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Coastal Barrier Island Breaching, Part 2: Mechanical Breaching and Breach Closure

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PURPOSE: The Coastal and Hydraulics Engineering Technical Note (CHETN) herein describes case studies of the mechanical closure and creation of coastal barrier island breaches. Emphasis is on breaches that form near inlets, with examples also given of breach opening for environmental enhancement. Part 1 in this technical note series reviews the causes of breaching and measures to prevent breaching (Kraus and Wamsley 2003). Subsequent technical notes will describe models under development in the Coastal Inlets Research Program (CIRP) for predicting the inception and evolution of breaches.

BACKGROUND: In a coastal context, a breach is a new opening in a narrow landmass such as a barrier spit or barrier island that allows water to flow between the water bodies on each side. Every year around the coast of the United States, breaches occur at barrier islands, barrier spits, and closed river mouths. Breaches occur naturally or they can be purposefully dug or dredged, and a breach may have positive or negative environmental consequences. Unintended breaching of barrier islands and barrier spits is often a serious concern to society.

The U.S. Army Corps of Engineers is routinely called upon to permit coastal breach closing and opening operations. In emergencies, the Corps may take an active role in designing and supervising mechanical closure or opening of breaches. Mechanical cutting of breaches typically requires local, state, and Federal permits. Discharges of dredged material or fill into wetlands or other waters of the United States are regulated by the Corps under Section 404 of the Clean Water Act. The Corps has permit authority under provisions of Section 404 of the Clean Water Act (33 U.S.C. 1344) and under Section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. 403), the latter concerning navigable waters.

Results of breaches may include loss of property due to flooding, wave attack, and erosion; loss of navigability in adjacent inlets sharing the same water body as the breach; destruction of roads, highways, utilities, and other infrastructure; and creation of environmental concern over loss of habitat and unwanted increases or decreases in water level and salinity. Breaches usually enlarge rapidly, increasing the complexity and cost of breach closure construction with time. Therefore, it is often desirable to mechanically close breaches in the most timely and efficient manner possible. Breaches that occur adjacent to or near Federal navigation projects with jetties are of particular concern, and an overview of this situation is given next.

BREACHING ADJACENT TO JETTIES: Jetties interrupt the natural pathway of sediment that is transported alongshore by obliquely incident waves and the associated longshore current. As one geomorphic response, the shoreline adjusts through the redistribution of sediment both near the inlet and, typically, for a considerable distance updrift and downdrift. The distance depends on the length of the jetties and dredged channel, wave height, and balance of net and gross longshore sediment

transport, among other factors. Recession of the shoreline adjacent to a jetty, whether on the ocean side (Kraus and Wamsley 2003) or the bay side (Seabergh 2002), weakens the barrier island and increases breaching susceptibility.

A breach located near an inlet will increase the effective channel cross-sectional area of the combined opening to the ocean, reducing the tidal current through the inlet and its scouring action. Reduction of the tidal current in the inlet is an indirect cause of channel shoaling and increased channel maintenance dredging. Material entering the bay through the breach may be transported into the navigation channel, a direct cause of channel shoaling.

Breaching adjacent to a jetty isolates the structure from land. In addition to exposing the jetty to a potential scouring current and waves that can undermine the structure at the landward end, similar to tip scour common at the seaward ends of jetties, landward access to the structure is lost for inspection and maintenance. Breaching produces an environmental change both locally and regionally through alteration of the horizontal pattern of the tidal and wave-induced current, which can change sedimentation patterns and, possibly, salinity in the bay or lagoon.

Breaching of narrow barrier islands or barrier spits is possible at either the downdrift or updrift beach adjacent to jetties, and selected processes are discussed here, with examples.

Breaching Downdrift of Jetties. Chronic erosion is commonly observed on the downdrift side of stabilized inlets on coasts where there is a strong net direction of longshore sediment transport. The beach between the downdrift jetty and downdrift attachment bar can become isolated from sediment sources in severe cases (Hanson and Kraus 2001). Such is the situation at Shinnecock Inlet, a federally maintained inlet on the eastern end of Long Island, NY, where potential breaching of the downdrift (west) beach has been imminent several times since jetty construction by the county in the 1950s.

Figure 1 shows Shinnecock Inlet in October 1996, with the western beach (left side of jetties) eroded to endanger the public road and the marina complex on the north (bay) side of the barrier island. Emergency measures have been taken by the county and town during severe storms to prevent breaching. The U.S. Army Engineer District, New York, places material dredged from the Federal channel onto the eroding beach segment as a least-cost disposal alternative.

As another example, a downdrift breach occurred at Mattituck Inlet, Long Island, NY, which faces the Long Island Sound. Regional net transport is from west to east on this coast. The Federal jetties at Mattituck were constructed in the early 1900s. The shoreline directly east of Mattituck Inlet receded rapidly during the 1920s and 1930s, and a landward breach at the base of the east jetty at Mattituck Inlet opened in or around 1935, resulting in the formation of a west-directed spit (Figure 2) at the base of the east jetty that protruded into the navigation channel. In response to the breach, the New York District extended the east jetty landward in 1946, and material dredged during this time was placed onto the beach directly east of the inlet, the first known beach nourishment for this location (Morgan et al. 2005).

Figure 1. Shinnecock Inlet, NY, showing severely eroded downdrift beach adjacent to downdrift jetty

Breaching Updrift of Jetties. A porous jetty near the shore or a jetty that does not extend sufficiently landward to avoid flanking will promote erosion of the updrift beach by allowing sediment to enter the inlet through or behind it. In such a situation, the inlet blocks sediment arriving to the updrift beach during times of reversals in longshore transport, whereas a portion of the sediment brought to the beach from the dominant longshore transport direction passes through or around the jetty. The result is that the updrift beach can erode, and the shoreline will recede.

