.1.3. Hurricane Pre-Landfall (Hs 8.1 feet, Tp 13.5 s from 103°)

For the hurricane pre-landfall scenario, the significant wave height (Hs) for existing conditions and the differences between existing conditions and the alternatives are presented in Figure 4-7. The wave propagation shows that for this condition, shoaling starts at approximately 2,000 feet from the beach shoreline and the wave breaks at approximately 1,000 feet from dry beach. For the other wave conditions in the hurricane pre-landfall scenario, an Hs focalization caused by wave refraction/diffraction is observed at the borrow pit. In this case, the wave height is focused at R132 and between R133 and R134. For all alternatives a reduction of wave height is observed near the coast due to reduction of depth at that area and increase of bottom friction and/or wave breaking. As Alternative 7a presents higher nourishment volumes, the differences are more noticeable in this alternative. This alternative presents higher Hs as well as higher wave period compared to the existing conditions and other alternatives. Also, in Alternative 7a conditions, the waves will break in deeper water (compared to cold front and southeast waves) and there will be no observable differences in wave height at the surf spots.

Figure 4-8 presents the water surface elevation at the Pier for existing and alternatives conditions, at the analysis points presented in Figure 3-2. All alternatives presented very similar timeseries with very small variations, indicating that at the analyzed points, there will not be significant changes in wave propagation.

Screenshots of hurricane pre-landfall simulations are presented in Figure 4-9. The parameters calculated from these screenshots are presented in Table 4-3. The breaker type for the Pier surfing spot for all simulated scenarios and alternatives is a spilling break with ξ_b of 0.3 for all analyzed waves.

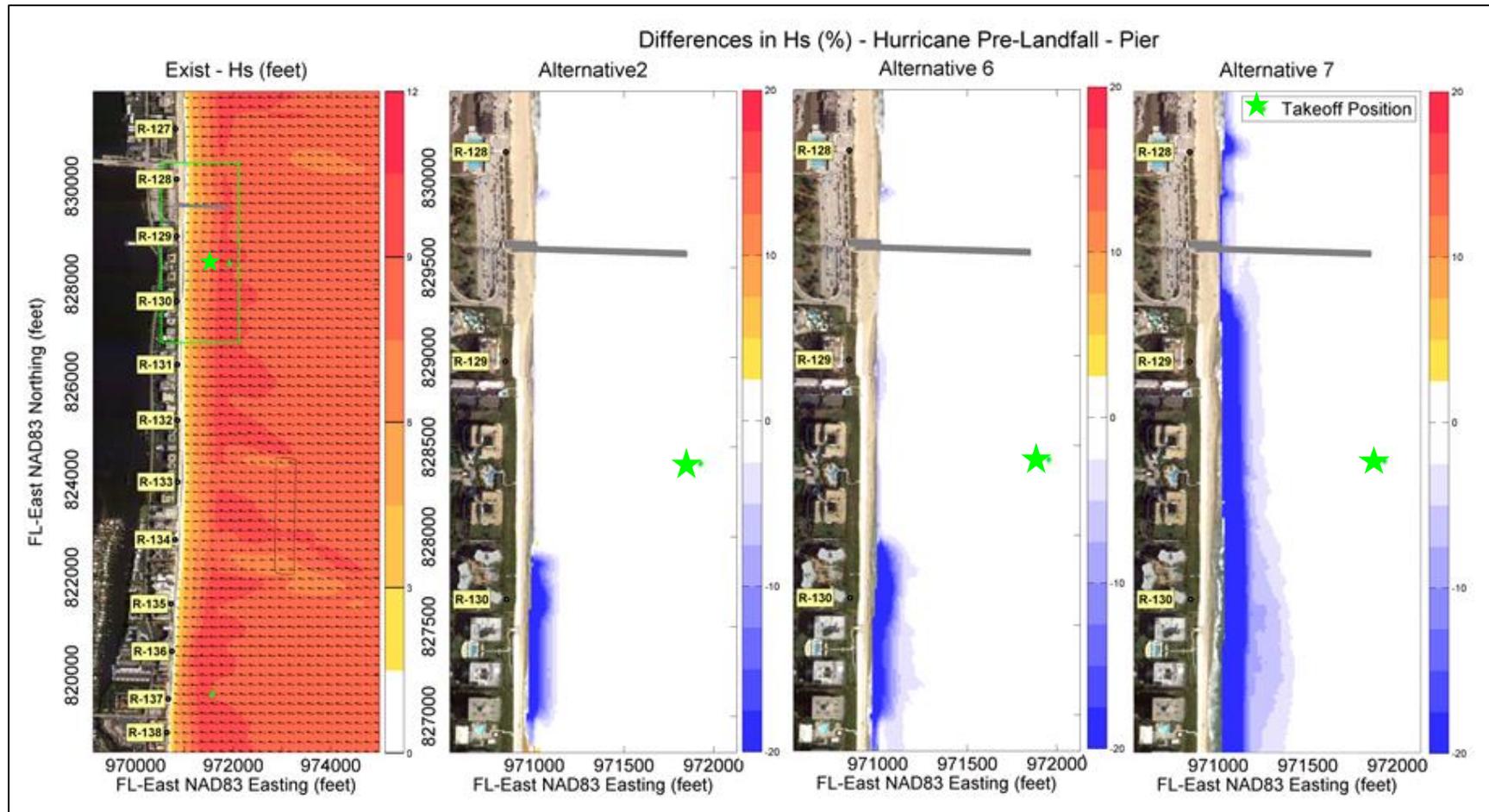


Figure 4-7. Significant wave height for existing condition and differences between each alternative and the existing condition for pre-hurricane at Pier.

