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Hatteras Breach, North Carolina

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) is intended to document the rapid response of the U.S. Army Corps of Engineers to engineer and construct a breach closure and the lessons learned. The note also documents the short-term morphologic evolution and hydrodynamic characteristics of the breach based on an analysis of collected data. Researchers are utilizing this important data set in the development of numerical models of coastal breaching and to further the Corps' understanding of the breaching process.

BACKGROUND: Hurricane Isabel made landfall along the North Carolina Outer Banks on 18 September 2003. The eye came ashore between Cape Lookout and Ocracoke Island, near Drum Inlet. Isabel was a Category 2 storm on the Saffir-Simpson scale with maximum winds of approximately 100 mph and produced storm surges 6.5 to 8 ft above normal tide level near the point of landfall. The storm breached Hatteras Island about 6 miles northeast of Hatteras Inlet between the villages of Hatteras and Frisco (Figure 1). The Hatteras breach quickly widened to an overall width of over 1,500 ft. The breach contained two "breach islands" that formed three distinct breach channels (Figure 2). The eastern-most channel was in alignment with a relict channel on the sound side, which connected the breach to the main body of the sound. The relict channel may have been formed after a breach occurred at this location during a storm in 1933. A bridge was being built over this new inlet in the 1930s, but the inlet closed naturally before the bridge was finished and construction was stopped.

This section of Hatteras Island is characterized by having medium-fine sand from the mean high water (MHW) line to 6-ft depths. The average significant wave height, as determined by the Wave Information Study (WIS) Level 3 for 10 years (1990-1999) at sta 262, is 3.6 ft with a standard deviation of 2.3 ft. Mean wave period is 6 sec with a standard deviation of 2.4 sec, and the predominant wave direction is from south to southeast. The mean tide range in this area, measured at the Cape Hatteras Fishing Pier, is 3.05 ft and spring tide range is 3.53 ft.

A coastal breach is a new opening in a narrow landmass such as a barrier island that allows water to flow between water bodies on either side of the barrier. Unintended breaches occur around the coast of the United States each year and are a serious concern in developed areas or areas of critical habitat (Kraus and Wamsley 2003). The Hatteras breach destroyed utility infrastructure and severed North Carolina Highway 12 (NC12), isolating Hatteras Village from the rest of Hatteras Island. Parking lots and buildings near the breach were also destroyed. NC12 is the only transportation route east from the village. The village was without electricity, water, food, and medical supplies, which had to be ferried 5 miles from Frisco, NC. Eventually temporary power and water lines were installed and a ferry service, using commercial fishing boats, was set up for residents. But access for tourists, which fueled the local tourist industry, and the transport of

needed rebuilding supplies, could not be restored until the breach was closed and the road rebuilt.

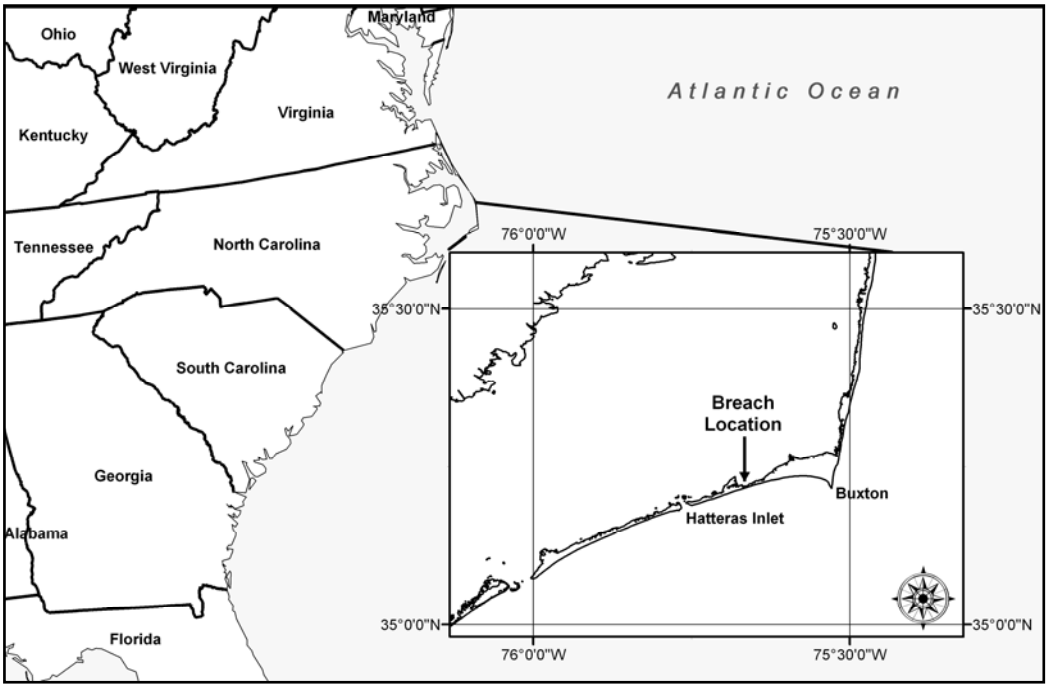

Figure 1. Location map for Hatteras breach.

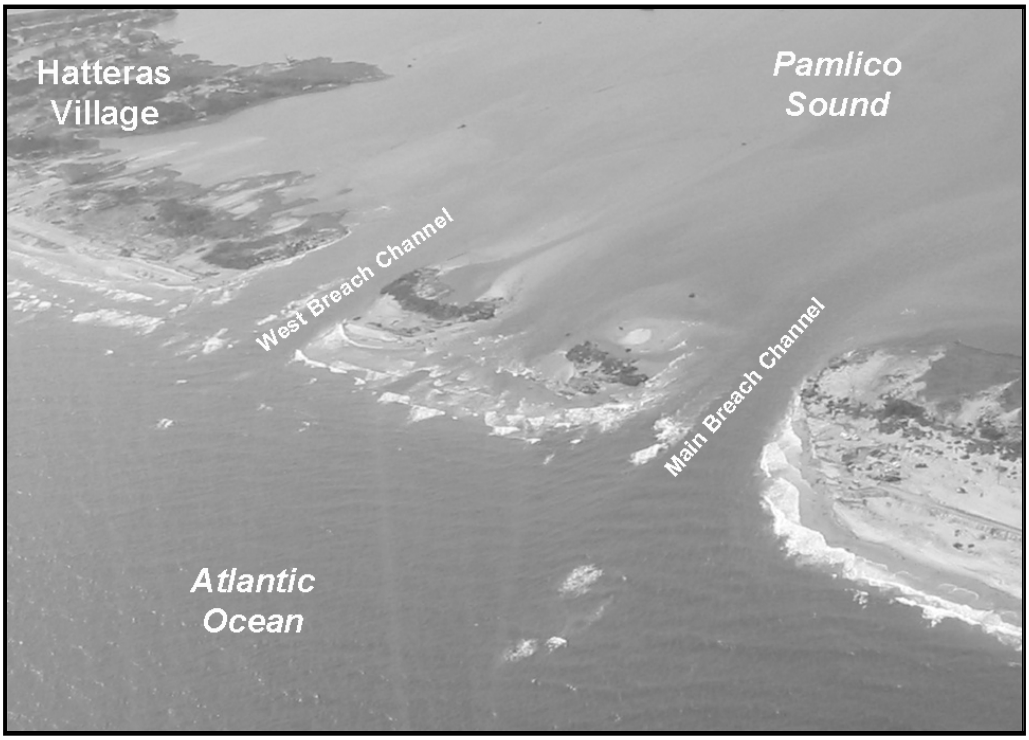

Figure 2. Hatteras breach, 22 September 2003.

On 20 September 2003, the Federal Emergency Management Agency (FEMA), along with the local sponsor, the North Carolina Department of Transportation (NCDOT), requested the U.S. Army Engineer District, Wilmington to reestablish the land connection to Hatteras Village. By 23 September, the Wilmington District had issued a letter contract to the Great Lakes Dredging and Dock Company and simultaneously began the surveying, geotechnical investigations, environmental coordination, engineering design, and contractual requirements.

To close the breach in an expedient and environmentally sound manner required interagency cooperation, coordination, and communication. A breach closure team, with members from the Corps, FEMA, NCDOT, U.S. Fish and Wildlife Service, North Carolina Department of Environment and Natural Resources, Coastal Area Management Agency, and the National Park Service, which oversees the Cape Hatteras National Seashore where the breach was located, held daily phone conferences and exchanged data via the internet. Representatives from NCDOT and the National Park Service were assigned to the Wilmington District to assist in formulating the design and environmental features of the breach closure. Team members participated in phone conferences from the breach site providing real-time information on endangered species habitat. The interagency cooperation allowed elements of the plan to begin before major design features were finalized and permitted. For example, the dredge and dredge pipe were being transported to the breach site before the borrow area and pipeline route were established. The Wilmington District completed the breach closure just 56 days after it opened on 18 September.

