Investigating the Collapse of the Puerto Colombia Pier (Colombian Caribbean Coast) in March 2009: Methodology for the Reconstruction of Extreme Events and the Evaluation of Their Impact on the Coastal Infrastructure

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ABSTRACT

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On March 7, 2009, a 200-m section of the Puerto Colombia pier collapsed when a cold front passed through the Atlántico Department of Colombia on the Caribbean coast. Herein, the most important meteo-marine event of the last 10 years in the Colombian Caribbean area was reconstructed using SWAN software and the WAVEWATCH III global wave model, which uses wind fields as input. The modeling method involved a nested grid approach for wave generation and propagation in a particular sector of the central Caribbean coast of Colombia. To validate the numerical model, the time series for the event generated using modeling data was compared with the recorded wave data from two buoys: buoy 42058, which is located in the Caribbean Sea and operated by the National Oceanic and Atmospheric Administration, and buoy 41194, which is located near the Magdalena River mouth and operated by the General Maritime Directorate (DIMAR). The simulation results were incorporated into the CMS-Wave and CMS-Flow models for reconstruction of the cold-front event. The modeling results were also compared with previously reported data for the waves generated by hurricanes Joan (1988) and Lenny (1999). The results revealed that the analyzed study area was more heavily affected by the ocean conditions than the 2009 cold front event produced compared with conditions produced by other hurricanes that have affected the Colombian Caribbean coast. The findings also indicate that the proposed methodology, which utilizes several wave propagation models, produces results that adequately characterize the processes in deep, intermediate, and shallow waters.

ADDITIONAL INDEX WORDS: Cold fronts, WW3, SWAN, CMS-Wave, CMS-Flow, hurricanes, waves, Puerto Colombia.

INTRODUCTION

Waves are the primary consideration in the design of marine and coastal structures, and they ultimately dictate the underlying design criteria and structural configurations. Adequate modeling of extreme events is fundamental to understanding the necessary components for prediction of coastal morphological changes and navigation conditions.

The lack of reliable data for significant wave height, period, and direction, as well as limited information on wind fields near coastal areas throughout the world, necessitates the establishment and implementation of methods for modeling hydrodynamic processes, particularly between intermediate and shallow waters. Marine climate information for the Colombian Caribbean coast is scarce, and the available data have low spatial and temporal resolution. In this region, meteo-marine events, primarily hurricanes and cold fronts, produce waves ranging from low to high intensity. The absence of reliable information has made coastal and oceanic engineering efforts rely on visual data of oceanic waves, despite the errors associated with these data and precision loss from low spectral quality, irregular spatial distribution, and low temporal resolution, as discussed by Osorio, Mesa, and Bernal (2009).

In this paper, we propose a methodology that facilitates reconstruction of the meteo-marine conditions during the 2009 cold front that affected the structural stability of the Puerto Colombia pier (Atlántico, Colombia). For this reconstruction, we used wind fields as input for the WAVEWATCH III (WW3) global wave model and reproduced and analyzed the effects in shallow waters using the Simulating WAVes Nearshore (SWAN), CMS-Wave, and CMS-Flow models. Finally, the results were compared with previously reported data from wave simulations generated for specific hurricane events.
DESCRIPTION OF THE STUDY AREA

Colombia is in the northern part of South America and borders the Caribbean Sea and the Pacific Ocean. The important ports and cities with considerable commercial and tourist activity are on the Caribbean coast. The 9.2-km area analyzed herein lies in the central part of this coastal region west of the Magdalena River mouth (Figure 1). In 2009, the Puerto Colombia Port collapsed during a cold front that lasted from March 5 to March 10. The pier was built in 1893 by the Cuban architect Francisco Javier Cisneros, and at a length of 4000 ft (1200 m), it was the longest pier in the world at that time. In 1936, the Magdalena River became accessible at Bocas de Ceniza, which redirected the port activity to Barranquilla, and the Puerto Colombia pier was subsequently abandoned (Franco, 2009; see Figures 2 and 3).