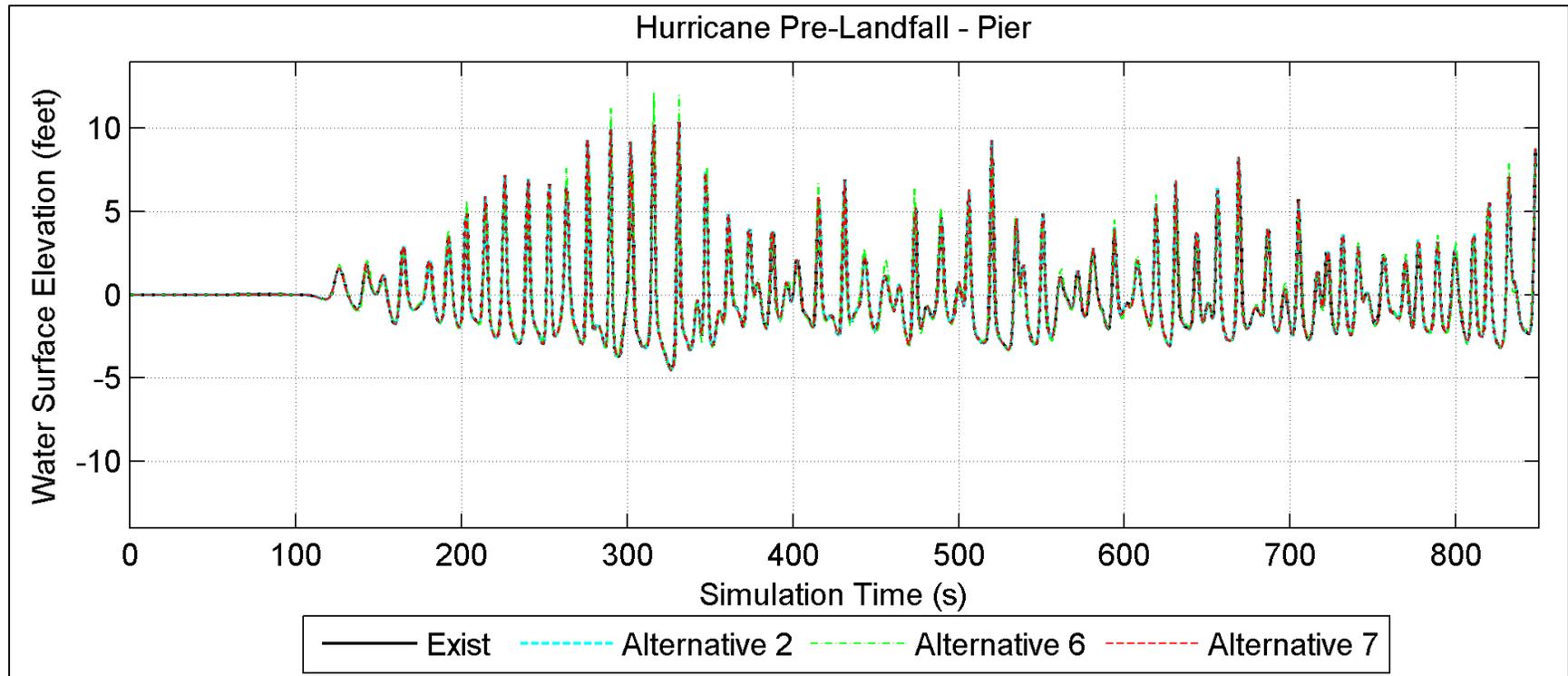


Figure 4-8. Water surface elevation at Pier for hurricane pre-landfall.

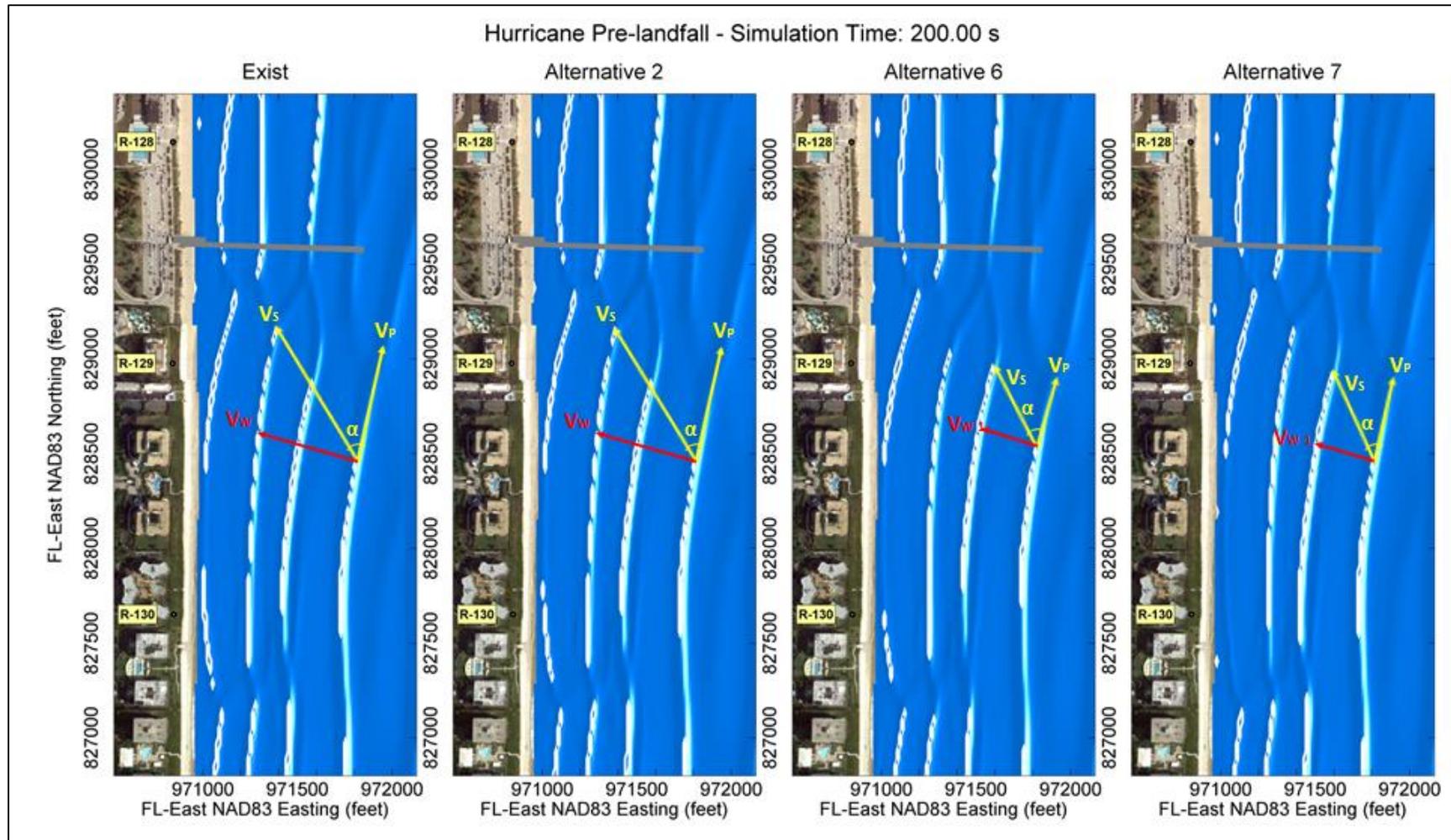


Figure 4-9. Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for hurricane pre-landfall at the Pier.

Table 4-3. Comparison of existing and alternatives conditions for hurricane pre-landfall at Pier.

Condition	ξ_b	Peel angle (°)	Velocity of wave (mph)	Peel rate (mph)	Velocity of surfer (mph)
Existing	0.3	45	15.1	15.1	21.4
Alternative 2	0.3	45	15.4	15.4	21.8
Alternative 6	0.3	42	15.8	17.5	23.6
Alternative 7a	0.3	38	15.3	19.6	24.9

4.2. Lantana Park

4.2.1. Southeast Waves (Hs 6 feet, Tp 6.1 s from 105°)

The significant wave height (Hs) for existing conditions and the differences between each alternative and the existing conditions at Lantana are presented in Figure 4-10. Analysis of the impact of each alternative on Hs revealed an increase of significant wave height at Lantana around the takeoff position. This increase in Hs is primarily due to the larger amounts of sediment located where the wave starts to “touch” the bottom before starting its shoaling process.