Despite the potential societal and environmental costs associated with breaches, relatively little information is known on the physical processes of breaches. The Hatteras breach was in close proximity to the U.S. Army Engineer Research and Development Center's (ERDC's), Field Research Facility (FRF), which provided an opportunity to study large breaches of barrier islands. With funding provided by the Inlet Geomorphology and Channels Work Unit of the Coastal Inlets Research Program (CIRP), ERDC, Geodynamics, LLC was contracted to conduct high-resolution surveys of the breach. The surveys produced needed data on the hydrodynamic and morphologic evolution of barrier breaches. The surveys not only qualitatively describe the course of breach evolution, but also provide quantitative data for numerical models of coastal breaching under development by ERDC. The data also provided information to assist in engineering the breach closure.

Two topographic and shallow-water surveys were conducted to capture the short-term temporal changes in breach morphology. The first survey was conducted over 3-5 October 2003. A single multi-beam survey was conducted on 5 October. The second survey was conducted from 13-16 October. The bathymetry surveys of the breach channels, margin shoals, and flood shoal were performed with a Real-Time Kinematic (RTK) Global Positioning System (GPS) Waverunner survey system. The system is designed for shallow-water applications and can reach areas not accessible with more conventional survey methods. Topography was surveyed with an RTK-GPS system to clearly identify the shoreline of the beach and breach edge. The "breach islands" in the middle of the breach were also topographically surveyed to capture their slopes and shorelines. The multi-beam survey measured the size and extent of the ebb shoal and also surveyed the main breach channel. Freeman et al. (2004) give a complete discussion of the survey plan and techniques.

During the first survey period, drogues were timed to estimate surface currents through the main breach channel. Drogue measurements were made at various times throughout the tidal cycle over 4-6 October 2003. The current was also measured with an Acoustic Doppler Current Profiler (ADCP) in the breach during two field deployments. The first current survey took place over 16-17 October near the time the second morphology survey was being conducted. The current was surveyed again on 24 October. Water levels were also recorded near the breach on both the Atlantic Ocean side and the Pamlico Sound side from 3 October to 12 November 2003.

BREACH FORMATION: Breaching potential is maximized if a barrier is low and narrow. Narrowing of the barrier results from shore erosion on either the ocean or bay/sound side. Lowering of the barrier results from dune degradation. Several causes of dune degradation can be identified, including fixed footpaths for beach access, seepage, undercutting and failure from wave attack, and wave overtopping. The narrowing and lowering of the barrier creates localized low profiles in the dune system. When water levels are elevated, inundation occurs and water begins to flow through the localized low areas. Once the dune crest is submerged, erosion occurs rapidly and can be catastrophic.

After the complete washout of the dune, a breach widens by erosion and collapse of the bank and deepens as flow scours the channel. Margin shoals are often formed immediately after breach opening. If the breach scour is sufficiently deep, water flow can occur between the two water bodies on each side of the barrier, even after the storm subsides. Tidal flow then continues to widen and deepen the breach channel. If the breach flow is strong enough to flush littoral drift-derived sediments from the breach faster than it is introduced, the breach is maintained and a tidal inlet formed. The flushing of sediment by the tidal current may create an ebb and/or flood shoal.

Hatteras Island was breached by elevated water levels and wave attack from the ocean side. The breach occurred at known erosion hotspots where the barrier is approximately 500 ft wide, one of the narrowest sections along Hatteras Island. The long-term shoreline recession rate at this location is about 3 to 4 ft/year (Overton and Fisher 2004). Airborne LIDAR surveys by the U.S. Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) show that the breach occurred not only at a location of minimum island width, but also at a minimum of island elevation (Sallenger 2004). The primary cause of the low dune elevations is likely wave attack as a result of the receding shoreline. However, beach access may also have contributed. The breach occurred near a parking lot for beach goers. Dunes at access points are often lower due to foot traffic. If possible, coastal managers should discourage beach access at narrow regions of barrier islands and establish access points where the barrier island is wide.

The narrowing and lowering of Hatteras Island at this location weakened the barrier and subjected it to breaching. Evidence of powerful overtopping water flow was observed at the breach. Brush and other vegetation adjacent to the breach channels were matted and flattened toward the Pamlico Sound by overwashing flow (Figure 3). Channelization at the lowest points in the barrier scoured the breach channels.

Figure 3. Matted vegetation flattened toward Pamlico Sound by strong overwashing flow.

BREACH MORPHOLOGY AND SHORT-TERM EVOLUTION: The morphology and short-term evolution of the breach were examined through spatial surface analysis of three-dimensional digital elevation models (DEMs) created with high-resolution topographic and bathymetric data. Depths over the ebb shoal were collected on 5 October, in addition to the surveys of 3-5 October (Survey 1) and 13-16 October (Survey 2). Survey 2 had best coverage of the nearshore region just seaward of the breach openings and, combined with the ebb shoal data, provides the most comprehensive data set. Figure 3 is a DEM created for illustrative purposes from Survey 2 data combined with the multi-beam ebb shoal data. Three breach channels, separated by breach islands, are well defined. The breach islands were not washed away because of resistance of peat outcroppings that fronted the islands on the ocean side (Figure 4). The peat acted as an erosion-resistant barrier, revetting the island at this location. The broad peat terrace extended from the eastern-most breach island, across the middle breach channel and west breach island (Figure 5).

Figure 4. Western edge of peat terrace, looking southeast. Peat extends approximately 1.5 to 2 ft above the adjacent sandy bottom.

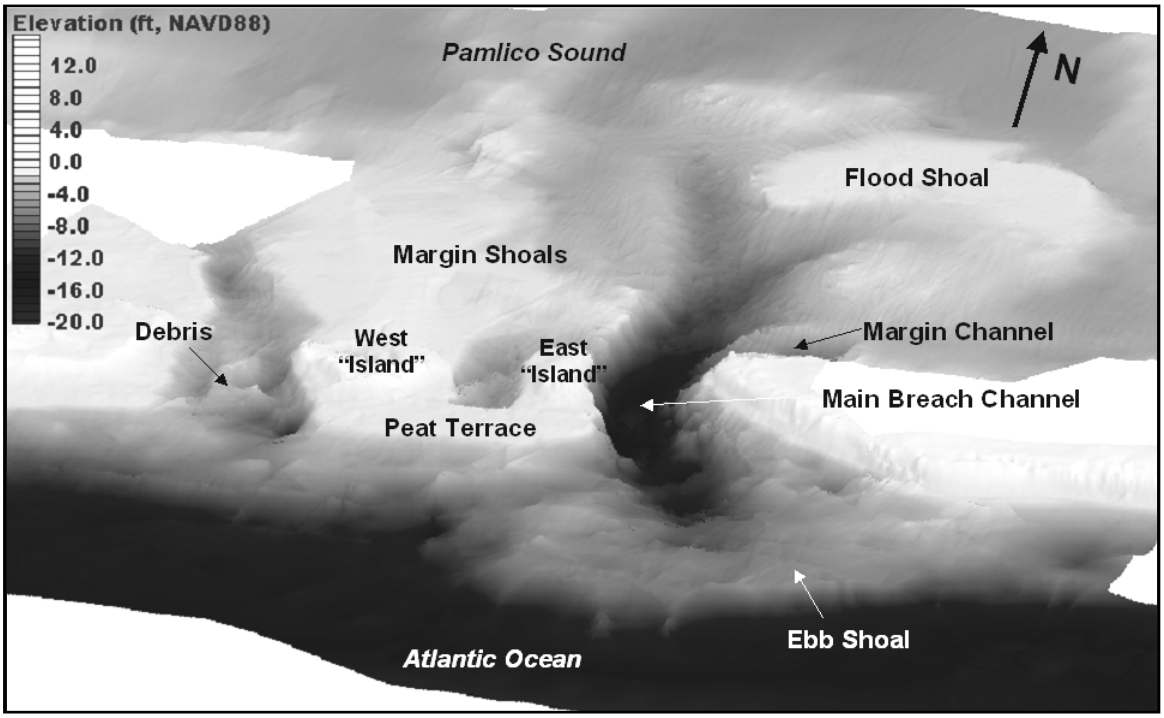

Figure 5. Digital elevation model of Hatteras Breach.

