Coastal and Hydraulics News

Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
Vicksburg, Mississippi USA 39180-6199

Vol CHL-01-1 **May 2001**

Overview of the National Shoreline Erosion Control Demonstration Program

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Introduction

The National Shoreline Erosion Control Development and Demonstration Program of the U.S. Army Corps of Engineers was established by Section 227 of the U.S. Water Resources and Development Act (WRDA) of 1996 with initial funding appropriated in FY00. Section 227 is authorized as a 6-year research and development effort that provides a means by which the Corps can evaluate the functional performance of innovative or nontraditional approaches for abating coastal erosion and improving shoreline sediment retention at prototype-scale. A variety of shore protection devices and methods will be constructed, monitored, and evaluated at sites that represent varying energy conditions and shoreline morphologies. This program builds upon the experience and lessons of the "Low Cost Shore Protection Demonstration Program (Section 54)" of the 1970s. The Section 54 Program, authorized by WRDA 1974, focused on testing technologies for survivability in low-wave energy environments (Headquarters, U.S. Army Corps of Engineers 1981).

Objectives of Section 227 are to assess and advance the state of the art of shoreline erosion control technology, encourage the development of innovative solutions to the shoreline erosion control challenge, and communicate findings to the public. Through an extensive technical transfer effort, the research and development program will provide a means for furthering the use of well-engineered alternative approaches to shoreline erosion control. Emphasis will be placed on the evaluation of technologies from both functional and structural perspectives, and will include bioengineered approaches.

The program has three tiers of investigation. At the highest level of participation, Section 227 will contribute funding for design, construction, and evaluation of a demonstration project. There will be a minimum of seven sites. In addition to constructed demonstration sites, the program will also take advantage of "targets-of-opportunity" to monitor sites where innovative shore protection approaches may be installed through the sponsorship of others (e.g., a site where another Federal or non-Federal organization has implemented an approach which shows engineering promise, but is not planning to extensively monitor or document project performance). At the third tier of investigation, the program will sponsor the development of a database that documents installations and case example reports.

Project Criteria

The Section 227 authorization states that a minimum of seven demonstration projects will be constructed on various coastlines around the nation: two on the Atlantic coast, one on the Gulf coast, two on the Pacific coast, and two on the Great Lakes. Project locations must be experiencing shoreline erosion at a manageable rate, and have sufficient shoreline length to demonstrate the functional performance of the technology selected for testing at that site. Additionally, sites must have suitable baseline control data

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or preproject monitoring records, and have identifiable spatial and temporal scales associated with localized coastal processes.

Selection criteria for demonstration technologies include applicability to project site, suitable and quantifiable performance prediction metrics, sound engineering design, and economic feasibility of construction and maintenance. Specific technologies identified as having a high priority for testing include innovative groin geometries and permeable groins, reef breakwaters and breakwater configuration, armoring alternatives, bioengineered and vegetative approaches, cohesive and bluff shore treatments, and other sand retention methods and site management strategies. All demonstration projects must meet local permitting and regulatory requirements.

Nominations for demonstration sites and technological applications are being coordinated through the coastal U.S. Army Corps of Engineers (USACE) District and Division offices. The Section 227 oversight committee (consisting of the civilian members of the Coastal Engineering Research Board, USACE Headquarters and U.S. Army Engineer Research and Development Center (ERDC) staff) reviewed the submitted site nomination packages and identified specific sites appropriate for further consideration. Thirty-seven nomination packages were originally submitted by 17 coastal Corps Districts. Technological advancements will be selected for demonstration by the committee based on scientific and engineering validity and on economics. Performance of the applied technologies will be evaluated as related to interaction with the coastal system and other engineering considerations such as constructability, structural stability, and life-cycle costs. The performance of all demonstration projects will be monitored under Section 227 for a minimum of 3 years. Evaluation of functional performance will be documented and widely disseminated to the coastal engineering community.

Project Implementation, Fiscal Year 2000

During fiscal year 2000, primary sites were selected for project implementation plan development including:

U.S. Army Engineer District, Philadelphia, Cape May Pont, NJ. The borough of Cape May Point, NJ, was specified in the appropriations language of Section 227. Cape May Point is a 1.8-km-long beachfront community located on the southern tip of New Jersey. Cape May Point is particularly vulnerable to storm damage due to exposure to waves from both the Atlantic Ocean and the Delaware Bay. Existing shore protection structures along the shoreline at Cape May Point include a series of nine groins with a spacing that varies from 150-300 m, and a rubble revetment armoring the shoreline in the easternmost groin cell (Figure 1). While these engineered efforts have “held the line” in most sections with regard to erosion, that “line” is at a critical position and the width of the back beach is severely compromised. There is virtually no buffer from storm events that can severely damage the area, and this absence also contributes to saltwater intrusion of a nearby critical freshwater wetland.

The compartmentalized beach at Cape May Point presents an opportunity for researchers to evaluate the effectiveness of narrow-crested submerged breakwaters such as the

Figure 1. Borough of Cape May Point, NJ. Narrow-crested submerged reef structures (Beachsaver) will enclose groin cells to be used to retain beach-fill material

Beachsaver™ (Figure 2) and sills to retain sediment on the active beach profile. In cooperation with the State of New Jersey, Department of Environmental Protection, a project implementation plan was approved and construction was initiated for continuous submerged breakwaters and sills across selected groin compartments in an effort to retain beach-fill material. An assessment will be made to determine the effectiveness of these structures when used to extend the renourishment interval by retaining sand on the active profiles contained in the groin cells. District POCs: Randall A. Wise (Randall.A.Wise@nap02.usace.army.mil) and Susan S. Lucas (Susan.S.Lucas@nap02.usace.army.mil).