Figure 4-11 presents the water surface elevation at Lantana for existing and alternatives conditions. The analysis points are presented in Figure 3-2. All alternatives presented very similar timeseries with very small variations, indicating that at the analyzed points, there will not be significant changes in wave propagation.

BOUSS-2D wave simulations screenshots at Lantana are presented in Figure 4-12. The parameters calculated from these screenshots are presented in Table 4-4.

The breaker type at Lantana did not change between the existing conditions and the alternatives. For all cases, the Iribarren calculated was 0.2, indicating a spilling break type. It is noted that the takeoff position in Alternative 7a is further landward than in the other alternatives and the existing conditions. This can be due to wave energy dissipation over the bottom. Since Alternative 7a is shallower, the wave dissipates more energy before breaking and this dissipation leads the wave to break closer to the shore.

The existing conditions and Alternative 2 would be rated a 5 in Hunt *et al.* (2001) classification (see Table 2-1), as compared to a 6 for Alternative 6 and a 7a for Alternative 7a. The velocity of wave did not change significantly between alternatives and existing conditions.

Table 4-4. Comparison of existing conditions and alternatives for southeast waves at Lantana.

Condition	ξ_b	Peel angle (°)	Velocity of wave (mph)	Peel rate (mph)	Velocity of surfer (mph)
Existing	0.2	54	10.5	7.6	13.0
Alternative 2	0.2	55	10.3	7.2	12.6
Alternative 6	0.2	47	10.4	9.7	14.2
Alternative 7a	0.2	26	10.4	21.2	23.6

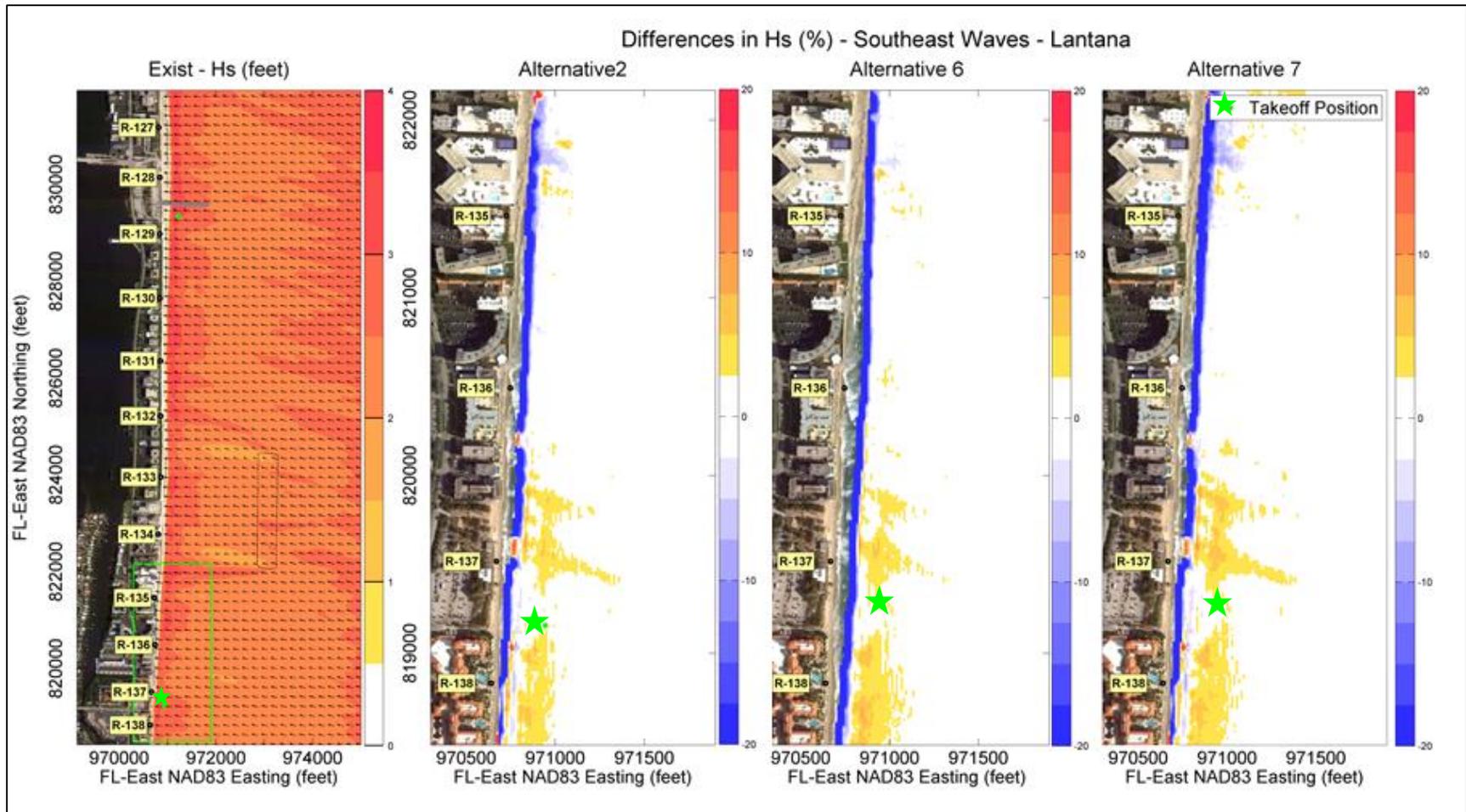


Figure 4-10. Significant wave height for existing condition and differences between each alternative and the existing condition for southeast waves at Lantana.