The peat terrace restricted flow in the middle breach channel, which was about 225 ft wide. Water flowed through the middle channel and over the peat terrace only at higher tide elevations. The restricted flow resulted in little scour of this channel. Maximum depths in the middle channel were about 5 ft NAVD88 (1988 North American Vertical Datum). The west channel was about 350 ft wide and littered with debris (Figure 6). Pilings from the bridge partially constructed in the 1930s extended across the channel on the ocean side. Large chunks of asphalt and roadbed material were visible at lower tide elevations, particularly on the west side of the channel. Near the center of the channel was a peat outcropping with large chunks of asphalt resting on top. The flow through the west channel was somewhat greater than that of the middle channel. Survey 2 maximum depths in the west channel were 7 to 10 ft NAVD88. The eastern-most breach channel was approximately 325 ft wide on the sound side and 350 ft wide on the ocean side and was the main channel as it captured a majority of the tidal prism. The unrestricted flow through this channel created scour depths down to 20 ft NAVD88.

Figure 6. West breach channel, looking east, 5 October 2003. Note old bridge pilings on right and extensive road debris in channel.

The flood shoal is readily identifiable in Figure 5. The Survey 1 DEM showed that a flood shoal formed within 2 weeks after the breach opened with the centroid approximately 1,750 ft from NC12. The shallowest water over the flood shoal was less than 0.5 ft NAVD88 and had to be surveyed by wading, as depths were too small even for the waverunner system. The second survey showed little growth of the flood shoal. A volumetric analysis indicates that the flood shoal gained on the order of 10,000 cu yd of sand over the 10-day period. A well-defined ebb shoal also formed by 5 October (Figure 5). The ebb shoal extended offshore as far as 1,250 ft from the former location of the highway. Depths over the ebb shoal were 4 to 6 ft NAVD88. Waves were often observed breaking on the ebb shoal.

The DEM analysis indicates rapid morphology change. Figure 7 is a comparison plot of breach cross sections from Surveys 1 and 2. Comparisons are made only where sufficient coverage of the channel was captured by both surveys. Due to debris and wave conditions, the seaward end of the west breach channel was not measured in Survey 1. As Figure 7 shows, there was little change in the west channel, because of the substantial amount of armoring by debris and peat. Flow velocities were significantly weaker than observed in the main channel. The sound end of the middle channel shoaled approximately 2.5 ft in the 10 days between surveys. The sediment likely originated at the margin shoals on the sound side and could not be flushed out by flow restricted by the peat terrace. The central and seaward portions of the middle channel did not change between Surveys 1 and 2.

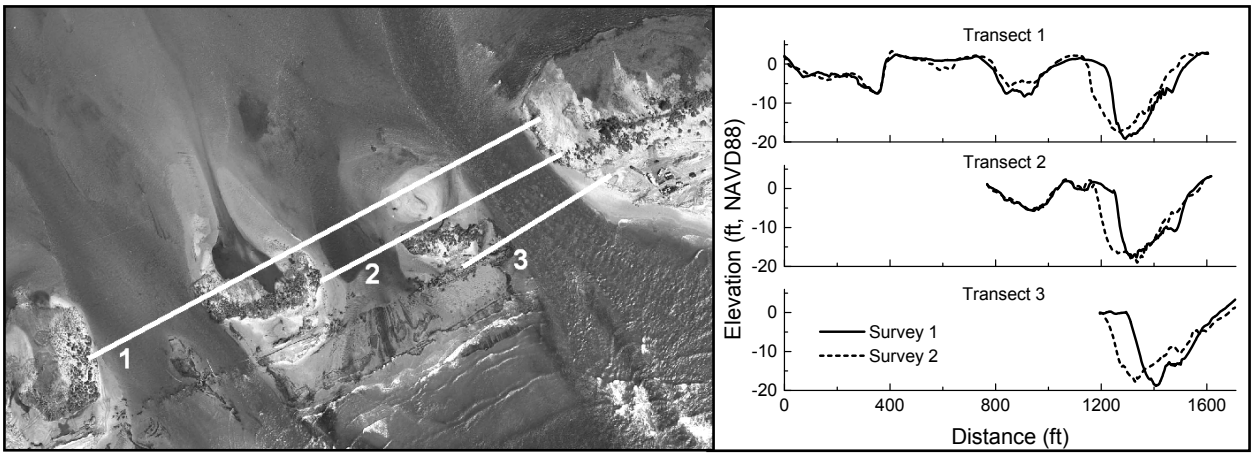

Figure 7. Comparison of Survey 1 and Survey 2 breach channel cross-sections (NCDOT photograph).

The main breach channel experienced the greatest amount of change. Defining breach width as the distance across the channel between the NAVD88 0-contour (which corresponds to +0.44 ft mean sea level), the breach widened by approximately 125 ft on the ocean side, 65 ft through the middle part of the channel, and 25 ft on the sound side. From the center of the barrier toward the sound, the main channel migrated approximately 20 ft to the west over the 10-day period while on the ocean side the channel migrated over 80 ft to the west. The average channel depths were maintained and maximum channel depths generally increased through the middle part of the channel and decreased on the sound side over the 10-day period. The average cross-sectional area of the breach channel increased from 3,400 to 4,000 sq ft.

Figure 8 is a comparison of the 0-contour (NAVD88) between Surveys 1 and 2. The recession of both channel banks at the ocean end of the breach is evident. The east bank receded 25 to 45 ft while the west bank moved 40 to 80 ft. On the sound end of the breach channel, the east bank advanced approximately 25 ft, pushing the channel to the west. This end of the channel also continued to widen, however, as the west bank receded about 45 ft.

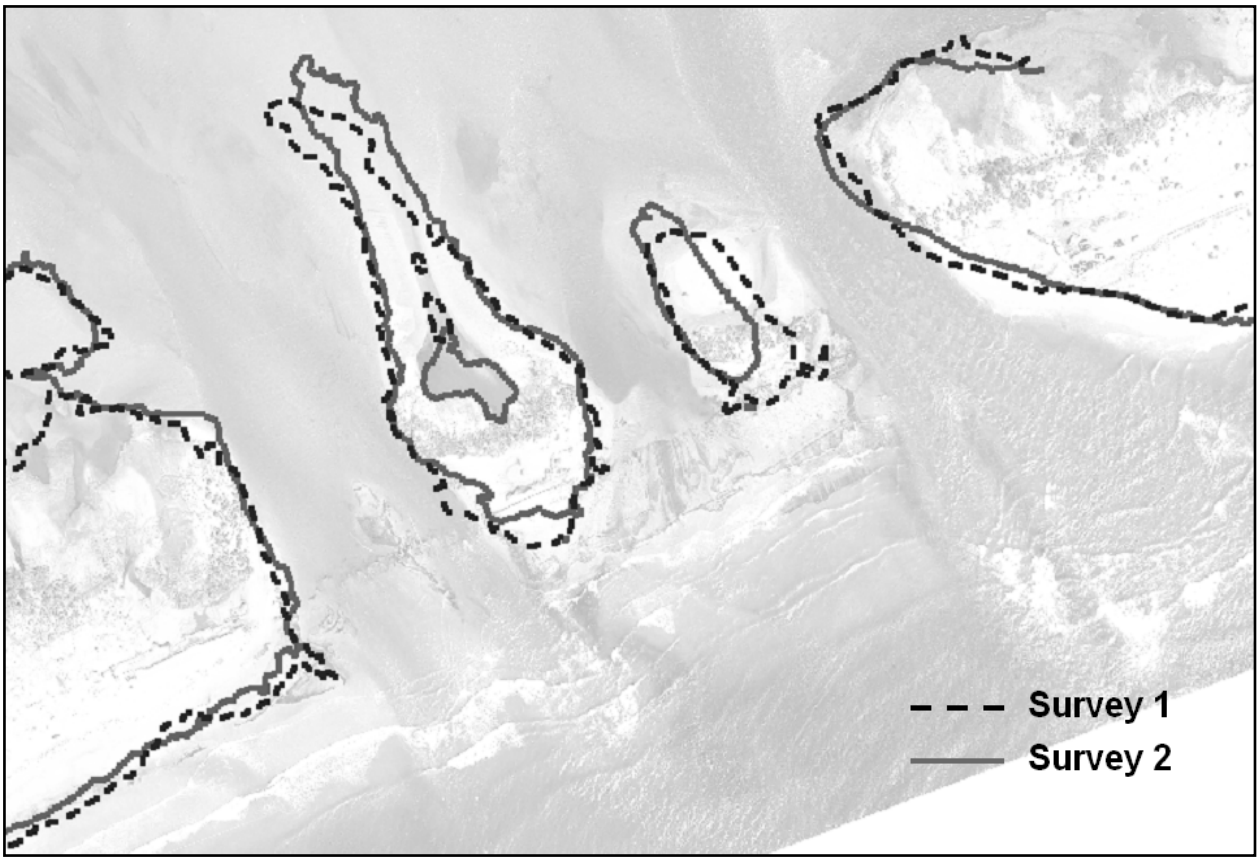

Figure 8. Comparison of the 0-contour (NAVD88). Aerial photograph was taken on 24 September, tide elevation -1.3 ft NAVD88 (NCDOT photograph).