U.S. Army Engineer District, Galveston, Jefferson County, TX. The second demonstration site to be initiated is located on the Gulf Coast in Jefferson County, TX, about 50 km west of the Texas-Louisiana border. The beach is representative of beaches of the western Gulf Coast, which vary in texture and composition from mud or thin sand veneer over mud with high concentrations of caliche nodules and shell material to dominantly sand with minor shell material. Typical topography consists of a flat-sloped nearshore, a steep beach, and a wash-over terrace. The elevation of this wash-over terrace, which is the highest point on the shore, is slightly above normal high-tide elevation. Previous shore protection attempts (e.g., sheet pile or wooden bulkheads) have since been removed by coastal storms.

The principal cause for shoreline recession in the area is storm-related erosion. Under storm conditions, the protective veneer of sand is eroded and the underlying mud beach is exposed to waves for further erosion (Figure 3). Due to a deficit of sand in the littoral system and storm-related downcutting of the cohesive material, the eroded profile never recovers to its post-storm state. The phenomenon of cohesive profile downcutting is not unique to the western Gulf Coast as it also occurs in the Great Lakes and bay environments of the Atlantic and Pacific coasts.

In cooperation with the State of Texas General Land Office, the Jefferson County demonstration site will be designed with two primary shoreline erosion abatement goals in mind: prevention of cohesive bottom downcutting and prevention of overwash. It is expected that these goals will be addressed though a combined use of geotextile

Figure 2. Beachsaver reef units to be implemented at Cape May Point, NJ, demonstration site. The narrow-crested precast concrete units will enclose groin cells to serve as sediment retaining structures

Figure 3. Lowlying upland areas and cohesive material outcrop on Jefferson County, TX, beach. Innovative measures will be implemented at this site to prevent the landward overwash of beach sand, and to prevent erosion of the emergent and submerged beach profile

structures, beach nourishment, and vegetative methods. District POCs: Robert K. Sherwood (robert.k.sherwood@swg02.usace.army.mil) and Richard Medina (richard.medina@swg02.usace.army.mil).

U.S. Army Engineer District, Detroit, Allegan County, MI. The shoreline at Allegan County, MI, is representative of many in the Great Lakes region. Receding bluffs carved into glacial tills or lacustrine deposits occupy over 60 percent of the shoreline (Figure 4). Till bluffs exist also along the New England coast, in river valleys, and in countless lakes and reservoirs throughout the northern U.S. and Canada. In coastal scenarios, the blame for most slope movements is commonly placed on toe erosion created by storm waves. Although other factors (notably groundwater) are contributors to slope instability, they are typically ignored when erosion abatement strategies are planned. At this location, lake level receding from the toe of the actively eroding bluff results in groundwater being a significantly contributing factor to slope instability.

The project area has been monitored for the past five years with respect to slope displacements versus causative factors by investigators at Western Michigan University (WMU). Study results demonstrate the significance of groundwater activity as the prime contributor

Figure 4. Frozen perched groundwater seeps at Allegan County, MI, on the eastern shore of Lake Michigan. Bluff dewatering measures will be implemented to reduce coastal bluff instability caused by perched groundwater effects

to bluff movements, and that slumps are most prevalent when perched groundwater levels are high regardless of wave activity or lake level. In partnership with the WMU and the State of Michigan, bluff dewatering technology will be evaluated at this location to reduce or eliminate coastal bluff instability. If proven functional, the dewatering of shoreline bluffs will be an inexpensive, noninvasive, and effective method of erosion control. District POCs: James P. Selegean (James.P.Selegean@1re02.usace.army.mil) and Scott J. Thieme (Scott.J.Thieme@1re02.usace.army.mil).

U.S. Army Engineer District, New York, Babylon, NY (optional). Gilgo Beach, located in the community of Babylon on Jones Island, NY, is a 4.8-km-long portion of a barrier beach located on the south shore of Long Island between Jones and Fire Island Inlets. Northeasters and hurricanes periodically impact the southern shores of Long Island. These storms produce tides and waves which cause dune erosion. The only existing form of beach erosion control at Gilgo Beach is the placement of sand material removed from Fire Island Inlet every 2 to 3 years. An engineered berm with an elevation of approximately 3.6 m above mean sea level, provides protection to a roadway located immediately landward of the beach. Shore protection structures such as timber groins and bulkheads have been destroyed by wave action.

At Gilgo Beach, it is anticipated that the State of New York, Department of Environmental Conservation, will serve as a cooperating partner. Two methods of open-coast dune restoration and stabilization are proposed for investigation: The first is a combination of a timber or recycled plastic horizontal lattice structure and dune grass plantings (Dune Ladder™, Figure 5). The concave-shaped lattice structure will be located in the seaward face of the dune. Vegetation will be planted between the plank members. The second method of dune stabilization to be investigated will be an expandable three-dimensional sand confinement grid system adapted from use in inland flood control (Rapidly Deployed Flood Wall™ (RDFW), Figure 6). The geosynthetic grid cells will provide a protective framework for the engineered dune, and dune grass will be planted within the cells of the structure. Dune restoration via use of recycled glass combined with vegetative plantings may also be considered for demonstration at this site. District POCs: Odile Accilien (Odile.Accilien@nan02.usace.army.mil) and Lynn M. Bocamazo (Lynn.M.Bocamazo@nan02.usace.army.mil).