As shown in Figure 4, the bathymetry of the study area is characterized by four zones: the first zone covers the area from the coastline to approximately 650 m and has a 0.63% mean slope, the second zone is between 650 and 2100 m and has a 0.24% mean slope, the third zone is between 2100 and 6900 m and has a 0.12% mean slope, and the fourth (and steepest) zone extends into deep waters. The continental shelf extends with a gentle slope and reaches depths greater than 12 m within 7 km of the coastline.

In general, the ocean floor within the study area comprises terrigenous sediments of alluvial origin trans-
ported by the coastal current from the Magdalena River mouth. The Puerto Colombia coastal sands have a 0.2-mm average diameter ($D_{50}$), as measured using granulometric analysis.

METHODS

Winds

The methodology described below is based on the wind field modeling reanalysis used by the National Oceanic and Atmospheric Administration (NOAA) to fit the WW3 global wave model. The information that generated spatial resolution at $0.5^\circ \times 0.5^\circ$ and 3 hours temporal distribution was downloaded from the NOAA (2011a) FTP site.

The wind fields were decoded and reconfigured by converting them into ASCII files, which were uploaded to the SWAN wave model (Booij and Holthuijsen, 1987). The contribution of local wind fields to high-energy wave generation is minimal; consequently, the same wind fields used by the WW3 model are considered representative and appropriate for use in the SWAN model. Additionally, the time of year for wave events is associated with cold fronts passing over the Caribbean Sea and corresponds to the dry season, which is characterized primarily by persistent and intense winds from the northeast.
### Bathymetry

The deep-water bathymetries were downloaded from the ETOPO1 project (NOAA, 2011b). ETOPO1 is a 1 arc-minute global relief model of Earth’s surface that integrates land topography and ocean bathymetry. The bathymetries for intermediate and shallow waters were generated by the Universidad del Norte during the project “Estudios para la recuperación de playas entre el tanque del acueducto en Salgar y el cerro Morro Hermoso. Diseños para estabilizar la playa de Pradomar.” The equipment used included an echo sounder and a global positioning system coupled to software for information acquisition and processing. The bathymetries were reduced to a mean water level.

### Numerical Simulations

In this work, two models were used: the SWAN as well as the CMS-Wave and CMS-Flow models (Aquaveo, 2011). SWAN is a third-generation wave model similar to WAVE prediction Model (WAM) and WW3, and it computes random, short-crested, wind-generated waves for coastal regions and inland waters. SWAN solves the spectral wave action equation on a mesh using a fully implicit upwind scheme in geographical space. In frequency and directional space, the user can select the accuracy and diffusion levels. This implicit scheme is unconditionally stable. The version used in this study was 40.85.

CMS-Wave is a component of the Coastal Modeling System developed by the U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory. CMS-Wave is a two-dimensional, finite-difference numerical approximation of the depth-integrated continuity and momentum equations.

The spatial and temporal resolutions were improved through sequential experiments using the nested grid approach. Figure 5 shows the areas modeled in SWAN and the different nestings performed (image obtained from the CIOH nautical charts, Nos. 007, 612, and 613). Table 1 lists the information for the nesting grids used for the analysis and the sizes of the grid cells for each nesting used in the SWAN model.

After defining the nestings, we calculated the processes of wave generation and propagation in accordance with the wind fields using the SWAN model. We then compared the wave height results with the available data from two existing deep-water buoys: 42058, which is operated by the NOAA, and 41194, which is operated by the General Maritime Directorate (DIMAR). The data from buoys 42058 and 41194 were obtained from the National Data Buoy Center (NOAA, 2011c).

Figure 6 shows the buoy locations (image obtained from the CIOH nautical charts, Nos. 007, 612, and 613). To verify the difference between the measured and calculated time series, indices for agreement ($D$) and the average deviation ($P$) were applied according to the method of Willmott (1981). As elaborated by Wornon and Welsh (2002a, 2002b), Willmott’s $D$ index is very sensitive to the root mean square error for the differences between the predicted and observed values. $D = 0$ indicates total dissociation, whereas $D = 1$ indicates perfect association between the measured and calculated data. Willmott’s $D$ index is defined as follows.