The prograding shoulder of the barrier island was supplied sediment from the ocean end of the breach bank and the sound side of the barrier island. A strong current was observed in the margin channel on the east side of the breach. Bank erosion was easily observed at this location. As the tide fell, a scarp formed on the sound side of the barrier. During lower tide elevations, the strong flow removed sand from the base of the scarp until a tension crack formed, leading to mass failure. The sandy bank material slumped into the margin channel, moving down the bank slope where the tidal current carried it downstream. At higher tide elevations, the scarp became submerged and was smoothed by the current flow and wave action. Recession of the 0-contour as a result of this process is seen in Figure 8. The maximum shoreline recession measured over the 10-day period at the margin channel was approximately 20 ft.

Figure 8 illustrates the elongation of the margin shoals behind both breach islands. The east island shoal advanced approximately 65 ft. The west island shoal migrated in a northerly direction and also elongated by approximately 65 ft. The 0-contour on the front side of each island receded. This recession, however, was not from erosion of the peat terrace. The peat terrace elevation was below 0 NAVD88, and the sandy material on top eroded during higher tide elevations.

Figure 8 also shows beach shoreline change within about 500 ft of the breach. On the west side, the beach eroded approximately 35 ft. Sediment supplied by longshore transport advanced the

shoreline to the east by as much as 55 ft within about 425 ft of the breach channel. The beach tended toward erosion at greater distances from the breach.

WATER LEVEL MEASUREMENTS: Water level differences between the sound and ocean drove the currents that maintained the breach. Two Seabird SBE-26 gauges were installed to measure water levels in the sound and ocean from 3 October to 12 November 2003. The sound gauge was deployed approximately 1,650 ft north-northeast of the breach in a water depth of 4 ft NAVD88. The sensor on the gauge was at approximately 2.3 ft NAVD88. The ocean gauge was attached to a piling near the seaward end of the damaged Cape Hatteras Fishing Pier in Frisco, NC. The pier gauge was 1.4 miles east-northeast of the breach where the nominal depth was 10 ft NAVD88, and the sensor was located at a depth of 5.6 ft NAVD88. The tide gauges sampled pressure at 4 Hz and recorded a mean value at 10-min intervals. Temperature and conductivity were also measured, from which salinity and density were computed. Water level was adjusted for variations in density. For shallow water, the corrections were small (~ 0.03 ft) compared to elevation differences (~ +/- 1.6 ft).

The measured water level (head) difference between the ocean and sound are plotted in Figure 9. Water level head differences exceeding 2.3 ft were observed on both flood and ebb currents. Water levels for the pier, sound, and the head difference from 14-18 October are plotted in Figure 10 along with wind measurements from the Hatteras Weather Service (Mitchell Field, 2.5 miles east of the breach). Wind contributes to head difference, particularly in determining sound water levels. Pamlico Sound, having a large surface area and shallow water, can experience large wind-driven setup. On 15 October, the wind switched from having a west component to an easterly component, resulting in setup in the sound and a large negative head (ocean levels lower than the sound) of -3.1 ft. There was a gap in the wind data on 15 and 16 October, but based on measurements at the FRF (66 miles north of the breach), the wind continued to be directed toward the east and south, favorable for setup in the southeast corner of the Pamlico Sound near the breach. As a result, a nearly continuous ebb current flowed for approximately 32 hr.

CURRENT MEASUREMENTS: The current through the main breach channel was estimated by timing surface drifters during Survey 1 and measured with an ADCP during two field deployments, the first of which coincided with Survey 2. Drogues were timed during the flood tide on 4 October and during ebb tide on 6 October. Surface current velocity was estimated from these measurements, as listed in Table 1.

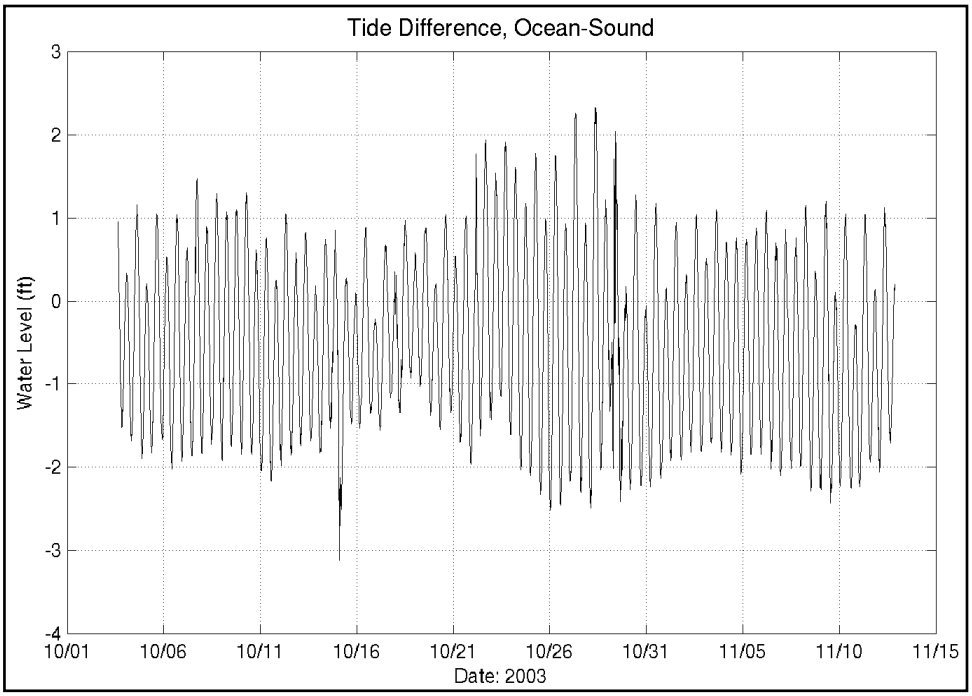

Figure 9. Pamlico Sound and ocean water level difference, 3 October to 12 November 2003.

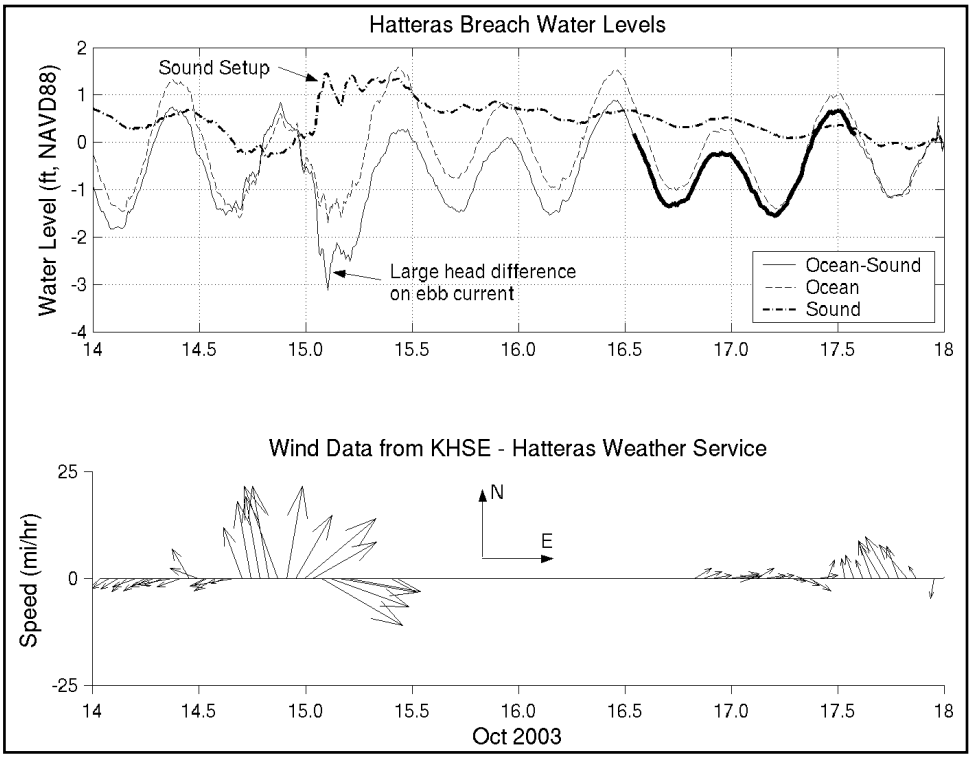

Figure 10. Ocean and sound water levels, head difference, and wind vectors. Bold line indicated times when bottom mounted ADCP was operational.