Figure 5. Dune Ladder , which will be implemented at Gilgo Beach, Jones Island, NY, combines a structural and vegetative approach to prevent coastal dune erosion

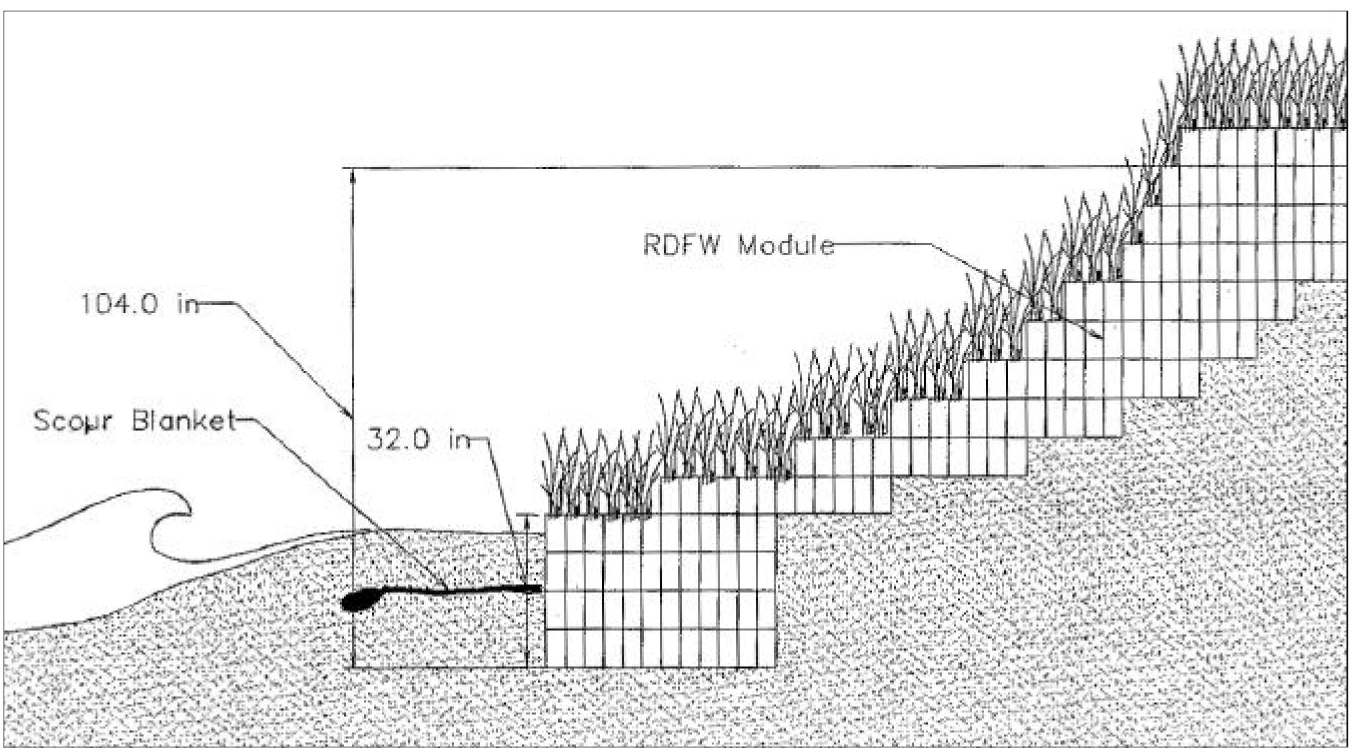

Figure 6. Conceptual drawing of the Rapidly Deployed Flood Wall (RDFW) to be implemented at Gilgo Beach, Jones Island, NY. The project will combine structural and vegetative methods to prevent coastal dune erosion

U.S. Army Engineer District, Jacksonville, Miami Beach, FL. The City of Miami Beach was specified in an amendment to the authorizing language as a demonstration site for implementation of innovative erosion control methods. An erosional "hot spot" demonstration project site at the City of Miami provides an excellent opportunity to address hot spot issues that are experienced in many Federal and non-Federal shore protection projects. Three reaches of beach can be described as erosional hot spots within the Federally authorized Dade County Beach Erosion and Hurricane Protection Project (Figure 7). Shoreline recession in this area is directly correlated with local impacts of tropical and extratropical storm events. The authorized project is designed to provide a specific level of storm damage reduction and recreation benefit through the establishment and maintenance of a design template. This design template must provide protection for the life of the project for realization of a satisfactory return on Federal and non-Federal investments. A variety of approaches are being considered, including use of nearshore submerged breakwaters and nearshore sand placement strategies. The objective of the structural approaches will be to maintain the design template by retaining sand on the shore. District POC: Thomas D. Smith (Thomas.D.Smith@saj02.usace.army.mil).