### Table 1. Characteristics Of Nesting Grids In The SWAN Model.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Cell Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>$-80^\circ$ $W$–$70^\circ$ $W$</td>
<td>$10^\circ$ N–$16^\circ$ N</td>
<td>$0.25^\circ$ $\times$ $0.25^\circ$</td>
</tr>
<tr>
<td>Nested No. 1</td>
<td>$-77^\circ$ $W$–$73^\circ$ $W$</td>
<td>$10^\circ$ N–$14^\circ$ N</td>
<td>$0.033^\circ$ $\times$ $0.033^\circ$</td>
</tr>
<tr>
<td>Nested No. 2</td>
<td>$-75.125^\circ$ $W$–$74.625^\circ$ $W$</td>
<td>$10.925^\circ$ N–$11.425^\circ$ N</td>
<td>$0.005^\circ$ $\times$ $0.005^\circ$</td>
</tr>
</tbody>
</table>
\[ D = 1 - \frac{\sum_{n=1}^{N} (P_n - O_n)^2}{\sum_{n=1}^{N} (|P_n - O| + |O_n - O|)^2} \] 

(1)

\( P_n \) is the predicted value, and \( O_n \) and \( O \) are the measurements and measurement averages, respectively. The average deviation \( P \) is defined as follows.

\[ \text{bias}(P) = \frac{\sum_{n=1}^{N} (P_n - O_n)}{\sum_{n=1}^{N} O_n} \] 

(2)

For example, a \(-0.05\) deviation indicates a 5% mean underestimation.

We then calculated the height, period, and direction of waves for a virtual buoy at the coordinates 11.16° N, 74.95° W. The time series results were entered into the CMS-Wave model (Lin, Rosati, and Demirbilek, 2008, 2011; Mase, 2001; Mase et al., 2005), wherein a set of three structured grids was created, with the last two grids as nestings of the first. In the simulations, we considered the effects of wave reflection and diffraction produced by the cutwaters in Bocas de Ceniza at the Magdalena River mouth. Figure 7 shows the nestings and location of the Bocas de Ceniza cutwaters. Table 2 lists the characteristics of the grids used in the CMS-Wave model. Table 3 shows the information for the processes included in the SWAN and CMS-Wave model experiments.

The wave results from the CMS-Wave simulations were compared with the modeling results for shallow waters using SWAN. Additionally, the CMS-Wave modeling results were integrated into the CMS-Flow model to generate currents for the duration of the scenario studied.

**RESULTS**

Figure 8 shows the cumulative probability distribution calculated by Osorio, Mesa, and Bernal (2009) for an area near buoy 41194. As previously described, the waves generated during the cold front correspond to the 99th percentile in the cumulative probability distribution, which emphasizes the significance of this event in the study area.

Figure 9 compares the significant wave height (\( H_s \)) data calculated using SWAN and the data from buoy 42058. Figure 10 shows the same comparisons for buoy 41194. As shown in

Table 2. Characteristics of the grids used for the CMS-Wave model calculations.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Cell Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>25,770 m</td>
<td>22,986 m</td>
<td>245 m \times 245 m</td>
</tr>
<tr>
<td>Nested No. 1</td>
<td>14,352 m</td>
<td>9000 m</td>
<td>75 m \times 75 m</td>
</tr>
<tr>
<td>Nested No. 2</td>
<td>3480 m</td>
<td>1800 m</td>
<td>20 m \times 20 m</td>
</tr>
</tbody>
</table>

Table 3. Physical processes used for the CMS-Wave and SWAN model calculations.

<table>
<thead>
<tr>
<th>Model</th>
<th>Physical Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWAN</td>
<td>Linear growth (Komen, Hasselmann, and Hasselman, 1984)</td>
</tr>
<tr>
<td></td>
<td>Nonlinear quadruplet wave interactions (Hasselmann et. al., 1985)</td>
</tr>
<tr>
<td>CMS-Wave</td>
<td>Refraction (Mase, 2001)</td>
</tr>
<tr>
<td></td>
<td>Shoaling (Mase, 2001)</td>
</tr>
<tr>
<td></td>
<td>Diffraction (Mase, 2001)</td>
</tr>
<tr>
<td></td>
<td>Breaking; extended Goda formula (Goda, 1970)</td>
</tr>
</tbody>
</table>

Figure 8. The cumulative probability distribution calculated by Osorio, Mesa, and Bernal (2009) for an area near buoy 41194.
these figures, $H_s$ doubled in magnitude during the cold front relative to the heights recorded during the event.