A strong rip current adjacent to the updrift jetty can also remove material from the beach, acting similarly to a porous jetty in causing local beach erosion. If the barrier island adjacent to the spit is narrowed by bank erosion in the tidal channel at the back bay (Seabergh 2002), as was the case at Moriches Inlet, NY, discussed later, or by formation of a headland bay beach as was the case at Grays Harbor, WA, in 1993, then breaching potential is increased during times of high-water level and high storm waves. Such inner bank erosion can occur either updrift or downdrift, or on both sides, of the inlet.

Perdido Pass, FL, is an example of breaching that occurs on the updrift side of the inlet because the jetty does not extend sufficiently landward (Figure 3). The updrift (east) beach adjacent to the east jetty is monitored and filled by the U.S. Army Engineer District, Mobile, to prevent further opening of breaches that occasionally occur there, such as after 2004 Hurricane Ivan.

Figure 2. Mattituck Inlet, NY, with a spit encroaching from east (from right side in photograph) through a breach in barrier island

MECHANICAL BREACH CLOSURE: This section compiles selected experiences with breach closure operations and the lessons learned at these sites.

Bayocean Peninsula, OR. The Bayocean Peninsula is located approximately 128.7 m (80 miles) west of Portland, OR, and about 80.5 km (50 miles) south of the mouth of the Columbia River. The peninsula is a spit formed across the mouth of Tillamook Bay. A small inlet at the north end of the spit connected Tillamook Bay with the Pacific Ocean. In 1917, a jetty was constructed on the north side of the entrance to provide a reliable navigation channel. By the late 1920s, erosion was apparent along the peninsula and continued at a rate of approximately 6.1 m/year (20 ft/year) until November 1952, when a storm breached the barrier at its narrowest and lowest point. The breach transported large volumes of sand into the bay, and large wing spits formed on both the north and south breach banks.

The breach reduced tidal current velocity through the inlet, which caused shoaling in the navigation channel and made navigation hazardous. Sand eroded from and transported through the breach covered the mud flats in the bay where oysters were grown. The breach also resulted in higher bay water levels, which overtopped farming dikes. In response, the U.S. Army Engineer District,

Figure 3. Perdido Pass, FL, February 2003, with spit on right side protruding into channel behind weir jetty

Portland, was authorized by Congress in 1954 to close the breach. In 1953, the breach was wide and shallow, estimated to require only a dredged sand fill to close it. However, by 1955, when planning for the work began, the breach had deepened to about 4.0 m (13 ft), and engineers determined that a rock fill was required. A complete discussion of breach closure construction is given by Henshaw (1956).

The project included both sand and rock fill and began in April of 1956. The work was accomplished between April and November to avoid winter storms. The sand fill was constructed from the north wing spit to the main body of the peninsula to reinforce the weakened area directly adjacent to the beach. It had a top elevation of 6.1 m (20 ft) mean lower low water (mllw) and a minimum top width of 122 m (400 ft). The bayward slope was 1 on 10, and the seaward side was graded to the dune elevation on the peninsula. The sand fill was planted with Holland beach grass to prevent wind and rain erosion.

The rock fill was placed across the breach channel from the mainland to the north wing spit. The first stone was placed in May of 1956. The rock fill was built with conventional end-dump methods (Figure 4). A dozer made the final placement of the rock. It had a top elevation of 6.1 m (20 ft) mllw and a top width of 4.6 m (15 ft). The side slopes were 1 on 1-1/2. Eighty percent of the rock on the

Figure 4. Rock fill by conventional end-dump method (Henshaw 1956)

seaward side of the fill weighed at least 2,268 kg (5,000 lb), and none of the stone on the seaward side weighed less than 1,360.8 kg (3,000 lb). Toe blankets 1.8 m (6 ft) wide and 15.2 m (50 ft) wide were provided on both the seaward and bayward sides of the fill.

The first phase of the rock fill construction began on the mainland and proceeded across a tidal flat to the south wing spit. A 243.9-m- (800-ft-) long tidal channel was left, and the fill was started across the main breach channel. To place the rock through the deepest section of the main breach channel, a trestle with a deck 4.3 m (14 ft) high and 6.1 m (20 ft) wide was constructed (Figure 4). As the trestle was constructed, stone was dumped on both sides forming a mound about 1.1 m (3.5 ft) high along the pilings to protect them from scour. The rock fill from the tidal channel to the north wing spit was completed in August 1956.

On 4 September, the bottom of the channel was armored for the final closure operation. The rock was dumped evenly along the entire 243.8-m (800-ft) width of the tidal channel to ensure that a constant elevation was maintained. Closure operations were shifted back and forth from the seaward and bayward sides until closure was made on 13 September. After closure, the superstructure and bracing of the trestle were removed, and the rock fill was completed to full grade. Final dressing of the rock fill was completed on 16 November.

With the breach closed, sand that had previously been transported into the bay was trapped by the breakwater, and sand accreted quickly on the seaward side of the fill. Accretion on the bayward side stopped, and tidal flow through the Federal navigation channel increased. Construction engineers

concluded that the tidal current velocity encountered during the closure operation was too great to close the breach with only a sand fill. They also believed that if the breach would have been closed by end-dumping a rock fill, the concentration of tidal flow would have scoured large volumes of sand that would have been expensive to fill. The key to a successful final closure was maintaining the top of the closure fill at an approximate constant elevation.

Buxton Inlet, NC. On 7 March 1962, the "Ash Wednesday Storm" breached the North Carolina Outer Banks 3.22 km (2 miles) north of the town of Buxton. The breach, called Buxton Inlet, destroyed the coastal road, isolating the residents of Avon from Buxton where children attended school. The breach was surveyed in June 1962 and had a width of about 213.3 m (700 ft) and maximum depth of 2.4 m (8 ft) at that time. The breach occurred on National Park Service property, and the U.S. Army Engineer District, Wilmington, was requested to close the breach and restore the barrier beach to its approximate prestorm condition. A complete discussion of the breach closure operation is given in USAED, Wilmington (1963).