Project Implementation, Fiscal Year 2001

During fiscal year 2001, the Section 227 Program will complete construction at the Cape May Point, NJ, project location, and initiate construction at a second location (upon satisfactory review of project implementation plans). Also during fiscal year 2001, other projects will be developed for several sites, including:

U.S. Army Engineer Districts, Baltimore and Norfolk (optional). Monitoring and documentation of nearly two dozen completed T-head groins, submerged breakwaters, headland breakwaters, and other classes of projects located on Maryland and Virginia shores of the Chesapeake Bay. District POCs:

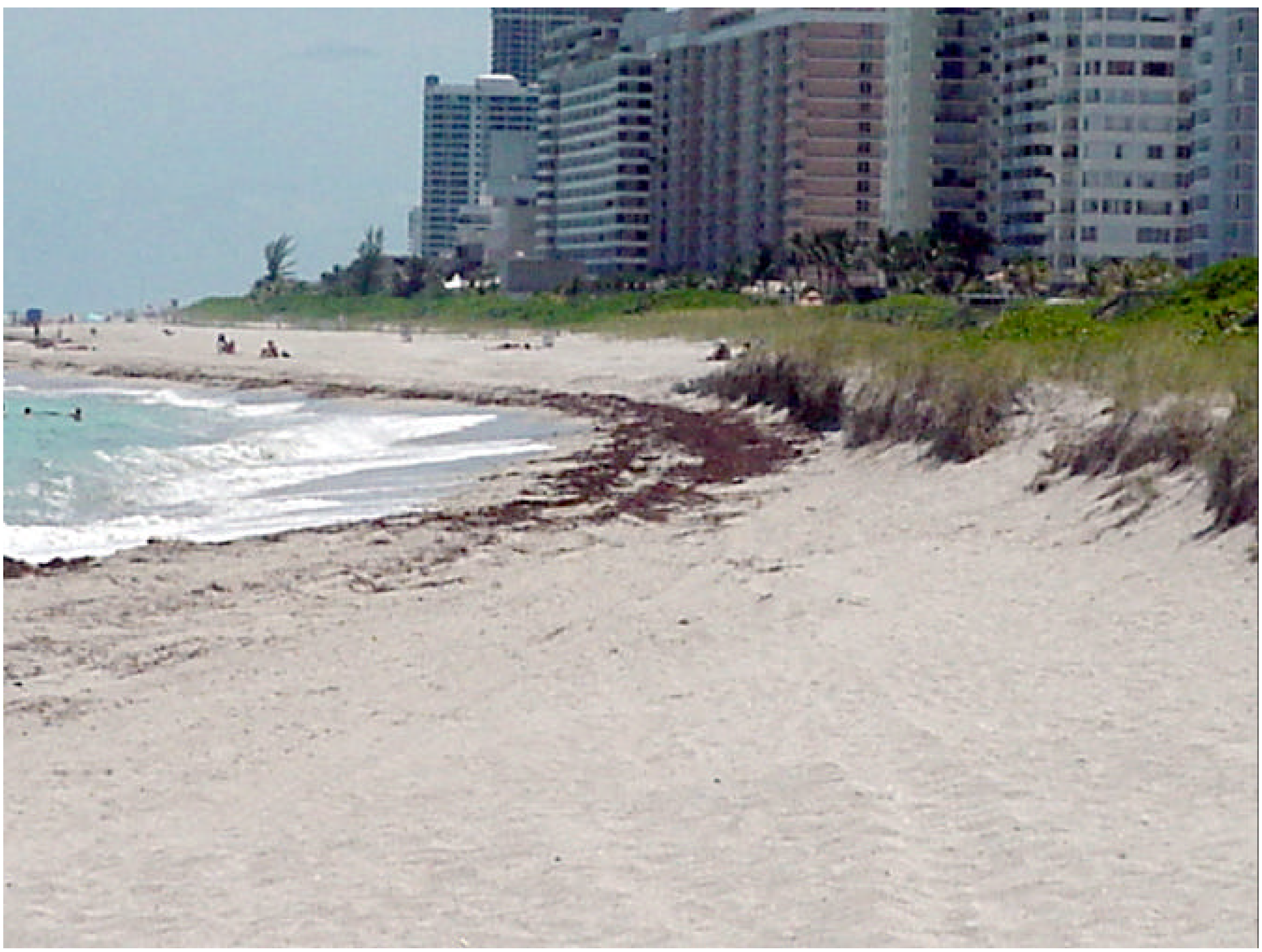

Figure 7. Example of erosional hot spot area at Miami Beach, FL. Note the encroachment of the shoreline on the coastal dunes at the apex of the hot spot. Innovative structural measures will be implemented to retain beach fill in these areas to maintain the design beach-fill profile

Mark H. Hudgins (Norfolk) (Mark.H.Hudgins@nao02.usace.army.mil) and Gregory P. Bass (Baltimore) (Gregory.P.Bass@nab02.usace.army.mil).

U.S. Army Engineer District, San Francisco. Construction at a tidal wetland environment located in east San Francisco Bay, CA, that is experiencing loss of substrate due to tidal currents and waves generated by wind and vessel traffic (Figure 8). The abatement of coastal wetland erosion is a challenge due to the environmental and visual effects of traditional shore protection methods. Since the site is currently an environmentally healthy marsh system, a shore protection device that can be installed with limited collateral damage is needed. Knowledge gained at this site will be applicable to other wave-influenced wetland environments whether they are located in bays, on lakes, or in other low-energy ocean environments. District POC: John H. Winkleman (John.H.Winkleman@spd02.usace.army.mil).

U.S. Army Engineer District, Los Angeles. Construction in San Diego County, CA, in cooperation with the State of California and the San Diego Association of Governments beach-fill program. The objective of the project will be to implement an innovative structural alternative that will retain sand on the beach and extend the renourishment interval. District POCs: Chuck Mesa (Chuck.Mesa@sp101.usace.army.mil) and Arthur T. Shak (Arthur.T.Shak@sp101.usace.army.mil).