Table 1. Surface current velocity estimates.

Day, October 2003	Time(EDT)	Velocity(ft/sec)	TideStage
4	1247	1.6	Flood
4	1307	2.9	Flood
4	1340	4.9	Flood
4	1432	6.9	Flood
4	1514	7.2	Flood
4	1549	7.5	Flood
4	1707	5.2	Flood
4	1743	4.3	Flood
4	1836	~0	Slack
6	0808	3.9	Ebb
6	0847	4.6	Ebb
6	0919	5.9	Ebb
6	0955	6.2	Ebb
6	1022	6.2	Ebb
6	1053	5.9	Ebb
6	1149	5.6	Ebb
6	1233	4.9	Ebb
6	1307	4.6	Ebb

The ADCP measurements were on 16, 17, and 24 October 2003. During the first deployment, a bottom-mounted ADCP was placed approximately midway along the channel where the surface currents appeared to be the strongest and where the channel was deepest according to previous bathymetric surveys. The ADCP was an RD Instruments (RDI) WorkHorse Monitor (1,200 kHz) and was fixed at a nominal depth of approximately 17 ft. The ADCP operated for 25 hr from 16 October 1300 EST to 17 October 2003, 1400 EST. Cross channel ADCP transects were also made from an instrumented Zodiac inflatable boat on 16, 17, and 24 October. The ADCP employed for the transect measurements was also a 1,200 kHz WorkHorse Monitor. ADCP data were collected with RDI WinRiver software set to sample at 5 Hz but was only able to maintain approximately 2.5 Hz. The program was configured for 1.31-ft range bins and also acquired serial data outputs from an echosounder and RTK GPS unit. The echosounder (Knudsen 320B Echosounder) operated at 200 kHz and a nominal sound speed of 4,921 ft/sec, with sampling rate of 5 Hz. The roving GPS was a Trimble 4700 equipped with a Compact L1/L2 antenna. The base station was a Trimble 4000SSE. Surveys were RTK with approximately 0.07 ft accuracy in both the horizontal and vertical. GPS coordinates were interpolated in post-processing to match the ADCP sampling rate. Echosounder data were sub-sampled by the WinRiver collection program because it only retains the most recent depth sample after the ADCP sample. The small mismatch in sampling times was not significant for this study.

Transect lines were chosen along three locations: approximately at the ocean end of the breach, near the middle, and on the sound side (Figure 11). The Zodiac crabbed (at an angle to the current) across the breach at a best attempt of constant speed, with each transect taking 2 to 3 min. Typically, two or three transects were made at each location before proceeding to the next line. Approximately 140 total transects were completed during both deployments. In addition, 12 current measurements were made using the boat as a drogue and currents computed from the recorded GPS time and position.

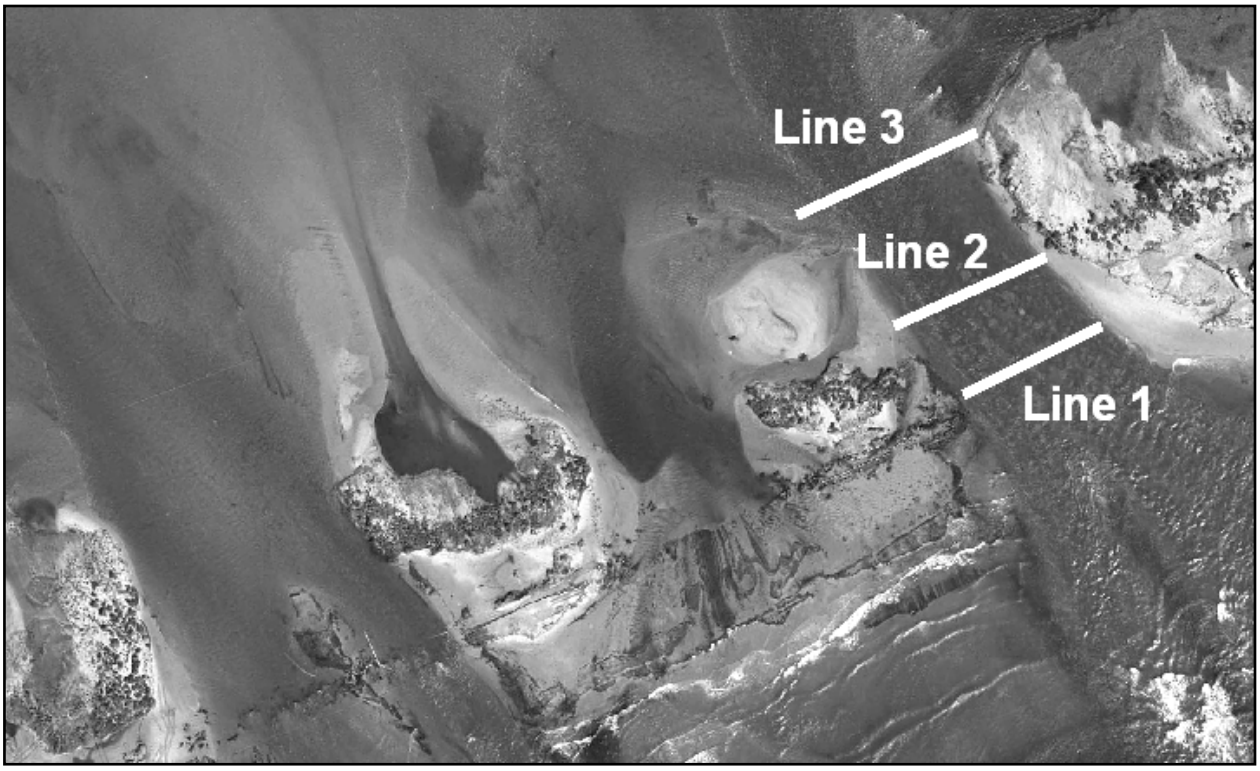

Figure 11. Approximate location of ADCP transects (NCDOT photograph).

The current velocity was calculated by averaging measurements from the repeated transects at each location. A best-fit line was computed (least square linear sense) for each group of transects. Current velocity measurements were then averaged at 16.4-ft intervals along the computed transect line using measurements within 16.4 ft (horizontally) of the interval coordinate. Current velocities were not averaged vertically, maintaining the 1.31-ft vertical spacing.

An example of an averaged ADCP ebb current transect is shown in Figure 12 for Line 1 on 16 October. Strongest currents are to the west (left) of the channel center. Ebb current transects for Line 2 indicate that the strongest currents tend towards the channel center. On Line 3, the strongest currents are observed to be east of the channel center and sometimes have two distinct maxima, one that parallels the main channel and another from the margin channel on the northeast side of the breach. This preliminary analysis of ADCP transect data corresponds to visual observations of surface currents, namely, that on ebb flow two distinct currents merged at the breach, and on flood flow there was a strong current through the main channel with a more diffuse current spread out over the area between the flood shoal and margin channel.

The collected morphologic and current data provide both qualitative and quantitative descriptions of breach evolution and are being applied in the development of numerical models of coastal breaching.