The breach closure plan called for pumping sand with a single 1,160-hp, 40.6-cm (16-in.) hydraulic pipeline dredge pumping from both sides of the breach. Pumping from both sides was accomplished with a submerged pipeline that extended from the dredge at the north breach bank across the inner bar to the south bank. A total of 37,845.5 cu m (49,500 cu yd) of sand was pumped into the breach from 22 November to 26 November 1962, when a storm struck and grounded the dredge. The submerged pipeline was lost in the storm. A survey after the storm showed that the breach had widened to approximately 457.2 m (1,500 ft) with a maximum depth of 3.4 m (11 ft). Given the increased size in the breach, it was decided that it would be necessary to employ a second 1,600-hp, 40.6 cm (16-in.) pipeline dredge to fill the breach. Each dredge was capable of pumping about 6,881 cu m (9,000 cu yd) of sand per day.

The original 1,160 hp dredge resumed operations on 27 December 1962. Sand pumped after the storm was deposited on the north bank of the breach. The south bank appeared to erode at nearly the same pace as the accretion on the north bank. To mitigate the south bank erosion, local interests dumped broken culverts, automobiles, and other nonengineered materials in late January and early February of 1963 (Figure 5). Approximately 371,573.7 cu m (486,000 cu yd) of sand was pumped by the single dredge over a 55-day period, but it could not close the breach. As the channel narrowed, the currents became stronger, and the depth increased. The strong shear stress scoured material from both banks. With the losses on the north side replenished by the dredge, the inlet migrated south, even with the makeshift revetment provided by the local concerns.

On 17 February, the second dredge finally reached the site. The two dredges pumped a combined 42,050.5 cu m (55,000 cu yd) over a 3-day period to close the breach. The second dredge provided enough pumping capacity to overcome the breach flow. USAED, Wilmington (1963) noted that "it seems quite clear that the incremental rate of discharge provided by the (second dredge) spelled the difference between futility and success." All sand was pumped from the north breach bank.

The Buxton Inlet experience taught that if a breach is to be closed by pumping alone, the pumping capacity must be sufficient to overcome scour as the breach closes. In addition, to reduce channel migration, the breach should be filled from both sides, or the bank opposite the fill operation should be revetted in some way.

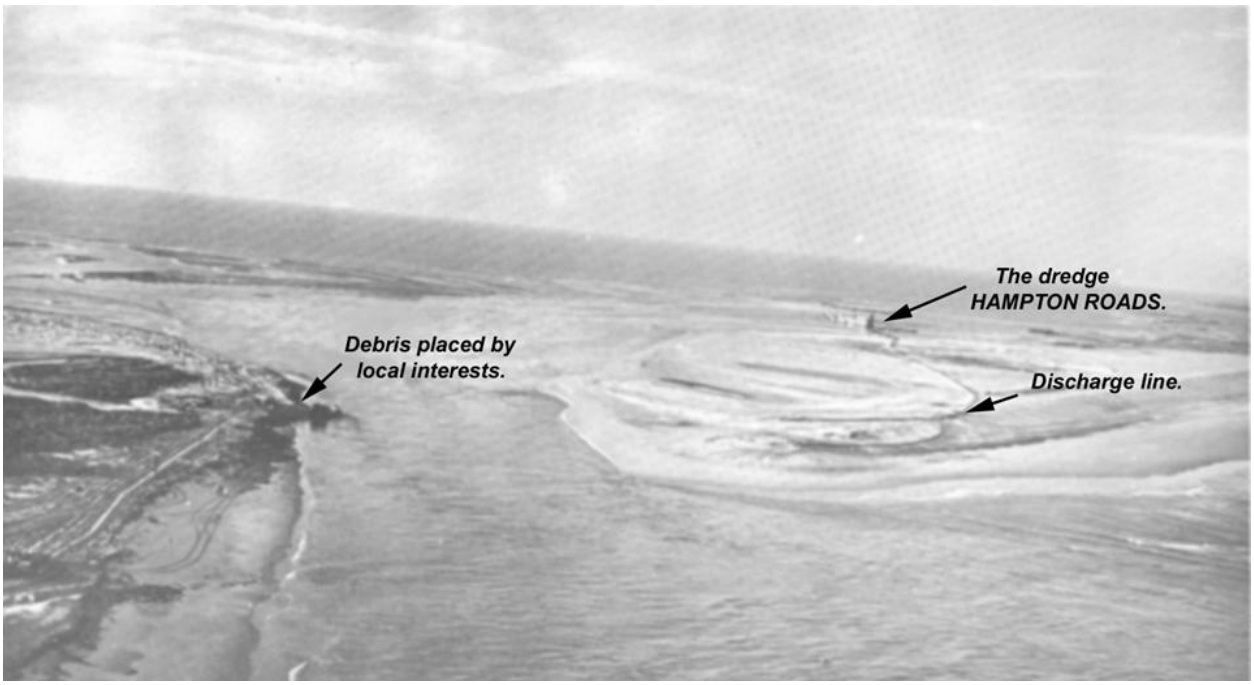

Figure 5. The Buxton breach, 29 January 1963, looking toward sound (Wilmington District 1963)

Moriches Inlet, NY. Moriches Inlet is located on the south shore of Long Island, NY, 72.4 km (45 miles) west of Montauk Point and 128.7 km (80 miles) east of New York City. The inlet connects Moriches Bay to the Atlantic Ocean and is protected by two rock jetties. A northeast storm in January 1980 breached the barrier island approximately 305 m (1,000 ft) east of Moriches Inlet. The initial breach width observed on 16 January was estimated at 91.4 m (300 ft), and the depth was approximately 0.6 m (2 ft) mean low water (mlw). The breach was surveyed on 20 January and had widened to 213.4 m (700 ft) with an average depth of just over 0.4 m (3 ft) mlw. The breach continued to grow, and by the fall of 1980 it was approximately 884 m (2,900 ft) wide with a maximum depth around 3.0 m (10 ft) mlw. Current velocity in the breach prior to its closure was estimated at as much as 1.5 m/sec (5 ft/sec).