U.S. Army Engineer District, Los Angeles. Monitoring at Ventura, CA, where a high-density polyethylene reef (Highwave™) will be constructed for the purpose of retaining sediment on the shoreline, enhancing recreational surfing conditions, and providing marine habitat (Figure 9). Private venture capital will fund design, construction, and maintenance of the structure. District POCs: Chuck Mesa (Chuck.Mesa@sp101.usace.army.mil) and Arthur T. Shak (Arthur.T.Shak@sp101.usace.army.mil).

U.S. Army Engineer District, Buffalo. Construction of a limited-length submerged breakwater and lake bed paving (i.e., beach nourishment using a range of coarse grain sizes) at the Sheldon Marsh Nature Preserve, Huron, OH

Figure 8. Wetland and coastal bank erosion in east San Francisco Bay, along the Pickleweed Trail, Martinez, CA. Environmentally- and aesthetically-desirable methods will be demonstrated to prevent bank erosion in this region of moderate wave energy and high-tide range

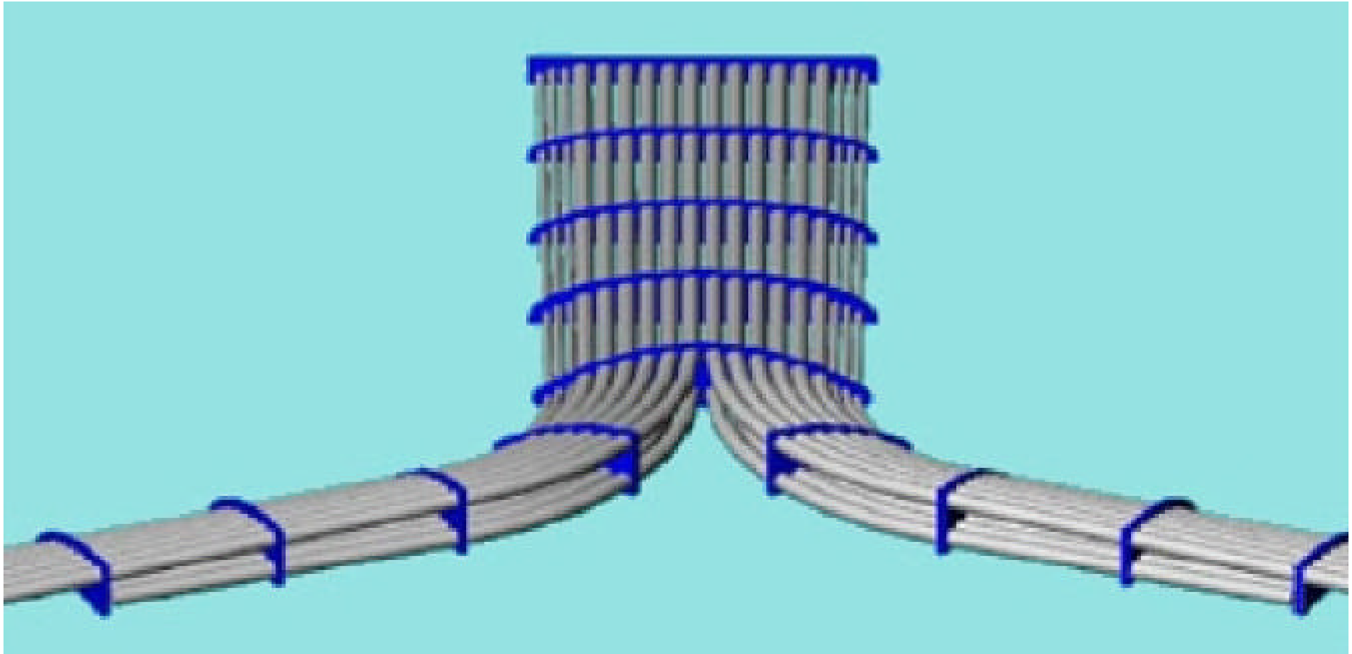

Figure 9. Conceptual drawing of the high-density, polyethylene Highwave to be constructed at Ventura, CA. The project will be monitored to evaluate the response of the beach planform to the structure, and for structural stability

Figure 10. Sheldon Marsh, Huron, OH, is protected by a narrow barrier beach. Use of coarse-grained beach fill (commonly called lake bed paving) and submerged structures will be implemented to prevent loss of wetland substrate and erosion of the cohesive lake bed

(Figure 10). This project site will provide an opportunity to evaluate innovative soft shore protection in conjunction with an unobtrusive structure to protect portions of a cohesive barrier beach and wetland substrate. If this submerged breakwater and lake bed paving proves effective, similar shore protection could have extensive application along former barrier beaches and wetlands in western

Lake Erie and other Great Lakes sites. District POCs: Thomas J. Bender (Thomas. J.Bender@lrb01.usace.army.mil) and Michael C. Mohr (Michael.C.Mohr@lrb01.usace.army.mil).

Request for Database Input

A database is being developed to document installations and case examples of innovative shoreline erosion control methods. This database and information on individual study demonstration sites will be available through the program Web site. In developing the database, the Section 227 Program has surveyed academic institutions, Federal and State agencies, and private consultants regarding recent advancements in shoreline erosion control technologies. The database should serve as a clearinghouse for innovative coastal erosion control information. It will be populated with information such as methods or product descriptions, functional performance summaries, references documenting laboratory or field evaluations, graphics, links to related Web sites, points of contact, etc. Three classes of technology solutions include coastal armoring (e.g., revetment/ armor units, seawalls/retaining walls), sediment retention devices (e.g., breakwaters/ reefs, groins, headland structures) and “soft” solutions (e.g., beach nourishment, beach dewatering, bioengineering). Included in the database will be information regarding innovative construction techniques and materials for the three classes of solutions.