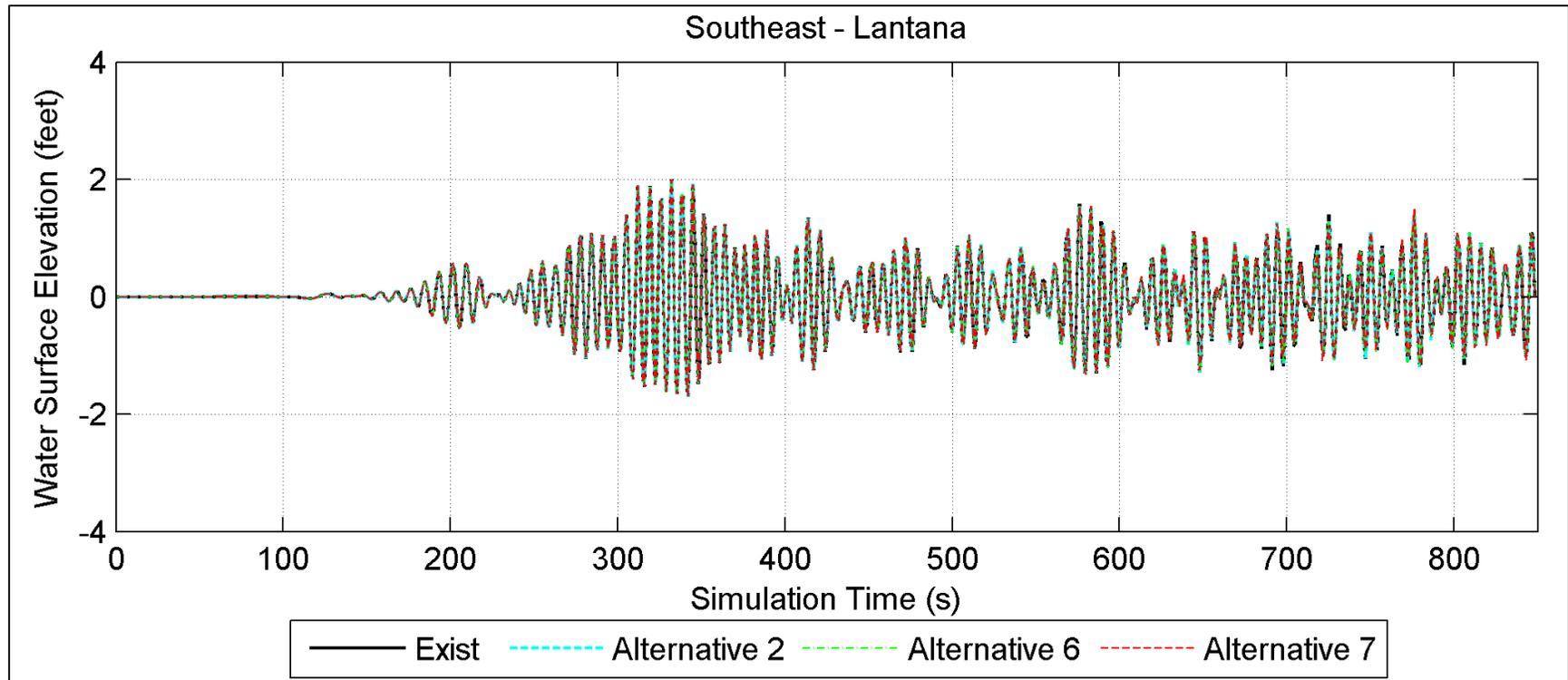


Figure 4-11. Water surface elevation at Lantana for southeast waves.

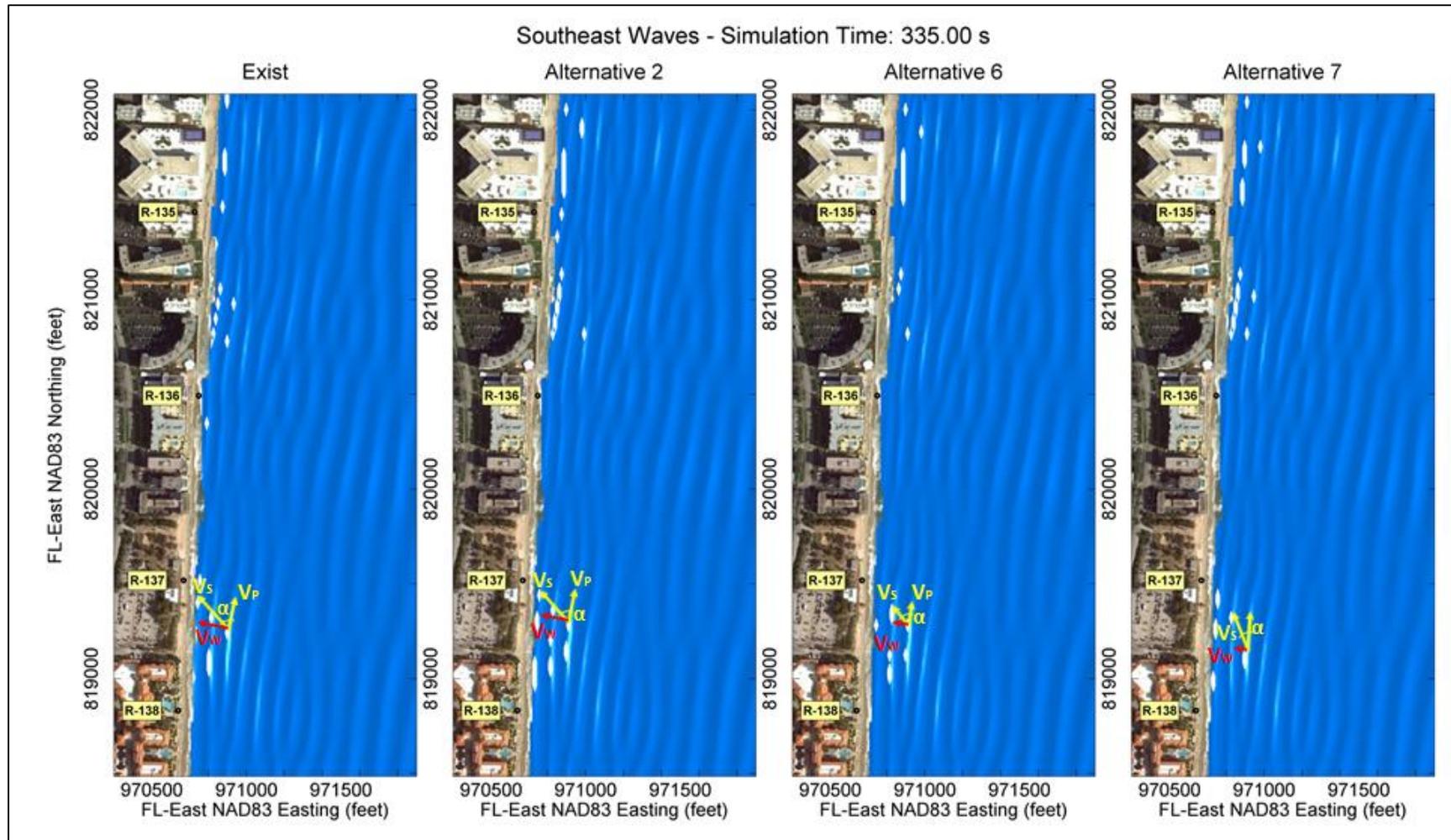


Figure 4-12. Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for southeast waves at Lantana.

4.2.2. Cold Front (Hs 7.4 feet, Tp 11 s from 65°)

For cold front scenarios at Lantana, the significant wave height (Hs) for existing conditions and the differences between alternatives are presented in Figure 4-13. The differences in Hs between the alternatives and existing conditions occur only shoreward of wave breaking, indicating that the bathymetric changes generated by alternatives does not impact the wave heights at the Lantana surf spot. Figure 4-13 presents the takeoff position of analyzed waves where it is clear that no changes higher than 2.5% in wave height occur.