The breach caused local concern about increased exposure to storm flooding in the backbay, as well as possible harm to the shellfish industry due to increased bay salinity. As a result, the New York District was requested to close the breach and began the filling operation in October of 1980. A monitoring program of the inlet and breach was conducted during construction of the fill to ensure that the system was responding as expected. Several design modifications were made during construction as a result of the monitoring program. A complete description of the monitoring program is given by Schmeltz et al. (1982), and the construction procedures are described by McCarthy et al. (1982). This breach was recently simulated with a numerical morphologic model (Kraus and Hayashi 2005), for which further documentation on the evolution of the breach width and depth is given.

The method selected for the breach fill included construction of two temporary sheet-pile walls 9.1 m (30 ft) apart and parallel along the bay side of the breach. The initial option of placing the sand with no temporary retaining structures was discarded because of the potential for a high loss of fill material as the operation was to take place during the winter storm season. In addition to minimizing

fill losses during construction, the expected advantages of the sheet-pile walls included control of tidal currents through the fill area and trapping part of the east to west littoral drift. Construction of the retaining walls on the bay side of the breach provided protection from wave attack and the bay side wall was further stabilized by driving short sheet-pile spurs at right angles to the main wall on the bay side.

Approximately half of the 0.9 million cu m (1.2 million cu yd) required to close the breach was obtained from an upland source and the other half was acquired by bay dredging. The fill material from upland sources was placed between the sheet-pile walls and along the ocean side of the breach. The dredged fill was placed between these two "protective arms" to minimize the loss of the dredged sand while it was in a slurry state. Several weeks after closure operations began, a storm with a 2-year return period struck, damaging the exposed sheet pile walls and eroding some of the fill. Engineers on site observed that without the sheet-pile walls in place, the majority of the fill would have been lost. By early December, the breach was nearing closure (Figure 6). To facilitate the final closure, a sheet-pile spur was constructed to deflect the ebb current away from the breach and through the inlet. As a result, sand began to naturally accumulate in the breach, and it was closed on 15 December. Sand placement continued through January of 1981, and the sheet-pile walls were removed with construction activities complete by the beginning of February 1981. Material losses were approximately 15 percent of the total placed, including losses from the storm. Subsequent to the closure, New York state constructed a rubble revetment on the bay side of the barrier island contiguous with the jetty and running along the bay shoreline of the barrier island.

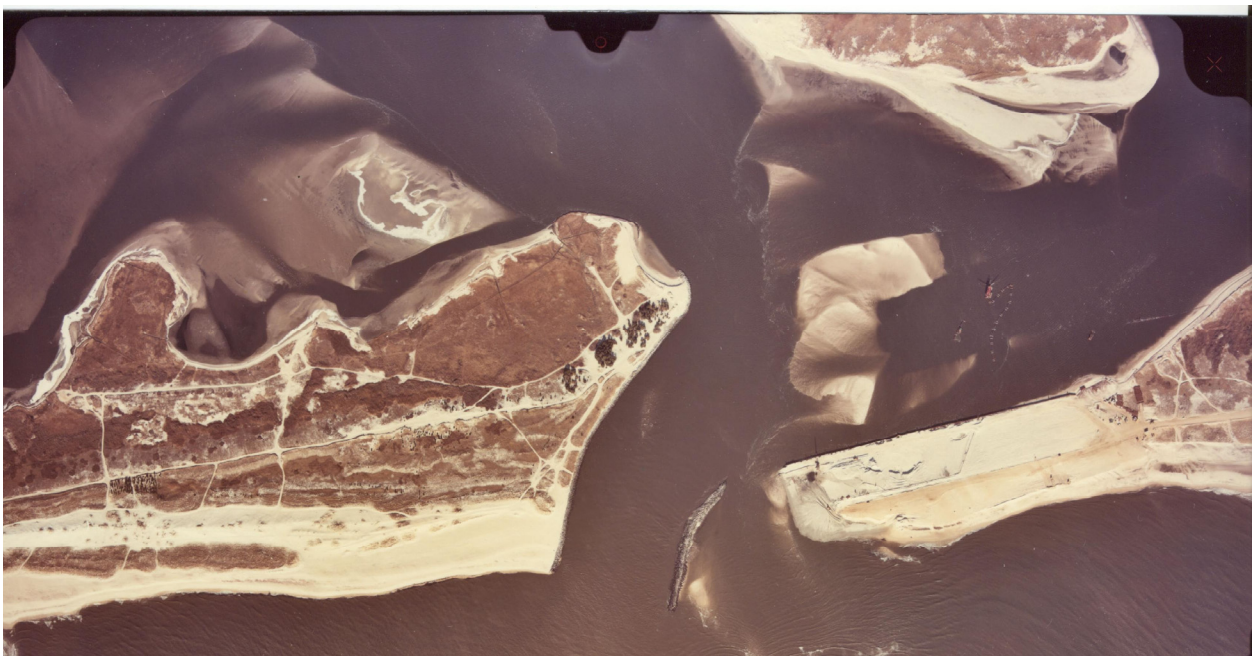

Figure 6. Moriches Inlet breach fill construction nearing completion, 4 December 1980

Westhampton Beach, NY. In December 1992, a northeast storm breached the barrier island at Westhampton, Long Island, NY, from the ocean side approximately 4.8 km (3 miles) east of Moriches Inlet, just downdrift from the Westhampton groin field (Terchunian and Merkert 1995). The island breached at two locations. The first, called Pikes Inlet, reached a width of more than

305 m (1,000 ft) and was initially larger than the second breach called Little Pikes Inlet. Little Pikes began as a shallow 30.5-m- (100-ft-) wide breach that could be traversed by foot over peat deposits.