Anyone who has participated in the evaluation or implementation of innovative or nontraditional methods of coastal shoreline stabilization or has knowledge of field application of unique approaches, and desires to contribute to this important database, is urged to contact:

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Coastal and Hydraulics Laboratory (CEERD-HC-S)
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Expressed permission from the appropriate source will be obtained by ERDC before any proprietary or copyrighted material is included in the database. The information provided to the database will be of eminent service to coastal engineers, scientists, public officials, and coastal managers in evaluating the applicability of innovative solutions to coastal erosion challenges.

Additional Information

Additional information regarding the National Shoreline Erosion Control Development and Demonstration may be accessed via the Internet at http://chl.wes.army.mil/research/cstructures/section227/.

Citations

Headquarters, U.S. Army Corps of Engineers. (1981). “Low-cost shore protection: Final report on the Shoreline Erosion Control Demonstration Program (Section 54),” Washington, DC.

The U.S. Army Corps of Engineers Field Research Facility: More Than Two Decades of Coastal Research

William A. Birkemeier[1] and K. Todd Holland[2]

Abstract

The Field Research Facility (FRF), located on the Atlantic Ocean in Duck, NC, was established by the U.S. Army Corps of Engineers in 1977 to support the Corps' coastal engineering research requirements. The facility consists of a 560-m- (l,840-ft-) long research pier, a main office building, field support building, and a 40-m- (130-ft-) high observation tower. Since its creation, the FRF has maintained a comprehensive, long-term monitoring program of the coastal ocean including waves, tides, currents, local meteorology, and the concomitant beach response. This monitoring program is supported by a small, highly-skilled field staff and several unique vehicles that permit successful operations in the turbulent surf zone. These capabilities have also supported a series of multiagency multiinvestigator experiments that have led to the Duck beach becoming the best-studied beach in the world. To date, approximately 150 journal articles, 108 reports, and 84 conference proceedings papers have been published using FRF data by more than 200 authors. This paper summarizes the capabilities of the FRF and reviews the impact of its first 23 years of operation.

Introduction

The U.S. Army Corps of Engineers' Field Research Facility (FRF) in Duck, NC, was officially dedicated by Congressman Walter Jones, Sr., in 1980, thereby ushering in a new era of nearshore research and discovery. Since its earlier construction in 1977 (Figure 1), the FRF has provided the Corps and the worldwide coastal research community with the capability of conducting complex and comprehensive nearshore research and engineering studies. Through its long-term measurement program and series of comprehensive multiagency multiinvestigator experiments, the FRF has contributed significantly to understanding the nearshore zone, an active area of the coast included in all shore protection and navigation projects. Because the Duck site is representative of many U.S. coastal locations, FRF data are helping to meet the need for field data to calibrate and verify the accuracy of analytical, numerical, and physical model predictions. Because of the ready availability and high quality of FRF ground-truth data, Duck has also been the site of a wide range of equipment and development efforts, particularly in remote sensing.

History of the FRF

In the 1960s little was known about the dynamics of the surf zone. Except for the classic studies of O'Brien, Shepard, Bascom and others during the Second World War (see Bascom 1987 for insight into these early experiments; Moore and Moore 1991), most field studies of the surf zone were conducted from fishing piers, including several in North Carolina. Coastal scientists and engineers conducting research in the harsh environment of the coastal zone faced particularly difficult data collection problems such as installation of instruments under less than ideal conditions and exposure to a variety of hazards, including storms and hurricanes. Accurate bottom surveys made by individuals wading through the surf zone or by amphibious military craft were extremely difficult or impossible to obtain. Because of these problems in collecting comprehensive and accurate field measurements, the state of the art of coastal engineering was slow to advance.

In response, the concept for a field research facility was proposed in 1963 by Mr. Rudolph Savage, Chief of the Research Division of the Coastal Engineering Research Center (CERC).[3] The recently created CERC was learning how difficult field data collection was through an ambitious wave measurement

1 U.S. Army Corps of Engineers, 1261 Duck Road, Kitty Hawk, NC

2 Naval Research Laboratory, Stennis Space Center, MS

3 The Coastal Engineering Research Center (CERC) was created by Congress in 1963, replacing the Beach Erosion Board (BEB). In 1997 CERC merged with the Hydraulics Laboratory to create the Coastal and Hydraulics Laboratory (CHL).

Figure 1. Aerial view of the Field Research Facility showing pier, buildings, and observation tower

program. Storms could not be well documented because the piers on which the gauges were mounted were either destroyed or were too shallow to measure unbroken waves. Establishment of the FRF would complement CERC's physical modeling facilities and serve the following functions (Mason 1979):

- Provide a rigid platform from land, across the dunes, beach, and surf zone out to the 6-m (20-ft) water depth from which waves, currents, water levels, and bottom elevations could be measured, especially during severe storms.
- Serve as a permanent base of operations for physical and biological studies of the site, the adjacent sound and ocean region by the Corps, other Federal agencies, universities, and private industry.
- Provide the Corps with field experience and data that would complement laboratory and analytical studies and provide a better understanding of the influence of field conditions on measurements and design practices.
- Provide a field facility for evaluating new instrumentation.