Figure 4-14 presents the water surface elevation at Lantana for existing and alternatives conditions at the analysis points presented in Figure 3-2. All alternatives presented very similar timeseries with very small variations, indicating that at the analyzed points, there will not be significant changes in wave propagation.

Bouss2D wave simulations screenshots for cold front waves at Lantana are presented in Figure 4-15. The parameters calculated from these screenshots are presented in Table 4-5. The breaker type for Lantana for all simulated scenarios and alternatives leads to a spilling break with ξ_b of 0.3.

For Lantana, the existing conditions and Alternatives 2 and 6 are likely to result in waves rated for surfers at a skill level of 6 (Hunt *et al.* 2001). Alternative 7a presented a sharper peel angle and it is likely to be surfed by surfers rated as 7 or higher. The velocity of wave for all simulated cases is 15 mph. Alternative 7a increased its surfer velocity to 24.8 mph as a result of peel angle sharpening.

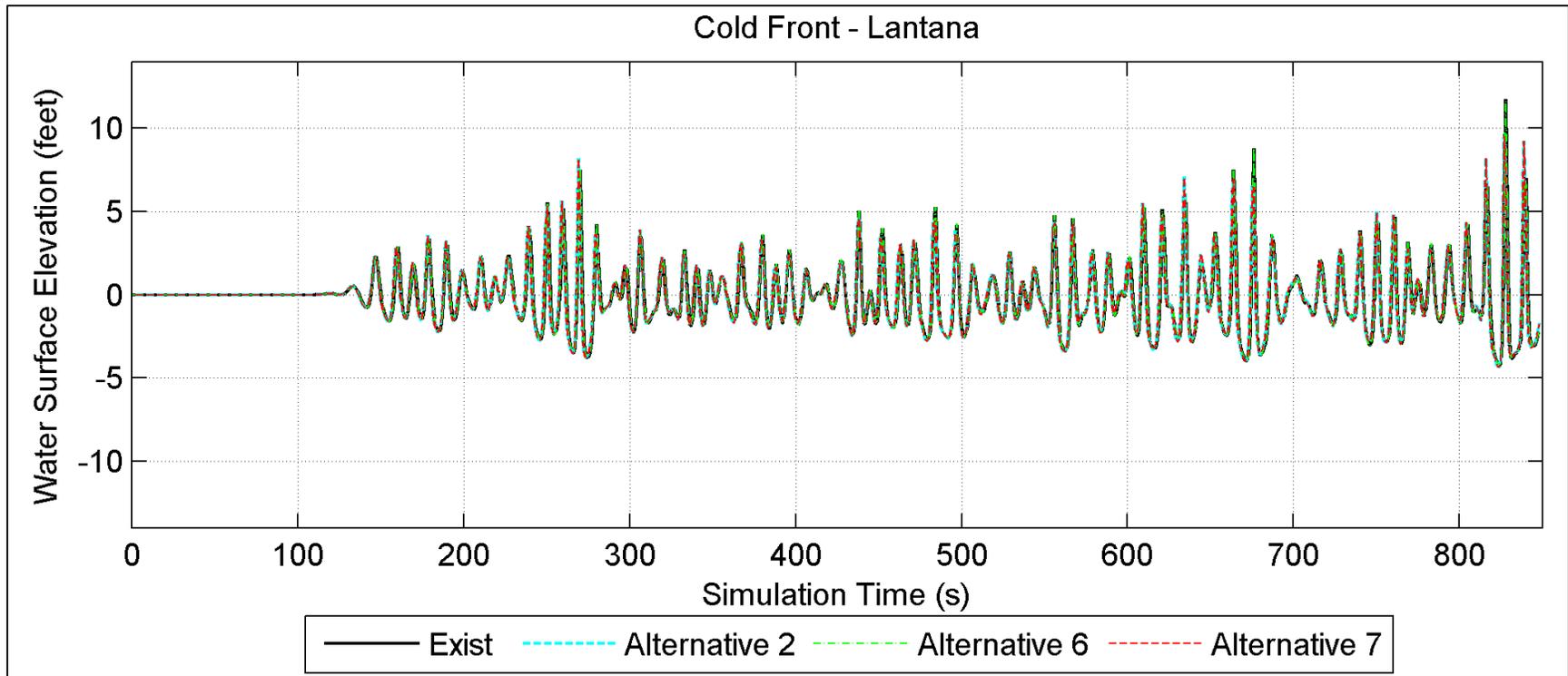


Figure 4-14. Water surface elevation at Lantana for cold front.