By February 2003, Pikes Inlet was closing naturally by sand transported alongshore, and the New York District completed the closure with sand dredged from a channel north of the breach. Little Pikes Inlet, however, continued to grow because it was located just 305 m (1,000 ft) from the end of the groin field updrift that reduced sediment transport. The closure of Pikes Inlet increased the tidal flow through Little Pikes, and the breach grew to a width of more than 914.4 (3,000 ft) with maximum depths of approximately 5.5 m (18 ft). The breach erosion created extensive flood and ebb shoals, as well as wing spits.

The New York District initiated emergency measures to close the breach in August 1993. The method selected to close the breach was similar to that applied to close the 1980 Moriches Inlet breach. Two sheet-pile walls were to be constructed 6.1 m (20 ft) apart and parallel to one another along the center of the island. The seaward wall was a permanent structure to protect against future breaching. The bayside wall was to be temporary and reduce sand losses during the filling operation. Sand from an offshore source was pumped to a staging area at the east end of the breach. The filling operation proceeded from the staging area with a 76.2-m (30-in.) pipeline dredge capable of pumping 15,291.1 to 38,227.4 cu m (20,000 to 50,000 cu yd) per day.

The initial fill method was cumbersome because the dredge could pump at large capacity, but the wall construction was slow. The engineers decided not to construct the temporary wall and pump as much sand as possible. The new procedure worked well, and construction proceeded with sand pumped on the seaward side of the permanent sheet-pile wall to minimize sand deposited to the bay. The initial fill pass created a 6.1-m- (20-ft-) wide berm and proceeded from east to west. A large emergent spit in the bay on the west side of the breach stabilized the west breach bank. The final closure procedure took advantage of the spit by changing direction of the fill abruptly to the north to connect the fill with the spit and allow for immediate closure of the breach. The breach was closed by early October. The remainder of the fill was placed from west to east and the final cross section was completed in December of 1993.

Grays Harbor, WA. Grays Harbor is located on the southwest Washington coast at the mouth of the Chehalis River, about 72.4 km (45 miles) north of the Columbia River mouth. The estuary is enclosed on the ocean side by spits that are separated by a 3.2-km- (2-mile-) wide opening that forms the natural harbor entrance. Two convergent rock jetties extend seaward from the spit points. The jetties are part of the Grays Harbor Navigation Project, which is a federally constructed and maintained navigation channel that allows deep-draft shipping.

Following construction of the south jetty, the shoreline on the bay side of the spit receded as a result of inner bank erosion. Inner bank erosion is a common phenomenon at the landward terminus of jetties on sandy shorelines and often creates a crescent shaped bay, as is the case at Grays Harbor. Recession rates on the bay side of the spit at the Grays Harbor south jetty have ranged from approximately 0.9 to 7.6 m (3 to 25 ft) per year since 1946. Beginning in the late 1960s, the ocean side of the spit also eroded with shoreline recessional rates ranging from 0.6 to 18.9 m (2 to 62 ft) per year (Osborne et al. 2003).

In December 1993, the persistent erosion on both the ocean and bay sides of the south spit at Grays Harbor culminated in formation of a breach between the south jetty and the adjacent beach. The breach widened rapidly, exposing the landward end of the jetty and eroding portions of the adjacent state park. Within hours of breach formation, the width was estimated by visual observation to be approximately 7.6 m (25 ft). Approximately 1 week later, aerial photographs show the breach had widened to approximately 83.8 m (275 ft). The breach reached a maximum width of approximately 165 m (540 ft) before it was mechanically filled by the U.S. Army Engineer District, Seattle, in the fall of 1994 (Wamsley et al. 2005).

The city of Westport became alarmed by the rapid growth of the breach and expressed concern for further expansion of the breach, damage to water wells and a sewer treatment plant, and consequences for the Grays Harbor navigation project as the breach continued to widen during the winter storm season. In March 1994, the Seattle District was directed by the Department of the Army to close the breach. In September 1994, the filling operation commenced. The breach closure was considered a temporary measure to protect the Grays Harbor navigation project and to alleviate local concerns.

The sand to fill the breach was dredged from the adjacent navigation channel. The channel was dredged with two small hopper dredges and pumped to the breach fill site with a 2,000-hp, 61-cm (24-in.) booster pump. Problems were encountered because the booster pump was underpowered. The filling operation began pumping coarse material, but had to switch to a finer source material because the coarse sand could not be efficiently pumped. As a result, the majority of the fill was constructed with finer-grained material. Filling with finer-grained material slowed the operation, as it did not accumulate as fast as the coarse material.

The sand was pumped unconfined on the upland adjacent to the breach and stockpiled until a sufficient volume was available to close the breach. The breach was closed by bulldozing the stockpiled material into the narrowest part of the breach. The closure operation began around low tide, and the initial closure was completed by high tide. The sand was pushed from the beach, across the breach toward the jetty. Maximum current velocity through the breach at the time of closure was about 2 m (6.5 ft) per sec, but there was little flow through the breach at low tide. With the initial fill cross section in place, the same technique was applied to complete the fill to the final design template. The breach fill was completed on 7 December 1994 with 458,732.9 cu m (600,000 cu yd) of sand dredged from the navigation channel. Photographs in Figure 7 show the breach area before and after closure.