The primary facility would be a concrete and steel pier constructed sufficiently high to be above expected storm waves and surge, and long enough to cross the most active zone of sediment transport. The search for a suitable site considered a large number of criteria including:

- Sand size typical of U.S. coasts and sufficient depth of sand to prevent underlayer exposure.
- Wave climate and storm exposure representative of U.S. coasts.
- Regular offshore bottom topography free of features that may alter the wave climate.
- Tidal range of 0.5 to 2.0 m (1.5 to 6 ft).
- Representative nearshore slope with the 6-m- (18-ft-) depth contour within 600 m (2,000 ft) of shore.
- A straight coastline outside the range of the effects of any significant littoral barrier.
- Control of the surrounding area to avoid interruptions in research programs.
- An adjacent sound or estuary area.
- Availability of commercial power and communication facilities.
- Usually free of fog or cloud cover to allow frequent use of aerial remote sensing.
- A stable coastline (on a time scale of 50 years)
- Natural dunes.

The FRF became a reality through the efforts of Colonel Donald S. McCoy, then commander of CERC (Moore and Moore 1991). Sites all along the eastern coast of the United States were considered and originally a site within the Assateague National Seashore in Maryland was selected. However, the site was changed to Duck, NC, when the National Park Service retracted their endorsement of the project.

Though more remote, the Duck site satisfied all criteria, except possibly the sediment one. Duck beach sands are typically bimodal comprised of a coarse (~1 mm) fraction with finer (~0.3 mm) sands. Offshore sediments are uniform and fine, decreasing to ~0.125 mm, 1000 m (3,300 ft) from shore.

The Duck site was previously occupied by the U.S. Navy as a target range for pilots operating out of the Oceana Naval Air Station in nearby Virginia. The Navy had recently decommissioned the site and the 176-acre property was transferred to the Corps. Appropriately, research into dune stabilization using vegetation to reduce aeolian movement of sand from uncovering buried ordnance was already being conducted on the site.

Facilities

The FRF facility includes the 560-m- (l,840-ft-) long research pier, a main office building, field support building, and an observation tower (Figure 1). The research pier is a reinforced concrete structure supported on steel pilings spaced 12.2 m (40 ft) apart on center along the pier length, and 4.6 m (l5 ft) apart across the width (Figure 2). The pier deck is 6.1 m (20 ft) wide and extends from behind the dune to a nominal depth of 6 m (20 ft), at a height of 7.6 m (25 ft) above the National Geodetic Vertical Datum of 1929 (NGVD). The influence of the pier on the adjacent bathymetry and processes is a concern examined by Miller et al. (1983) and Elgar et al. (2001). These studies concluded that the pier had an effect that varied with wave and current conditions and distance from the pier.

Located on the pier is the Sensor Insertion System (SIS), added in 1990 (Figure 3). The crane-like SIS can be moved to any location on the pier and is equipped with wave gauges, current meters, and sediment-transport sensors (Miller 2000). It can be operated in 5-m (16-ft) waves and is able to reach 15 to 24 m (50 to 75 ft) out from the pier to minimize the local influence of the pier on the measurements. The SIS was originally developed to measure sediment transport during storms but it has also found use as an ideal diverless-platform to temporarily deploy or test oceanographic sensors.

The main FRF building was completed in 1980 with accommodation for a permanent staff of two and visiting scientists. Originally designed around a central garage to house a planned, but never constructed precursor to the SIS, the main building immediately required modifications to adjust for changes in equipment and a permanent staff of 10. The dining room and bunk rooms were turned into offices, the large garage went through several different configurations until it was converted into offices, an electronics shop, and storage; and the kitchen was conveniently moved into an area that originally held shower stalls. In 1982, a vehicle garage was added to the facility, and in 1991 the garage was expanded to include a classroom, technical library, machine

Figure 2. Concrete abrasion collar being placed over a piling during pier construction. The collars protect the piling from erosion at the sand/water interface

Figure 3. Sensor Insertion System (SIS) with instrumented boom deployed during storm conditions

shop, dive locker, and general work space. The 40-m- (130-ft-) tall climbable observation tower to support video remote sensing observations and to hold radio antennas was added in 1986. With great ceremony, the tower was christened with a bottle of champagne dropped from the top deck, and bets were taken as to whether it would break or not—it did.

The FRF is probably best known for the CRAB or Coastal Research Amphibious Buggy (Birkemeier and Mason 1984). Designed and constructed by the U.S. Army Engineer District, Wilmington, the CRAB arrived at the FRF in 1978 to conduct some of the first surveys of the bathymetry near the pier. At that time it was not tall enough to drive around the pier, and became stuck on occasion trying to go under it. The height of the CRAB was later increased by 3 m (10 ft) to 11 m (35 ft), sufficient to pass around the pier, and it became a permanent part of the FRF in 1981. The CRAB is an aluminum tripod powered by a lightweight diesel engine that drives the variable stroke pump that powers the three hydraulic wheel motors (Figure 4). It is modeled after a similar looking vehicle designed by R.A. Stearn Inc. (Sturgeon Bay, WI) and constructed by Marine Travelift and Engineering for monitoring beach nourishment projects. Though primarily serving as a survey vehicle, the CRAB supports other tasks in the nearshore, such as: instrument deployments and maintenance; sand sampling and vibracoring; cable laying and retrieving; towing instrumented sleds; conducting sensor maintenance, and functioning as a mobile platform for diving operations. Top speed of the CRAB is 3 kph (2 mph) and it can be operated in waves up to 2 m (7 ft) high. Many operations at the FRF have only been possible because of the CRAB. In recognition of the value of the CRAB to surf zone operations, Dutch researchers, after visiting the FRF, have constructed a similar mobile platform, the WESP (http:// www.frw.ruu.nl/fg/wesp.html).