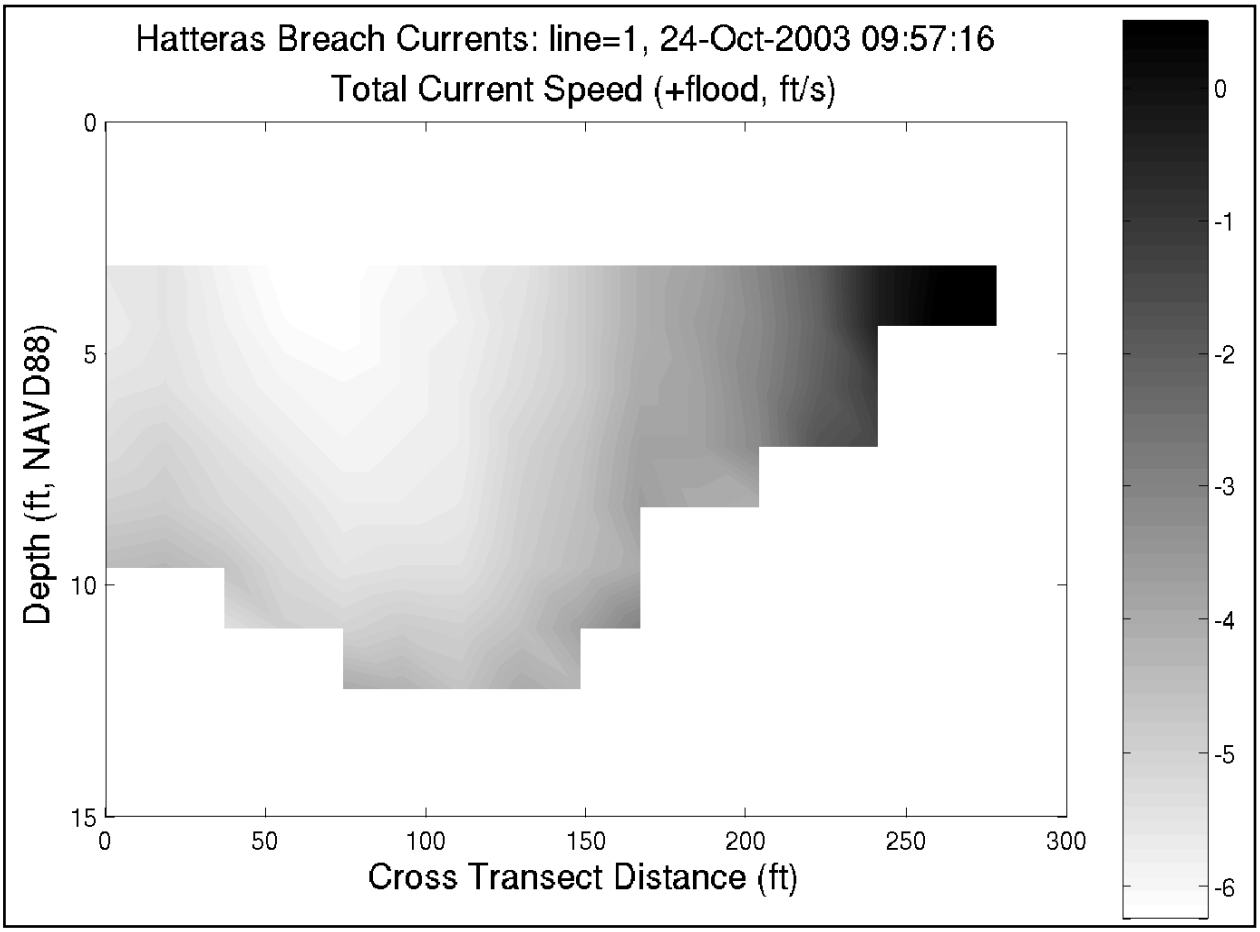

Figure 12. Example ADCP current transect at line 1.

CLOSURE DESIGN: The design criteria for the breach closure project were to build a berm along the alignment of NC12 of sufficient width to allow the reconstruction of the highway and to build a dune system similar to the pre-storm condition. The design was based on a Wilmington District breach closure in 1962 that was 10 miles to the north. The 1962 breach was referred to as Buxton Inlet and was opened on 7 March 1962, during the "Ash Wednesday Storm." Buxton Inlet was 1,650 ft wide and had a maximum depth of -12 ft NGVD (Figure 13). Two 16-in. dredges, with 1,160 hp and 1,600 hp, were employed in the Buxton Inlet closure. Each dredge was capable of pumping 9,000 cu yd a day from a borrow area located in the sound adjacent to the breach. Initially, one dredge was used to place fill material on the north side of the breach. The southern bank of the breach appeared to erode as fast as the northern shoulder accreted. Local interests dumped broken culverts, automobiles, etc., on the south shoulder, which seemed to slow the erosion. The single dredge pumped for 55 days and was unable to close the breach. When a second dredge was brought on site, the breach was closed within 3 days. A total of 588,000 cu yd were pumped at the time of closure (U.S. Army Engineer District, Wilmington, 1963).

The closure of Buxton Inlet demonstrated that the Hatteras breach could be closed by discharging dredged material into the breach without additional measures, such as the sheet-pile dike used in the closure of the breach on the south shore of Long Island, NY, at Moriches Inlet

(Sorensen and Schmeltz 1982). It also showed that erosion of the opposite shoulder of the breach could pose a problem. Based on the Buxton Inlet pumping volumes, the minimum discharge capacity to close the Hatteras breach was estimated to be between 9,000 and 18,000 cu yd/day.

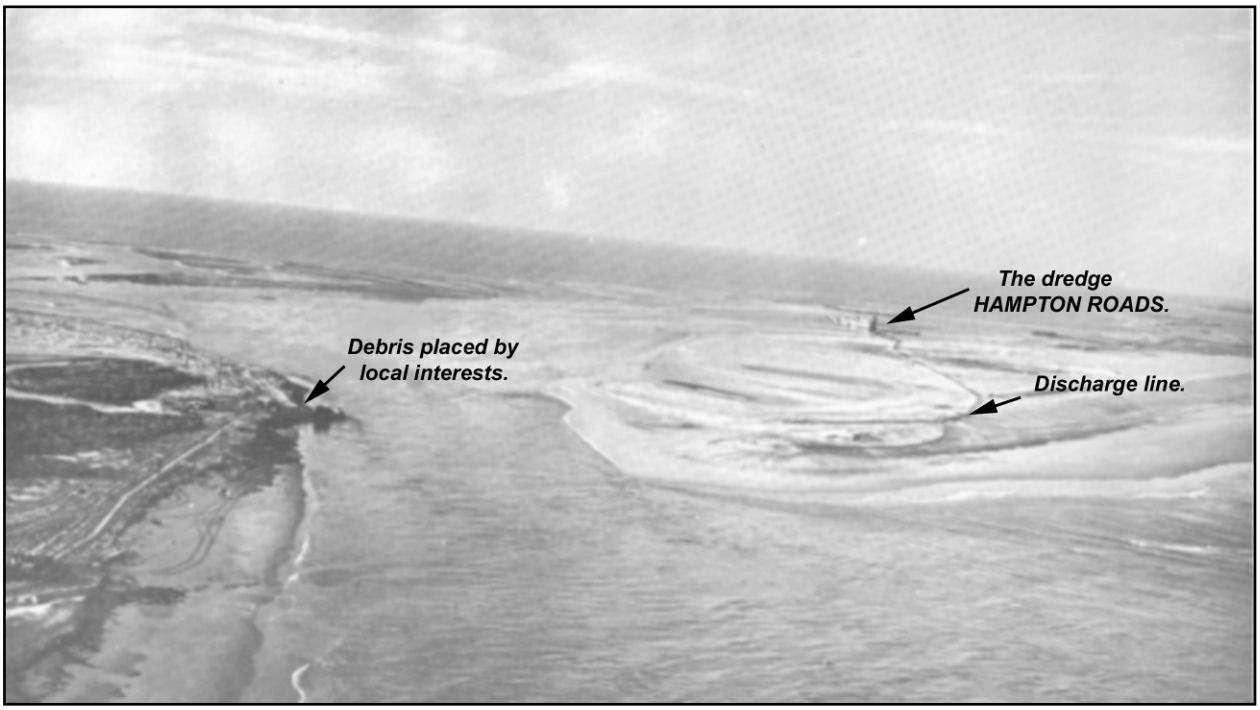

Figure 13. Buxton Inlet, 29 January 1963, looking towards sound.

The borrow area for the Hatteras breach closure were Ranges 5 and 6 of the State ferry channel, which are adjacent to Hatteras Inlet (Figure 14). In order not to disturb bottom habitat, the borrow area stayed within the footprint of the 150-ft-wide channel and went down from the channel's project depth of -12 ft mean low water (MLW) to -22 ft MLW. Sieve tests indicated that the borrow area sand had a median grain size of about 0.28 mm. The fill material was medium-coarse sand, as shown in Figure 15, which was desirable since it would help limit losses during the breach filling operation. The color, compaction characteristics, and low shell content of the borrow material also would not interfere with turtle nesting. A low percentage of fine material made it suitable for generating a low turbidity during placement.

The determination of the pipeline route was a compromise between environmental considerations and operational practicality. The dredge pipeline route needed to be as short and straight as possible to increase efficiency and avoid disturbing vegetation and endangered species habitat. Proposed routes had to be inspected for turtle nests that may have survived the storm and piping plover habitat. The initial locations identified and permitted for the pipeline route to cross over the island were: (1) a washover area located midway between the breach and the end of the island, and (2) the ferry terminal in Hatteras Village. The washover area was already environmentally disturbed by the storm. However, the dredging contractor found that the shallow depths on the sound side of the washover area prevented crane and pipeline barges from reaching the island to offload and lay pipe. Yet, the water was too deep for land-based equipment to reach

Figure 14. Plan view showing borrow area, pipeline route, and breach location.