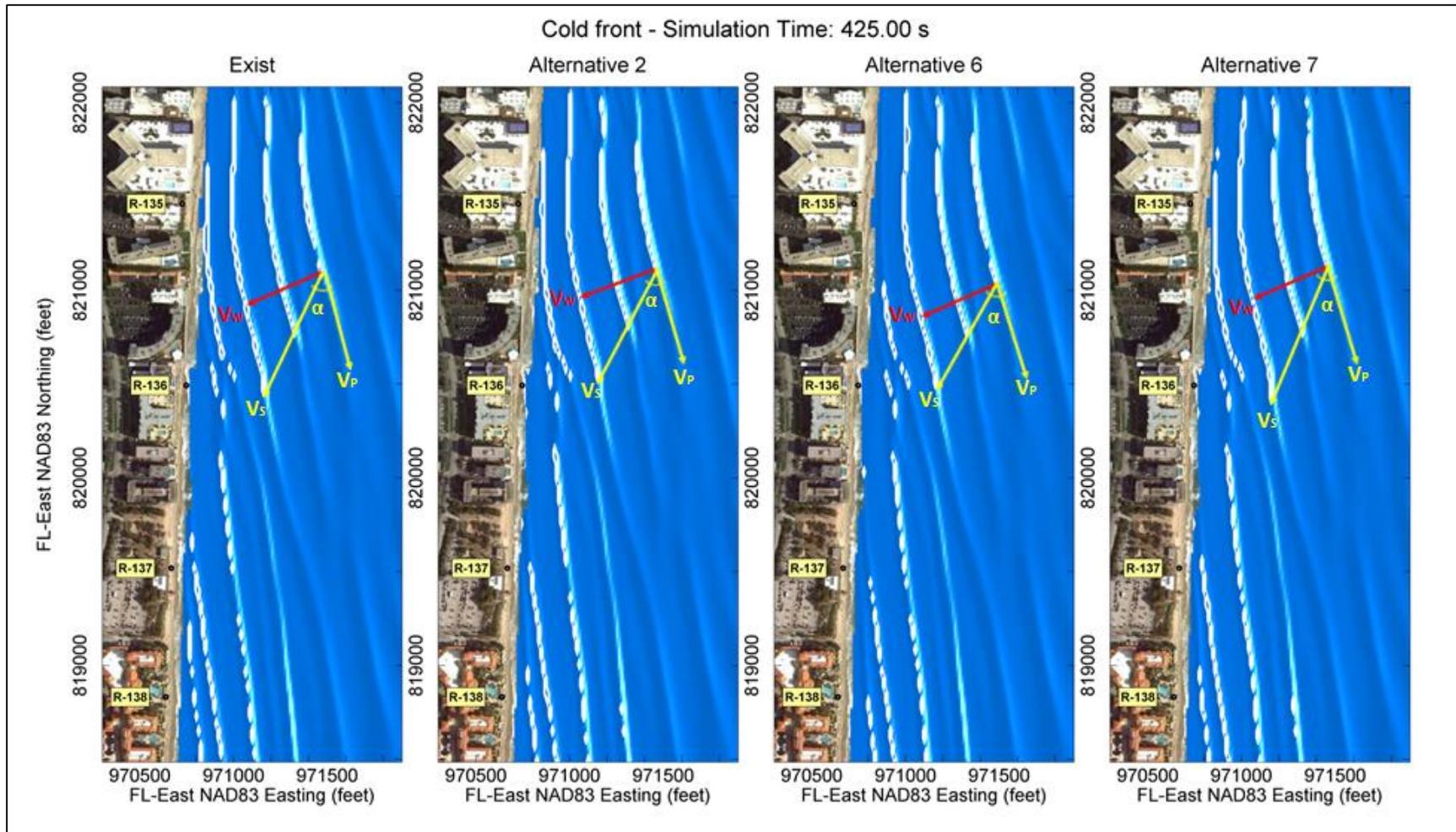


Figure 4-15. Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for cold front at Lantana.

Table 4-5. Comparison of existing and alternative conditions for a cold front at Lantana.

Condition	ξ_b	Peel angle (°)	Velocity of wave (mph)	Peel rate (mph)	Velocity of surfer (mph)
Existing	0.3	40	15.0	17.8	23.3
Alternative 2	0.3	43	15.0	16.0	21.9
Alternative 6	0.3	44	15.0	15.5	21.5
Alternative 7a	0.3	37	15.0	19.8	24.8

4.2.3. Hurricane Pre-Landfall (Hs 8.1 feet, Tp 13.5 s from 103°)

Figure 4-16 presents the differences in significant wave height at Lantana. For all alternatives, a reduction of wave height is observed near the coast due to reduction of depth at that area and increase of bottom friction and/or wave breaking. As Alternative 7a presents higher nourishment volumes, the differences are more noticeable in this alternative. Alternative 7a presents higher Hs as well as a higher wave period compared to the other wave conditions. For the hurricane pre-landfall condition, the waves break in deeper water (compared to cold front and southeast waves) and the differences in wave height are not observed at the surf spots.

Figure 4-17 presents the water surface elevation at Lantana for existing and alternatives conditions, at the analysis points presented in Figure 3-2. All alternatives presented very similar timeseries with very small variations, indicating that at the analyzed points, there will not be significant changes in wave propagation.

Screenshots of hurricane pre-landfall simulations are presented in Figure 4-18. The parameters calculated from these screenshots are presented in Table 4-6. The breaker type for both Lantana and the Pier for all simulated scenarios and alternatives is a spilling break with ξ_b of 0.3 for all analyzed waves.

At Lantana, the peel angle for existing condition is 63°, which is suitable for surfers rated at a skill level of 3 (Hunt *et al*, 2001). For Alternatives 2 (59°), 6 (58°) and 7 (58°), the peel angle decreases and the conditions would be suitable for surfers rated at a skill level of 4.

Table 4-6. Comparison of existing and alternative conditions for hurricane pre-landfall at Lantana.

Condition	ξ_b	Peel angle (°)	Velocity of wave (mph)	Peel rate (mph)	Velocity of surfer (mph)
Existing	0.3	63	16.4	8.3	18.4
Alternative 2	0.3	59	16.3	9.8	19.1
Alternative 6	0.3	58	16.4	10.2	19.3
Alternative 7a	0.3	58	16.3	10.2	19.3

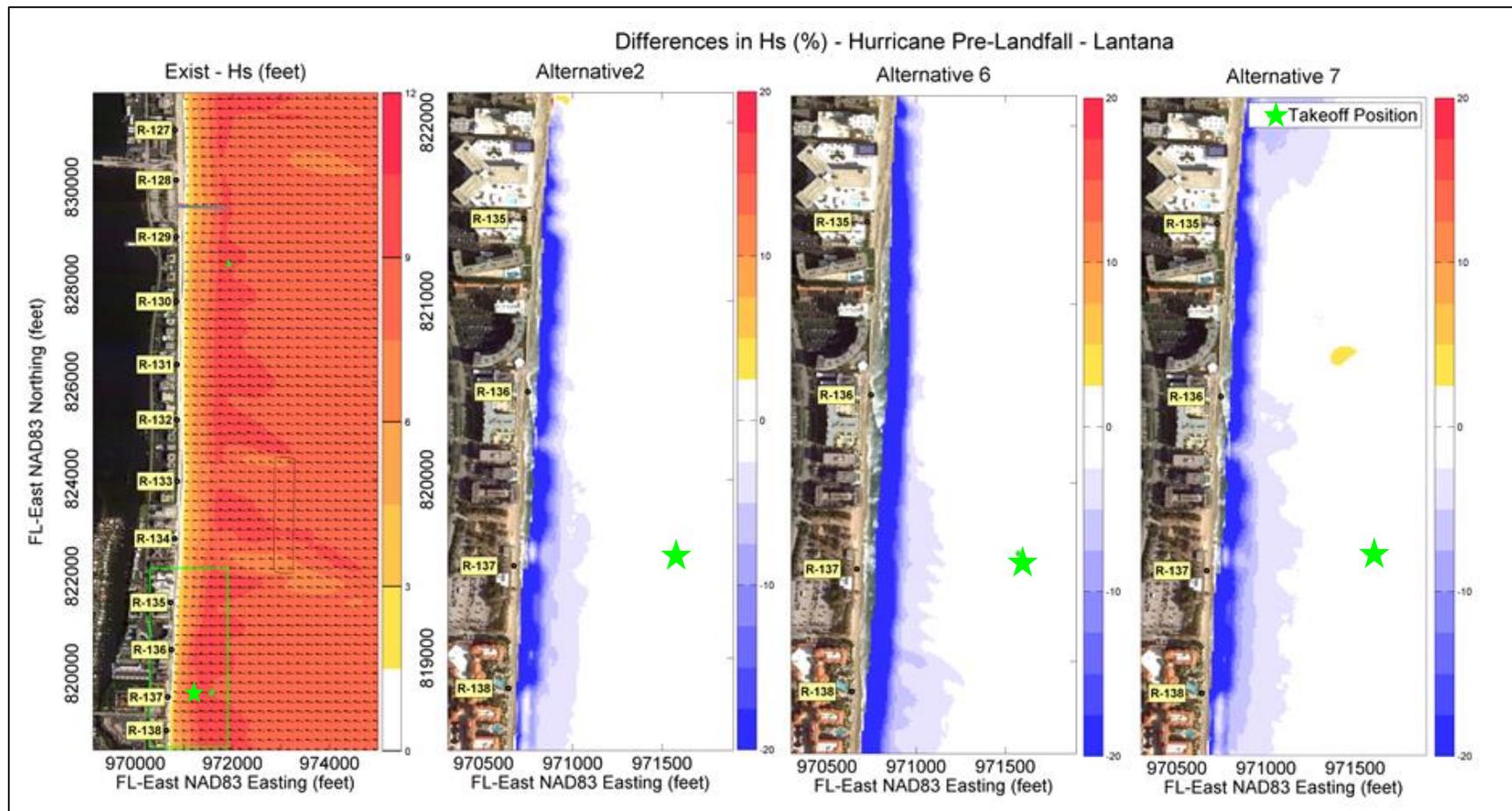


Figure 4-16. Significant wave height for existing condition and differences between each alternative and the existing condition for pre-hurricane at Lantana.