Coos Bay, OR. Coos Bay is an estuary on the Oregon coast about 321.9 km (200 miles) south of the Columbia River mouth. The entrance is enclosed by Coos Head to the south and a low sand spit on the north. The entrance is stabilized by rock jetties on both the north and south sides of the entrance. A 14.3-m- (47-ft-) deep channel extends between the jetties. Coos Bay is the largest deep-draft harbor between the Columbia River and San Francisco, CA, and is one of the largest shipping ports in the world for timber products.

a. Before closure, August 1994

b. After closure, September 1995. Closure was completed in December 1994

Figure 7. Grays Harbor, WA, breach area

Similar to Grays Harbor, the shoreline on the bay side of the north spit receded as a result of inner bank erosion following the construction of the north jetty. The ocean shoreline also receded as a result of transport directed offshore near the north jetty. In addition, the navigation channel migrated to the north, eroding the interior shoal that supported the base of the jetty and exposing the landward terminus of the north jetty to increased wave attack. Return flow from wave runup on the shoreface and overtopping of the north jetty formed runnels along the base of the jetty. These factors weakened the north jetty and culminated in a breach of the north jetty on 8 November 2002 during a storm with offshore waves in excess of 8.7 m (28.5 ft) in height and 17-sec period. The landward end of the jetty was breached, not the barrier spit (Figure 8). The waves approached from the west-southwest and directly attacked the landward terminus of the north jetty. The breach in the jetty was approximately 4 m (13.1 ft) wide. A complete discussion of the jetty breach and closure operation is given by Hays et al. (2003).

Figure 8. Coos Bay, OR, breach of north jetty (Hays et al. 2003)

Following the breach, the beach adjacent to the north jetty eroded, losing an estimated 30,582.1 cu m (40,000 cu yd) of sand through the breach and into the entrance. The beach profile elevation was lowered approximately 75 m (6.5 ft). Tidal flow through the breach widened the damaged area in the weeks following the storm. Approximately 40 days after the jetty breached, the opening had widened from an initial 4-m (13-ft) width to about 245 ft. The jetty breach caused rapid shoreline recession and, if not closed, could have resulted in a breach of the barrier spit.

Because of the continued damage to the jetty and the transport of sediment through the jetty and into the navigation channel, the U.S. Army Engineer District, Portland, initiated the coordination of an emergency repair on 25 November 2002. Construction began on 20 December 2002, and the repair was completed on 9 January 2003. The jetty was restored to the 1939 design cross section with slightly larger stone to improve structure stability. A jetty "bench" was also constructed along the structure to protect the foundation from return flow scour. The bench is a rubble mound constructed perpendicular to the jetty on the beach side to an elevation of +3 m (+9.8 ft) mllw and 6.1 m (20 ft) wide. The jetty repair also included a 38,227.7-cu m- (50,000-cu yd-) sand fill in the eroded area adjacent to the jetty breach. The fill replaced the sand lost through the breach and advanced the shoreline seaward of the repair area. The fill buried the bench and provides protection to the jetty root. The jetty has not sustained damage since the repair.

Hatteras Island, NC. Hurricane Isabel struck the North Carolina Outer Banks on 18 September 2003. The storm breached Hatteras Island about (9.7 km) (6 miles) northeast of Hatteras Inlet and quickly widened to an overall width of over 457.2 m (1,500 ft). With support from CIRP, the short-term hydrodynamic and morphologic evolution of the breach was monitored (Wamsley and Hathaway 2004). The Hatteras breach had three distinct breach channels because of underlying peat deposits that resisted erosion. Maximum current velocity through the main breach channel exceeded 6.1 m/sec (6 ft/sec), which scoured the channel to depths of approximately 6.1 m (20 ft).

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, restricting access for residents and tourists. The Federal Emergency Management Agency (FEMA), together with the local sponsor, the North Carolina Department of Transportation (NCDOT), requested the Wilmington District to reestablish the land connection to Hatteras Village as soon as possible. The breach closure operation required interagency cooperation, coordination, and communication. A breach closure team was formed with representatives from USACE, 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. A complete discussion of the breach closure is given by Wutkowski (2004).

The breach closure project was designed 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 prestorm condition. The Wilmington District applied the lessons learned from the 1962 Buxton Inlet closure and based the design on that breach closure, which was just 10 miles to the north. The closure of Buxton Inlet demonstrated that the Hatteras breach could be closed by pumping material into the breach if the pumping capacity was sufficient. Based on the Buxton Inlet pumping volumes, the minimum discharge capacity to close the Hatteras breach was estimated to be between 6,881 and 13,762 cu m (9,000 and 18,000 cu yd) per day. The fill material was medium-coarse sand, which limited losses during the breach filling operation.

The breach was closed with an 11,300-hp, 76.2-cm (30-in.) dredge. The dredge also had a 7,200 hp booster pump. The pumping capacity of this plant was greater than the minimum range of 6,881 to 13,762 cu m (9,000 to 18,000 cu yd) per day. The filling operation started at the west breach bank,

and filling was to be accomplished by pumping from one side only. The eastern bank was composed of an erosion resistant peat layer that allowed the design to omit armoring there. The peat layer was 0.9 to 1.2 m (3 to 4 ft) thick, several hundred feet wide, and was exposed at low tide.

The breach filling operation began on 17 October 2003. Two-thirds of the fill width was initially constructed. The sand was discharged on the west breach bank along the center alignment of the fill. Sand that accumulated at the discharge pipe was shaped by two bulldozers according to the fill template. The first two channels of the breach and three-quarters of the main channel were filled within 15 days. The first two channels filled quickly as they captured relatively little of the tidal prism, and breach flow velocity was weak. The dredge averaged 15 hr/day of pumping time with a production rate of 16,820.2 cu m (22,000 cu yd) a day. The largest 1-day production was 31,346.8 cu m (41,000 cu yd).