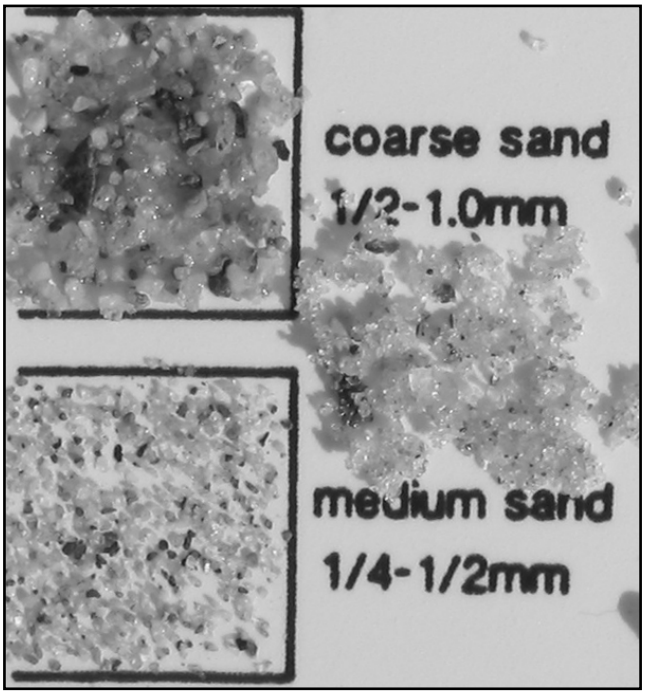

Figure 15. Sand taken from discharge area on sand classification card.

the barges. The alternate crossover site at the ferry terminal was paved, and thus, there was minimal environmental concern. However, the pipeline route at this site would be too circuitous, which would reduce the hydraulic efficiency of the pipeline and the dredge's pumping capacity. A third pipeline route was found, inspected, and permitted. The dredge pipeline route crossed the island near Hatteras Inlet and ran along the ocean beach seaward of the vegetation line (Figure 14). The route was chosen due to the relatively deep-water access at the sound side of the island, which facilitated the pipe laying operation, and its minimal impact on endangered species and vegetation. The maximum length of the 30-in. discharge line was 34,000 ft.

The design cross section consisted of a berm at elevation +7.0 ft NGVD with a 10-ft-wide dune at +15.0 ft NGVD (Figure 16). The berm and dune elevations were chosen to be consistent with the pre-breach elevations. The pre-breach berm elevation was +6.0 ft NGVD and the average pre-breach dune elevation was +15.0 ft NGVD. Factors influencing the width of the berm were that the berm had to contain enough sand to fill the scour channels formed by the breach, the width of the berm had to be at least 100 ft after waves and currents adjusted the fill profile, and the fill had to transition into the adjacent shoreline. To determine the design berm widths, a design template with a berm width of 100 ft was superimposed on a digital terrain map that was generated from surveys. The volume to construct the design template and fill the scour channels was calculated. Construction berm widths that contain the calculated volume of sand were determined and then the widths were adjusted to transition into the adjacent shorelines. The width of the berm varied from 150 ft in the center breach channel to 300 ft in the main breach channel.

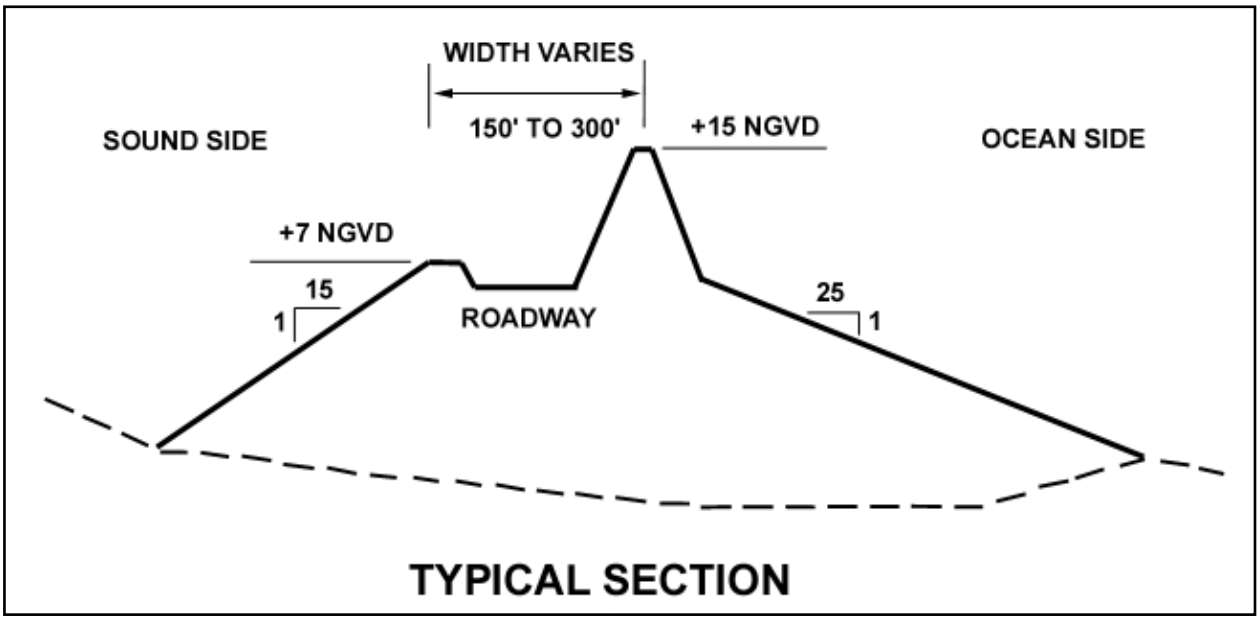

Figure 16. Typical fill cross section.

The dredge selected for the closure was the *Illinois,* an ocean certified 30-in. dredge with 11,300 hp. A 7,200-hp booster pump was also selected. The daily production of this plant would far exceed the minimum range of 9,000 to 18,000 cu yd/day. The filling operation would start at the west breach bank, which was closest to the borrow area. The large production capacity along

with an erosion resistant peat layer at the eastern bank of the breach allowed the design to omit armoring there. The peat layer was 3 to 4 ft thick, several hundred feet wide, and was exposed at low tide as shown in Figure 17. There was broken asphalt near the high-water line of the east bank of the breach, the peat layer extended 20 ft further into the breach than the broken asphalt and did not appear to erode.

Figure 17. Exposed peat layer on eastern bank of breach.

CLOSURE OPERATION: The filling phase of the operation began on 17 October 2003. Two-thirds of the fill width was initially constructed. This shortened the time required to close the breach and reduced the potential for the currents to erode the advancing fill. The discharge pipe outlet was laid on the west bank of the breach along the center alignment of the fill and directed towards the breach. Sand that accumulated at the discharge pipe outlet was shaped by two bulldozers according to the fill template. The sand was never directly discharged into the breach. Sheet flow, created by the discharge from the dredge pipe, carried the sand into the breach (Figure 18). After the design template at the discharge pipe outlet was constructed, additional pipe was laid on the newly filled section and the discharge pipe outlet was advanced. This procedure continued for 15 days. The first two channels of the breach were filled without a noticeable reduction in the rate of advancement of the fill. Three-quarters of the main breach channel was

also filled during this period. The dredge averaged 15 hr/day of pumping time with a production rate of 22,000 cu yd a day. The largest production in a 1-day period was 41,000 cu yd.

Figure 18. Discharge at western shoulder of breach. View is towards northeast. Island dividing west and center breach channels is in background.

On 1 November 2003, at 9:30 a.m., the tide was low and there was 75 to 100 ft of the breach remaining to be filled. As the cross-sectional area of the breach was reduced, the current velocities increased to the point where much of the sand that was deposited at slack tide was disbursed when the tidal currents strengthened. To facilitate a rapid advance of the fill and close the remaining portion of the breach, the dredging contractor decided to push a narrow mound of sand across the breach at slack tide and stop the water from flowing through the breach. Once the flow of water was stopped, additional material could be added to the narrow mound to fill the remaining design template without the losses caused by the tidal currents. Therefore, the filling procedure was changed from an unconfined discharge, which filled about 150 ft of the design template width, to a new procedure that confined the discharge so that only 20 ft of the design template width was filled. To confine the discharge, two sand dikes about 50 ft apart were constructed on either side of the discharge pipe (Figure 19). The two dikes protected the sand that accumulated at the discharge pipe outlet from erosion due to waves and currents and directed the growing mound across the breach. The distance between the sand dikes needed to be wide enough to allow the bulldozers to maneuver while they pushed the accumulating sand onto the dikes to advance them across the breach. No material was stockpiled in advance of the start of this procedure but the dredge production rate had been as high as 2,300 cu yd of sand in an hour, which provided a sufficient source of sand to build a small dike across the remaining breach.

Figure 19. View of first attempt to complete closure looking to west from eastern bank of breach.