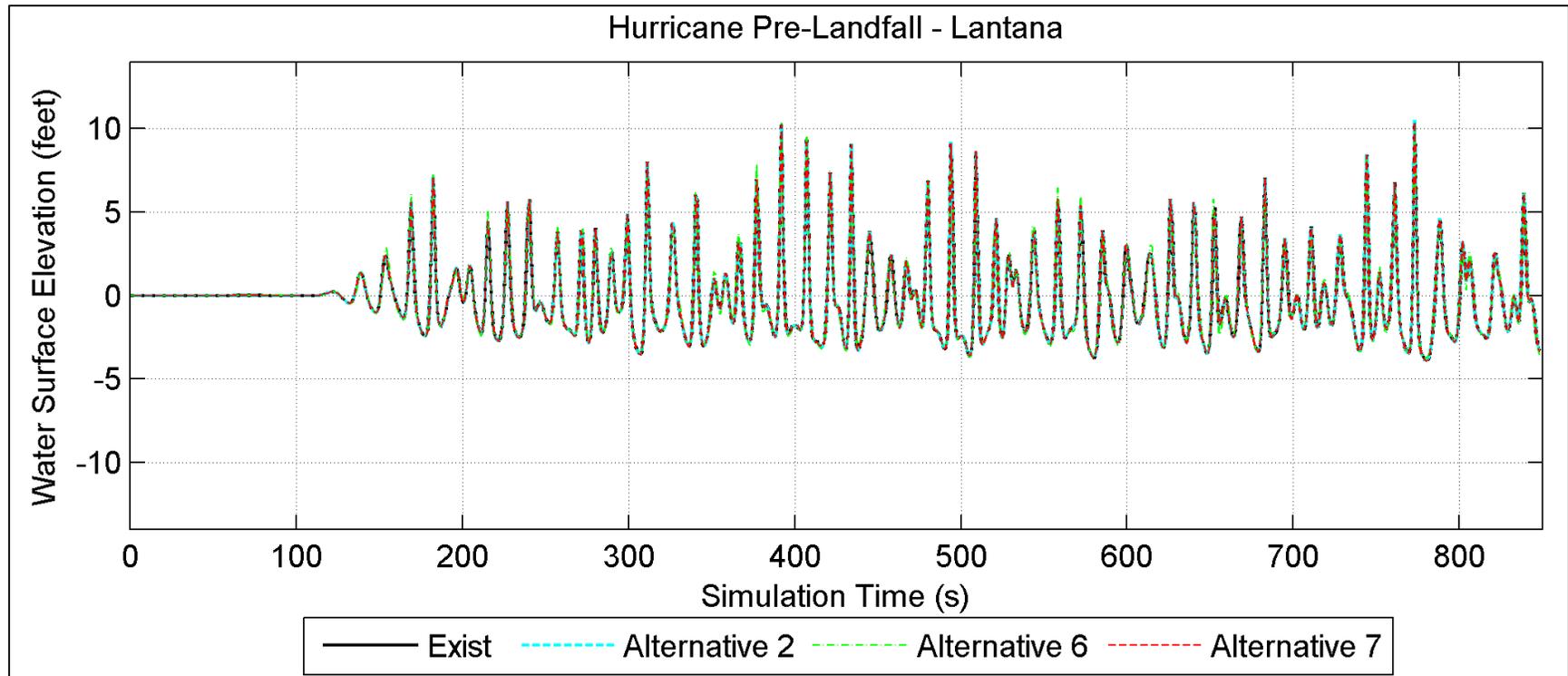


Figure 4-17. Water surface elevation at Lantana for hurricane pre-landfall.