On 1 November 2003, approximately 30.5 m (100 ft) of the breach remained to be filled. Similar to Buxton Inlet, as the cross-sectional area of the breach was reduced, the current velocity increased and scoured much of the sand that was deposited, even with the large pumping capacity. To facilitate rapid advance of the fill and close the remaining portion of the breach, a narrow mound of sand was bulldozed across the breach at slack tide to prevent water flow through it (Figure 9). Once the flow of water was stopped, additional material was added to the narrow mound to fill the remaining design template without the losses caused by the tidal current. The final closure began at high tide and was completed at low tide, thus allowing several hours for the berm to be widened before wave runup began to erode the berm at higher water levels. No material was stockpiled in advance, but a 1,758.5 cu m (2,300 cu yd) per hour dredge production rate provided a sufficient source of sand to build a small dike across the remaining breach. It was observed that the final closure would have been facilitated by stockpiling sand on the bank opposite the dredge pipe outlet. The stockpile would have allowed sand to be pushed from both sides of the breach.

Surveys of the breach area indicated that approximately 336,404.1 cu m (440,000 cu yd) was placed in the breach area, with sand loss of only approximately 8 percent. Sand losses were low compared to beach nourishment projects, which typically range from 10 to 20 percent. The low loss is attributed to the medium-coarse sand that resisted dispersing forces of the waves and current during placement. The rebuilding of NC12 was completed on 18 November 2003.

MECHANICAL BREACHING: Breaches can have positive consequences and, therefore, creation of controlled breaches is common. Breaches may lower the water level in coastal ponds, lagoons, and bays, thereby reducing the risk of flooding to adjacent property; decrease or increase water salinity in the pond, lagoon, or bay; improve water quality by promoting water exchange; or facilitate the migration of marine organisms. Therefore, it can be desirable to mechanically breach a coastal barrier, if its size and longevity are limited (controlled). The following case studies document several experiences with mechanical breaching.

Rollover Pass, TX. Rollover Pass is an inlet created by mechanical breaching that is located on Bolivar Peninsula, 35.4 km (22 miles) northeast of Galveston, TX. Bolivar Peninsula is a low barrier island that separates East Bay from the Gulf of Mexico. The peninsula was breached under the direction of the Texas Game and Fish Commission (now the Texas Parks and Wildlife Department) at a low, narrow area to allow fish migration and to improve water quality.

Figure 9. A view of first attempt to complete closure looking to west from eastern bank of breach (Wutkowski 2004)

Dredging of the breach cut began in October of 1954 and was completed by February 1955. A channel was to be dredged across the peninsula to a depth of 2.4 m (8 ft) at mlw and 24.4 m (80 ft) wide. The cut was to be flared on the gulf side and extended into the gulf to a depth of 0.9 m (3 ft) mlw, and to a depth of 1.2 m (4 ft) mlw on the bay side. The plan also called for the construction of a sheet-pile retaining wall on the southwest bank of the cut that extended from the middle of the barrier island to the gulf to resist erosive wave action in this area. A complete discussion of the Rollover Pass project is given by the U.S. Army Engineer District, Galveston (1958).

Breaching of barrier islands will cause significant change to the local circulation and sediment transport, and care must be exercised to avoid unwanted erosion. Rollover Pass is an example of a purposeful breach that produced an excessive tidal current and caused unwanted and uncontrolled rapid erosion of the channel banks. Before the work was completed, the breach channel had eroded to 9.1 m (30 ft) below mean tide level at the center line of the barrier island, and the gulf side entrance widened to nearly 152.4 m (500 ft). A bridge spanned the cut and the current through the breach caused erosion that threatened to undermine the bridge abutments. Immediate protective measures constructed included additional pilings to protect the bridge abutments, a groin along the northeast side to stop the breach from widening, and a revetment of the exposed banks with broken concrete, shell, stone, and other rubble.

Despite the additional measures taken, erosion of the breach cut and the adjacent gulf shore continued. In 1955, shoreline recession on the southwest side of the breach cut continued for approximately 1.6 km (1 mile) down the coast. Four houses had to be moved by the owners. The bridge abutments showed signs of undermining by scour. To protect the bridge, a sheet pile bulkhead was constructed across the cut on the gulf side of the bridge to a depth of about 0.6 m (2 ft) below mean tide level (mtl) to permit some exchange of water while controlling the erosion. The pass was

inspected in October 1956, and evidence of shoaling was found, including a bar that had formed across the mouth of the cut. The Galveston District evaluated the pass and surrounding area, and published a report in April of 1958. Based on the recommendations in that report, sills were constructed at the center line of the barrier near the bridge and at the gulf entrance to reduce tidal current velocity. Bulkheads were also constructed along both banks across the barrier to halt erosion within the breach. Following construction of the improvements, the pass has not exhibited the large-scale widening that characterized the initial cut.

Redwood Creek, Northern California. Artificial breaching has been conducted at several California river entrances for purposes such as improvement of water quality, mitigation of flooding, and opening of fish migration paths. One example is Redwood Creek. The mouth of Redwood Creek is located in Redwood National Park, west of the town of Orick in northern California. The creek mouth is located in the park, but upstream portions of the estuary lie outside the park boundary and private lands flood if the creek mouth closes and water levels rise. A sand spit created by longshore sand transport typically builds across the mouth of the creek in late spring and early summer, causing the mouth to migrate and forming an embayment. The southward migration increases the length of the outflow channel and reduces the flow gradient, decreasing water velocity. As the water discharge decreases, the water in the embayment rises to a level that floods private property used for cattle grazing and crop production. To alleviate the flooding, landowners breached the berm to allow their fields to drain. The breaches rapidly drained the embayment, destroyed fish habitat, and prematurely flushed young fish into the ocean (Hofstra and Sacklin 1987).