Applying the new procedure, the remaining breach was narrowed to approximately 50 ft in 1.5 hr when at 11:00 a.m. the shaft on the booster failed. The booster was repaired by 4 p.m., but during the 5 hr of inactivity, the dikes, which were as long as 50 ft, were now 10-ft stubs. At 4 p.m., the slack of high tide, another attempt was made to close the breach with the same procedure. At 5:30 p.m., the two dikes were again approximately 50 ft long. This was a sufficient dike length to protect the discharge area from waves and currents and only one of the dikes was extended further to close the breach. As the tide fell and the ebb currents increased through the breach, progress slowed but, at 8:40 p.m., on 1 November 2003, the breach was closed. Throughout the night, the narrow section of the berm was widened to prevent it from breaching during the next high tide. At closure, approximately 300,000 cu yd had been dredged (Figure 20).

As mentioned previously, only two-thirds of the design berm width was constructed to close the breach. With the breach closed, the dredge pipe was disassembled and the discharge pipe outlet was reassembled at the original west bank. From this location, the filling of the seaward third of the design template was begun. While the seaward third of the template was being filled, a contractor for NCDOT began laying the base course for the rebuilding of NC12. Filling of the design template was completed on 13 November 2003. The contractor was credited with dredging 482,685 cu yd. Surveys of the breach area indicate that 442,600 cu yd were placed in the breach area. Therefore, sand losses were approximately 8 percent. The sand losses were low compared to beach nourishment projects, which typically range from 10 to 20 percent. The low losses are attributed to the medium-coarse sand that resisted the dispersing forces of the waves

and currents during placement. The rebuilding of NC12 was completed on 18 November 2003, with the first vehicle driving over the breach area at 3:00 p.m.

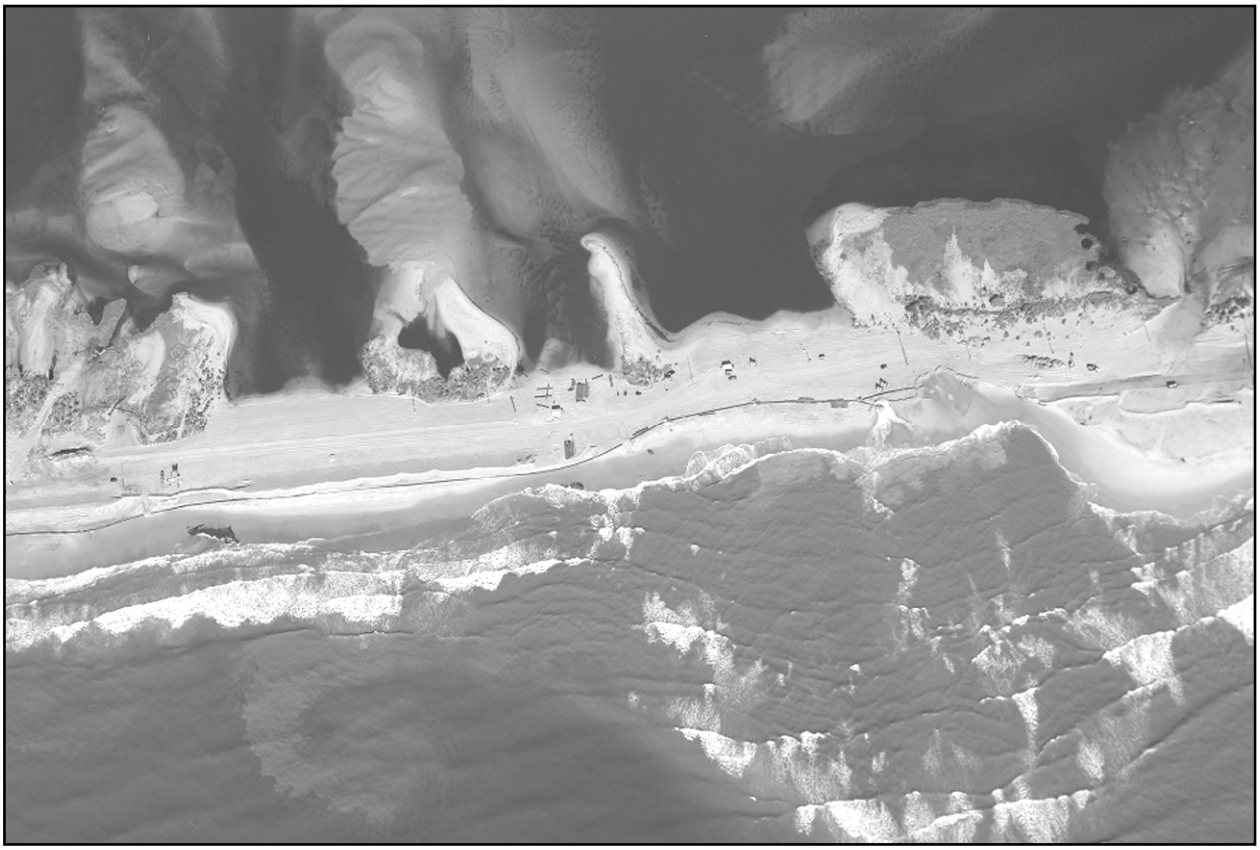

Figure 20. Aerial photo of closed breach on 3 November 2003.

CONCLUSIONS: Hurricane Isabel breached Hatteras Island by a combination of elevated water level and wave attack from the Atlantic Ocean side about 6 miles northeast of Hatteras Inlet. The breach occurred at a location of minimum island width and elevation. The close proximity of the breach to the FRF provided a unique opportunity to study breaches. As described in this paper, the breach was surveyed to provide data on the hydrodynamic and morphologic evolution of barrier island breaches.

Two topographic and shallow-water surveys were conducted 10 days apart to capture short-term temporal changes in the breach morphology. A flood shoal formed within 2 weeks after the breach occurred. A well-defined ebb shoal also formed during that period. Comparisons of the two surveys indicate rapid morphology change of the main breach channel. The main channel widened by as much as 125 ft and migrated to the west. Average channel depths were maintained and maximum depths increased through the middle part of the channel and decreased on the sound side over the 10-day period. On the west side of the breach, the beach eroded approximately 35 ft. Sediment supplied by longshore transport advanced the shoreline east of the breach by as much at 55 ft within about 425 ft of the breach channel. The beach tended toward erosion at greater distances to the east.

Water level was measured on the ocean and sound side of the barrier. Current velocity through the main breach channel was estimated by timing surface drifters and measured with an ADCP during two field deployments. Maximum current velocity was on the order of 7 ft/sec. On the Pamlico Sound side of the breach channel, the strongest currents were located east of the channel center line, tended to the center through the middle part of the channel, and were located west of the channel center line on the ocean side. The ADCP data correspond to visual observations and surface drifter estimates.

The strong currents, rapid morphology change, and substantial amount of submerged and floating debris presented challenges to acquiring the bathymetric and current data. The RTK GPS Waverunner survey system was well suited for this environment. The system is easily transportable and the shallow-water capability enabled data collection in areas inaccessible to many survey platforms. The original plan for the ADCP surveys was to also utilize the Waverunner system. However, the instrument mount on the contractors system was not designed for the additional weight of the ADCP. The mounting of the ADCP on the Waverunner would have provided greater flexibility and coverage for the ADCP survey.

From the time the breach was opened on 18 September 2003, it took 5 days to award a breach closure contract, 44 days to fill the breach, 56 days to complete the construction of the design template, and 61 days to restore the road link to Hatteras Village. This rapid response was due to working simultaneously on the various components of the project and to interagency communication and cooperation.

A procedure to close the breach similar to that applied to the Buxton Inlet closure in 1962 was effective and well suited for the situation. Sand losses were estimated at approximately 8 percent. The closure procedure of initially filling the breach with a reduced berm width from one side without armoring the opposite bank or stockpiling additional sand was made possible by the erosion resistant peat layer on the northern bank of the breach, a dredge with a high pumping capacity, and coarse sand. Also, by beginning the final closure at high tide and completing it at low tide, there were several hours available to widen the berm before waves began to run up on the berm. If the breach were closed at high tide, additional sand would have had to be supplied to replace the sand redistributed by wave action.

While the procedure was effective, requiring only 16 days of pumping to close the breach, there still are lessons that can be learned for future situations where conditions require additional components to the closing procedure:

- If the north shoulder of the breach did not have a peat outcropping, erosion protection in the form of large sand fill bags would likely have been required.

- Stockpiling of sand before attempting to close the final section of the breach would allow the berm to be pushed across faster. There were four bulldozers available for the final push. One bulldozer worked on top of the berm pushing sand to the end of the berm while the others pushed sand to the berm. It appeared that, if sand had been stockpiled, the bulldozers pushing sand to the berm could have been more effective. If sand had been stockpiled on the east side of the breach with a bulldozer, the final closure could have been accomplished from both sides and facilitated the final closure.

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