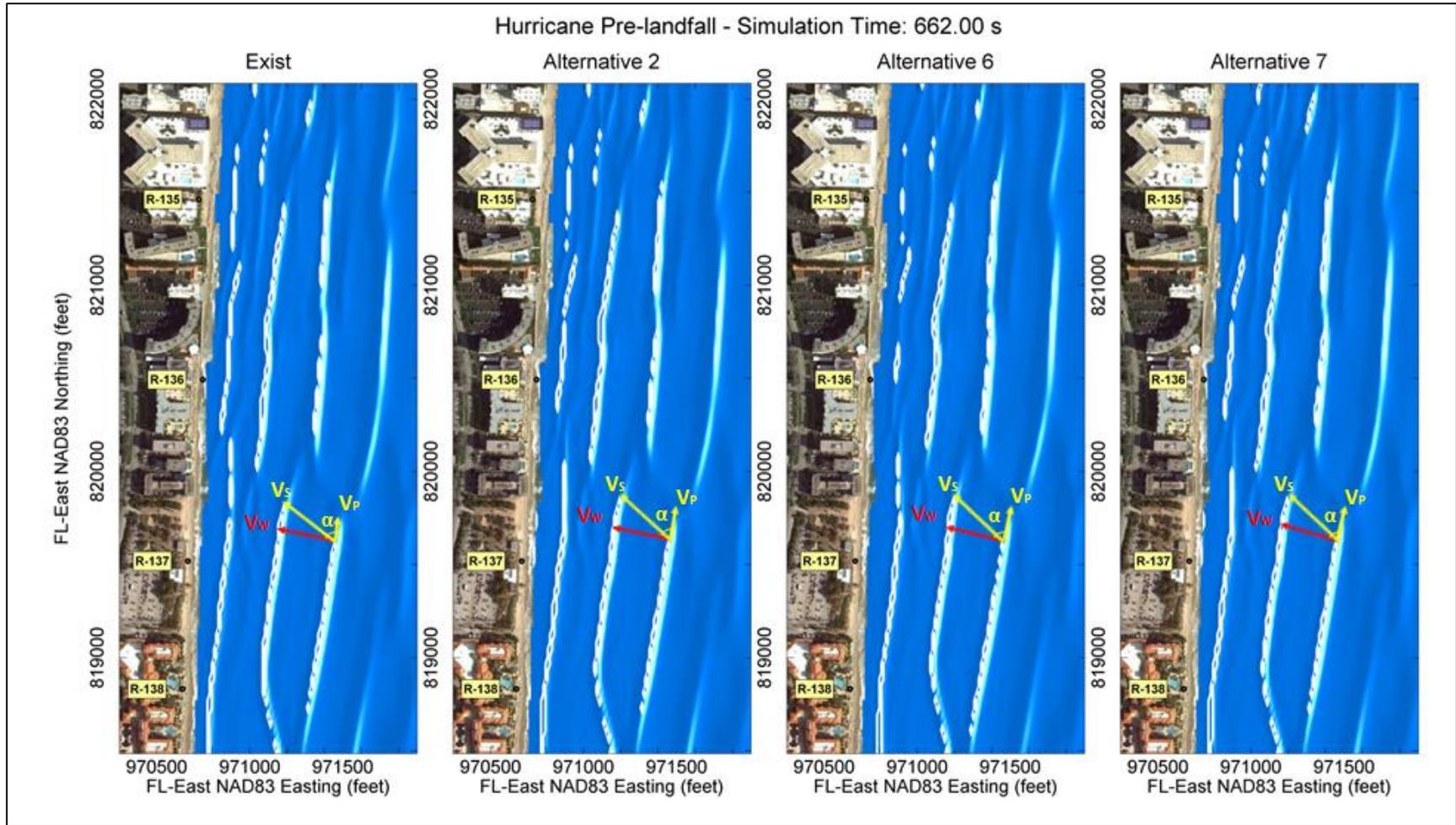


Figure 4-18. Peel angle (α), peel rate (V_p), wave velocity (V_w) and surfer velocity (V_s) identification for hurricane pre-landfall at Lantana.

5.0 SUMMARY AND CONCLUSIONS

A numerical modeling study utilizing BOUSS-2D model was conducted to simulate the potential impacts of Project alternatives to surfability at two points: nearby Lantana Beach Park and at the Lake Worth Pier. Three wave conditions: (i) southeast, (ii) cold front and (iii) hurricane pre-landfall, were used for model verification and model runs. The significant wave height for existing conditions was analyzed as well as the relative differences (%) between existing conditions and the alternatives. In addition, the main parameters to assess surfability (Iribarren number ξ_b , peel angle, velocity of wave, peel rate and velocity of surfer) were studied to evaluate the quality of wave for surfing.

The main conclusions of this BOUSS2D study are as follows:

- The minimum skill level required of surfers to surf at the two locations was rated at 5 (out of 10), representing an intermediate skill level.
- Differences of significant wave heights (H_s) between existing and alternatives scenarios were more noticeable for alternatives with higher amount of sediment placement.
- A decrease of wave height was observed near the beach for all alternatives. This decrease would not impact surfing directly since it happened after wave breaking, landward of surfing area.
- The wave condition that showed more impact from the alternatives was the southeast waves. Under this condition (smaller waves with smaller periods) the waves would break close to the beach where the differences in bathymetry (between alternatives and existing) are higher. For hurricane and cold front wave conditions (higher waves with higher periods) the waves would break offshore where the bathymetry presents little or no differences between existing conditions and the alternatives.
- An increase of wave height before wave breaking is observed for southeast waves conditions in Alternative 7a. This wave height increase is noticed due to

the combination of the wave conditions used in the model and the bathymetry of Alternative 7a. The southeast wave conditions have the smallest simulated wave height and period and Alternative 7a presents the highest amount of sediment placed.

- In general, a small variation in peel angle, peel rate, and the velocity of the surfer was observed in all the simulations for the different alternatives. The changes in the surfability at the two locations due to the alternatives were also small.

The results of this numerical modeling study should be used in conjunction with other coastal engineering assessments and prudent engineering judgment.

6.0 LITERATURE CITED

Battjes, J. A. 1974. Surf Similarity. Coastal Engineering. 466-480 p.

Benedet, L., T. Pierro, and M. Henriquez. 2007. Impacts of coastal engineering projects on the surfability of sandy beaches. Shore & Beach 75(4), Fall 2007, American Shore & Beach Preservation Association, Ft. Myers, FL, pp 3-20.

Black, K.P. 2001. Artificial Surfing Reefs for Erosion Control and Amenity; Theory and Application. Special Issue 34 (ICS 2000), Journal of Coastal Research, pp 1-7. 312.

Black, K.P. and S. Mead. 2001. Design of the Gold Coast Artificial Surfing Reef: Surfing Aspects. In: K. Black (ed) Natural and Artificial Reefs for Surfing and Coastal Protection. Special Issue 29, Journal of Coastal Research, pp 115-130.

Coastal Planning and Engineering, Inc. (CPE). 2009. Boussinesq Wave Modelling for Evaluation of Impact of Proposed Structures on Surfing Conditions. Technical Report. 48p.

Dafferner, G. and A.H. da F. Klein. 2009. The Relationship between Morphodynamics and Surfability at Brava Beach, Southern Brazil. Reef Journal 1(1):153-161.

Demirbilek, Z., A. Zundel, and O. Nwogu. 2005. BOUSS-2D Wave Model in the SMS: 1. Graphical Interface. US Army Corps of Engineers – Engineer Research and Development Center. Vicksburg, MS.

Goda, Y. 1985. A new method of wave pressure calculation for design of composite breakwater, Proceedings 14th international conference on Coastal, ASCE. Pp 1702-1720.

Hubertz, J.M. 1992. User's Guide to the Wave Information Studies (WIS) Wave Model: Version 2.0, WIS Report 27, US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, 41 pp.

Hutt, J.A., K.P. Black, and S.T. Mead. 2001. Classification of surf breaks in relation to surfing skill. *Journal of Coast Research*. SI 29. 66-81 p.

Nwogu, O. 1993. Alternative form of Boussinesq equations for nearshore wave propagation. *Journal of Waterway, Port, Coastal and Ocean Engineering*, ASCE, 119(6), 618-638.

Nwogu, O. 1996. Numerical prediction of breaking waves and currents with a Boussinesq model. Paper presented at the 25th International Conference on Coastal Engineering, ICCE '96, Orlando, FL.

Nwogu, O., and Z. Demirebilek. 2001. BOUSS-2D: A Boussinesq wave model for coastal regions and harbors. ERDC/CHL TR-01-25, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Peregrine, D. H. 1967. Long waves on a beach. *Journal of Fluid Mechanics* 27, 815-827.

Scarfe, B.E., M.H.S. Elwany, S.T. Mead, and K.P. Black. 2003. The science of surfing waves and surfing breaks – A review. Scripps Institution of Oceanography – UC San Diego. Technical Report. 1- 12.

Walker, J.R. 1974. Recreational Surf Parameters, Technical Report 30, Look Laboratory, University of Hawaii, 311 pp

Wei, G., J.T. Kirby, S.T. Grilli, and R. Subramanya. 1995. A fully nonlinear Boussinesq model for surface waves, Part 1, highly nonlinear unsteady waves. *Journal of Fluid Mechanics* 294, 71-92.