To control water level in the estuary without destroying fish habitat, a process referred to as controlled breaching was developed and implemented in the early 1980s. Controlled breaching releases water at a rate in which fewer fish are entrained in the outflow and the embayment and fish habitat is maintained. Hofstra and Sacklin (1987) provide a more comprehensive description of the controlled breaching management plan. Controlled breaching of the creek mouth was typically accomplished with hand tools or conventional earth-moving equipment. A controlled breach increases the flow gradient and flow velocity by reducing the length of the outflow channel before the mouth is completely closed by the sand spit. The breach was controlled by carefully selecting the location along the prograding spit that the breach cut was made. The closer the breach cut is made to the embayment, the faster the outflow and the lower the resulting embayment water level.

The controlled breaching method was successfully implemented from the early 1980s to the late 1990s to control flooding, maintain embayment integrity, and minimize fish losses. The permit required to breach the Redwood Creek mouth expired in 2002, because changing physical and political conditions have not required purposeful breaching in recent years.

San Dieguito Lagoon, Southern California. San Dieguito Lagoon is a 56.7-ha (140-acre) wetland located just north of the city of Del Mar in San Diego County, CA. The lagoon is located at the mouth of the San Dieguito River and forms an inlet to the Pacific Ocean. San Dieguito Lagoon is typical of lagoons located on the southern California coast, providing a fish nursery and endangered species habitat as well as food sources for migrating birds. Many coastal lagoons in southern California are only marginally stable. Tidal flow and natural flooding from rainwater runoff are often insufficient to keep coastal lagoon inlets open. After the inlet closes, water quality decreases, and increased water levels create flooding problems (Elwany et al. 1998).

On time scales longer than a few years, river flooding is the primary process determining whether San Dieguito Lagoon Inlet is open or closed. Over shorter time periods, the inlet condition is controlled by river and lagoon bathymetry, the available tidal prism, and sand transport along the beach (Elwany et al. 1998). Plans for maintaining healthy lagoons have often been based on increasing the tidal prism with large-scale dredging to deepen the lagoon and constructing jetties to stabilize the inlet. An alternative inlet maintenance strategy applied at San Dieguito is to purposefully breach the inlet, as necessary. The plan, coupled with scouring from seasonal rainwater runoff, properly maintains tidal flushing (Elwany et al. 1997).

The lagoon inlet is breached with conventional earth-moving equipment and timed to coincide with the spring tide to achieve maximum tidal flushing of the lagoon. The sand removal is conducted with a front-end loader, excavators, and scrapers. The volume of sand removed ranges from 3,822.8 to 11,468.3 cu m (5,000 to 15,000 cu yd) and is typically placed on the beach south of the inlet so that the predominant south-directed longshore transport does not return it to the inlet (Elwany et al. 2003). The opening of the lagoon reduces flooding to property and improves water quality in the estuary.

Coastal Ponds on Atlantic Coast. Coastal ponds on the Atlantic coast are often mechanically breached for environmental reasons and to reduce the risk of flooding. On the south shore of Long Island, NY, Mecox, Sagaponack, Wainscott, Georgica, and Hook are all brackish ponds that are breached, typically annually or more frequently, to alleviate flooding and improve water quality. The ponds are breached by digging a pilot channel with conventional earth-moving equipment from the ocean toward the pond and from the pond toward the ocean, leaving a sand plug in a convenient location to be excavated. The plug is removed at low tide and preferably during a period of low waves to prevent premature closure of the breach by longshore transport. Figure 10 shows a recent breach cut made at Sagaponack Pond. The breaches are left unattended to close naturally by infilling through longshore transport. As a breach closes, the ephemeral ebb shoal created by the opening may weld to shore and contribute to closure and beach healing (Kraus et al. 2002). Smith and Zarrillo (1988) document the natural closure of Mecox Pond after mechanical opening.

Typically, pond opening is conducted during time of low tide and moderate to calm wave conditions. In this way, water will ebb from the pond rapidly, increasing the width of the breach, while minimizing formation of a flood shoal. An increase in volume of the flood shoal decreases pond area and removes sediment from the beach.

CONCLUSIONS: The case studies reviewed in this technical note document lessons learned through experiences with mechanical breaching and closure of breaches. Experience has taught that breach closures require the quickest possible response to minimize cost. What may start as a small breach that could easily be plugged by conventional methods can become a large inlet requiring millions of dollars to fill. Rapid response is supported through effective interagency coordination. Efficient closure of breaches is facilitated by proper timing of the fill operation. If possible, seasonal considerations should be made, with closures made during calm, summer months. If a closure operation is performed during the winter storm season, a temporary wall to limit losses may be required. Final closure of a breach should be made during time of low tide. Fills should be made with the largest grain size possible, and a high pumping capacity is required to overcome the strong

Figure 10. Breach cut at Sagaponak Pond on Long Island (looking toward pond), 4 March 2005

current as the breach becomes constricted. Even large breaches can be overcome by large pumping volumes, provided that filling is accomplished from both sides or a temporary revetment made on the breach bank opposite the filling operation. Final closure can be accomplished more efficiently if sand is stockpiled on each breach bank to be pushed into the breach channel by bulldozer. Breach closures may need to be vegetated to protect against wind and rain erosion.

Mechanical breaching is typically accomplished by conventional equipment that can operate in 0.9 to 1.2 m (3 to 4 ft) of water. Larger breach cuts may require additional sand removal by a dredge. Artificial breaching requires careful planning to avoid excessive erosion of both the cut and the shoreline or to avoid too rapid of a closure by natural processes. The hydrodynamic conditions at a proposed breach location should be studied to understand the potential tidal prism captured by the breach, the resulting tidal current velocity, and the longshore sediment transport along the beach. Artificial breaching should also be timed to ensure adequate water flow in the direction desired and to avoid premature closure during times of large volume of longshore transport.

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