To verify the difference between the measured data from buoys 42058 and 41194 and the results from the SWAN model, which accounted for mean sea level and information available from WW3, we applied Willmott’s test as described above. The results of the analysis are shown in Tables 4 and 5. Willmott’s index was not calculated for buoy 41194 because there was insufficient WW3 information on this buoy.

As shown in Table 4, application of Willmott’s test to the time series generated using the SWAN model showed that the model results were 97% and 90% consistent with the data for buoys 42058 and 41194, respectively. Table 5 shows the average deviation for the SWAN model using Willmott’s method. The results indicate a deviation of less than 3% above the estimate for buoy 42058 and a 1.2% underestimation for buoy 41194. These calculations indicate that application of the model at the oceanic level generally yields dissimilar results compared with the real events analyzed.

Figures 11 and 12 show significant wave height scatter plots for the buoy data and the SWAN modeling results. As shown in Figures 11 and 12, the slope of the line is near 1, which indicates a 1:1 relationship between the significant wave heights calculated using the SWAN model and the measured wave heights. These results are consistent with the findings reported by Ortiz and Mercado (2008). The time series shown in Figures 9 and 10 suggest that the parameters for wave growth due to wind that are incorporated into the SWAN model (Komen, Hasselmann, and Hasselman, 1984) underestimate the wave response compared with the equations used in the WW3 model (Tolman and Chalikov, 1996).

Figure 13 shows the time series for $H_s$, peak period (PP), and Mean Wave Direction (MWD) for the virtual buoy from Figure 6. The time series shown in Figure 13 was used as the boundary condition for modeling the wave transformations in intermediate to shallow waters. The model accounted for astronomical tide-producing forces in the study area. As such, Figure 14 shows results for the $H_s$ coarse mesh on March 7, 2009 (0000 local time). The results primarily reflect refraction effects, wave shoaling due to bottom friction, and diffraction and reflection of the Bocas de Ceniza cutwaters located northeast of the study area.

To achieve greater precision for the wave results, the necessary conditions for adequate estimation of the waves and currents in shallow waters were determined, and the nestings shown in Figures 15 and 16 were performed. Figure 16 shows how waves modified the direction of propagation as they approached the coastline. In the area surrounding the Puerto Colombia pier, the waves propagated from the north with a nearly perpendicular front impact angle. The results demonstrate the significance of the proposed methods on the structural design of the pier.

As shown in Figure 17, the greatest $H_s$ was measured on March 7, 2009 (the date that the pier collapsed), and its magnitude was 2.27 m. Figure 18 shows an example of the magnitude and direction of the currents during the cold front along the Puerto Colombia coast. The sections analyzed for comparison with the currents during development of the cold front are outlined in the figures.

The temporal evolution of the meteorological event analyzed herein and its effects on the nested 2 mesh are shown in Figure 19. In 2009, the magnitudes of the currents from March 7 to March 10 were twice as great as the magnitudes observed from March 1 to March 5.

The transport of sediments associated with the coastal current shown in Figure 19 is a first approximation of the degree of conservation and sedimentological uniformity of the coast. This analysis indicates that the control cross section, which encompasses the Puerto Colombia Port, was exposed to currents with magnitudes twice as large as currents in the downstream area. Therefore, these findings suggest that the area analyzed herein has undergone powerful erosive processes.

### DISCUSSION

Understanding the effect of waves, currents, and sediment transport at a global level and in locations where instrumentally measured wind and wave data are unavailable is an important research area, especially in light of extreme conditions.
meteorological events. Few researchers are studying these phenomena and their effect on the coastal hydrodynamics of the Caribbean Sea. Until now, research in this field has largely emphasized simulated swell waves from the deep sea and estimated the propagation of these events directed toward the coast, and it has not considered changes in intermediate and shallow waters. For the Caribbean Basin in particular, all of the modeling research on wave propagation from extreme meteorological events has been conducted by two groups of researchers, the Lizano and Ortiz groups (Lizano, 1990; Lizano et al., 2001; Lizano, 2006; Ortiz, 2009; Ortiz et al., 2008), who have contributed significantly to forecasts for waves generated by cyclone winds.

A study conducted by Ortiz et al. (2008) modeled the wind fields and waves generated by Hurricane Joan in 1988, which had a trajectory in close proximity to the Colombian Caribbean coast. Although the total duration of the event (i.e., the time for the tropical depression to develop into a hurricane and then dissipate) was 13 days; only two of those days had any effect on the study area. Modeling indicated waves with heights up to 2.4 m in the sector of interest.

In conjunction with the previous study, a second analysis (Ortiz, 2009) focused on wave simulation generated by the winds from Hurricane Lenny in 1999, which had an 80-day total duration. For two of these days, the hurricane generated direct effects on the Colombian coast. Whereas Hurricane Lenny, unlike Joan, did not reach land, the swell waves generated by the two hurricanes were comparable. More specifically, Hurricane Lenny also produced significant wave heights up to 2.4 m in the area studied herein, which corresponds to the 70th percentile (Osorio, Mesa, and Bernal, 2009).

Modeling the significant wave heights from Hurricane Lenny and Hurricane Joan yielded a magnitude of approximately 57% compared with the heights recorded by buoy 41194 for modeling the cold front event. Additionally, the time series shown in Figure 12 reveals that the cold front event produced significant wave heights greater than 2.4 m over a 5-day period, which is 3 days more than the number of days the Colombian coast was affected by either of the hurricane events analyzed.

Figure 11. SWAN modeling results vs. buoy 42058.

Figure 12. SWAN modeling results vs. buoy 41194.

Figure 13. Time series for Hs (m), PP (s), and MWD (degrees) for the virtual buoy.

Figure 14. Hs contours on March 7, 2009 (0000 local time) for the coarse mesh.
It is interesting to highlight the nesting method for the two types of wave propagation models; the CMS-Wave model resolves the phase, and the SWAN model is a spectral model. Herein, SWAN contributes to the CMS-Wave model as a boundary condition by generating the directional spectra of waves propagated from deep waters. It is well known that the SWAN model is a powerful tool for propagating the spectrum of waves from undefined waters to shallow waters, but it has certain limitations in representing certain wave transformation processes, especially diffraction-refraction. The CMS-Wave model compensates for this deficiency, and greater precision was maintained in the wave calculation as well as in the diffraction-refraction effects generated by the coast configuration and bathymetry. The coupled models herein provide the advantages of each model, which contributes to improved precision in the results.

CONCLUSION

The level of precision required for reconstruction of a coastal event is highly dependent on numerous factors, including accuracy of bathymetric measurements, available wind field approximations, and various numerical errors typically associated with equation solutions for different ocean dynamic processes in deep, intermediate, and shallow waters. As more precise estimations of wind fields yield more reliable reproductions of the coastal processes in shallow waters, wind fields in shallow waters must be studied more rigorously.
The study herein details the level of precision generated by the described methodology. The agreement between the measured waves and the data generated by the model ranged from 90% to 97% according to Willmott’s tests, and an underestimation of 1.2% was calculated for the data deviation. In agreement with the findings by Ortiz and Mercado (2008), the calculated waves generally underestimated the measured values, and this discrepancy reflected the weak response of the growth equations to the wind input in the SWAN model.

The adjusted time series reliably modeled the different coastal processes, and the results were validated by multiple visual wave measurements in the Puerto Colombia Port between March 7, 2009, and March 10, 2009. The coastal dynamics analyses highlight the necessity for evaluating the magnitudes of currents during periods with high-energy waves because these magnitudes can double during atypical events, such as the cold front discussed herein.

Consistent with the recent study by Ortiz (2012), the findings of the present study indicate that the sector analyzed along the central Colombian Caribbean coast is more susceptible to waves associated with cold fronts than hurricanes. Nevertheless, hurricane events should not be overlooked. Similar to the waves generated by the cold front event analyzed in this study, the waves generated by hurricane events also correspond to a high percentile (99th and 70th percentiles, respectively) of the cumulative probability distribution.

Finally, the methodological approximation presented in this study, which couples two types of spectral wave propagation models (the SWAN and CMS-Wave models), facilitates an improved calculation precision because of the advantages of both numerical approximations.

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LITERATURE CITED