Two reconditioned LARC-V (Lighter Amphibious Resupply Cargo) vehicles support operations in deeper water or remote from the FRF. Originally built for the U.S. Army to transport cargo between ships and land, these vehicles support diving operations; tow sidescan and sub-bottom seismic instruments; lay and retrieve cables; and deploy and maintain buoys and instruments. One LARC has been converted from the original mechanical drive to hydraulic drive for greater speed and reliability. It has also been equipped

Figure 4. Coastal Research Amphibious Buggy (CRAB) preparing to deploy Naval Postgraduate School instrumented sled during DUCK94 experiment

with a cabin and AC power to support data collection and survey work (Figure 5).

Personnel

The FRF staff includes three scientists, one engineer, two computer specialists, two civil engineering technicians, one equipment specialist, two electrical technicians, and an office administrator. They are well known for their expertise in conducting coastal field research and collectively have nearly 200 years of experience conducting experiments at the FRF and elsewhere. Six of the original 10 staff members[1] (Figure 6) are still working at the FRF, and four of the current staff began work in 1985 or 1986[2]. Part of the attraction of working at the FRF is the lack of a usual routine. Every staff member has multiple responsibilities, and every day is different–from rescuing boats at sea, to preparing the facility for hurricane evacuation or an invasion of scientists, to righting the CRAB after it turned over (only once, October 1987). In addition to conducting their own research, the staff also helps visiting scientists plan their experiments at the facility. Through their intimate contact with the environment, the staff has a unique sense of the conditions to expect and they have the knowledge of how to successfully deploy instruments in the surf zone so they survive.

Measurement Program

Central to all studies at the FRF are the long-term measurements that began in 1977 (Miller 1980). This program has evolved with the addition of new instruments and collection techniques. Measurements currently being made include:

- Wave height, period, and direction at 8- and 16-m (26- and 52-ft) depths;

1 Eugene Bichner, William Birkemeier, William Grogg, Michael Leffler, Carl Miller, Raymond Townsend

2 Clifford Baron, Kent Hathaway, Charles Long, Brian Scarborough

Figure 5. One of the Field Research Facility s Lighter Amphibious Resupply Cargo (LARC-V) vehicles conducting a bathymetric survey

Figure 6. Original Field Research Facility staff. Left to right (bottom row): Bill Grogg, Harriet Klein, Carl Miller (seated), Curtis Mason, Gene Bichner, and Mike Leffler. (Top row): William Birkemeier and Ray Townsend

- Wave height and period (three points along the pier);
- Vertical current profile at 8-m (26-ft) depth;
- Water level (four locations and National Oceanic and Atmospheric Administration/National Ocean Service primary tide station);
- Water temperature, visibility, salinity (surface and daily profile);
- Wind speed and direction;
- Atmospheric pressure, air temperature, humidity, precipitation;
- Bathymetry (biweekly);
- Annual aerial photography; hourly video imagery

Wave measurements have always been a primary interest. Buoy 44014 maintained by the NOAA/National Data Buoy Center (NDBC) provides directional wave measurements 94 km (58 mi) from shore in 47-m (150-ft) water depth, near the edge of the continental shelf. A Datawell® Directional Waverider Buoy measures nonbreaking wave conditions 4 km (2.5 mi) offshore in 16 m (52 ft) of water. Further inshore, the full directional wave spectrum is determined from the FRF's 8-m Directional Wave Array composed of 16 bottom-mounted pressure sensors arranged in a shore-parallel, shore-normal cross (Long and Oltman-Shay 1991). This array was deployed in 1986 and designed by Dr. Joan Oltman-Shay with the capability to resolve a unidirectional wave train to within 5 deg and two wave trains at the same frequency if they differ by 15 deg in direction. It may be the longest running high-resolution directional wave gauge in the world (Figure 7).

In order to maintain real-time observations, most FRF instruments are wired to the main building via a network of armored cables. Although the data from some sensors are collected digitally, most sensors, including the 8-m Directional Wave Array sensors, provide a continuous analog voltage output that is digitized at the computer. A Global Positioning System (GPS) timeserver controls the digitization so that the phase relationship between sensors can be precisely measured. Originally, data from all analog sensors were recorded at a 2-Hz sample rate for 34 min every 6 hr, except during storms when data were recorded hourly. Improvements in data collection computers and storage capacity allowed for near continuous data collection starting in 1987. Raw time series, computed statistics and spectra are archived for each sensor and collection period.

Instrument observations are supplemented by a daily series of visual observations of parameters like cloud cover, air and water visibility, breaker type, alongshore surface currents, surf zone width, and rip current presence.

A NOAA/National Ocean Service (NOS) primary tide station (number 865-1370), located at the seaward end of the pier collects water-level data every 6 min. NOS has carefully monitored and maintained the tide gauge since installation in 1977 and, as a result, an excellent record of sea level rise, and water-level variation, has been obtained. During the period, NOS converted from their traditional punch paper tape measuring system to their next generation water-level station, based largely on development and performance tests

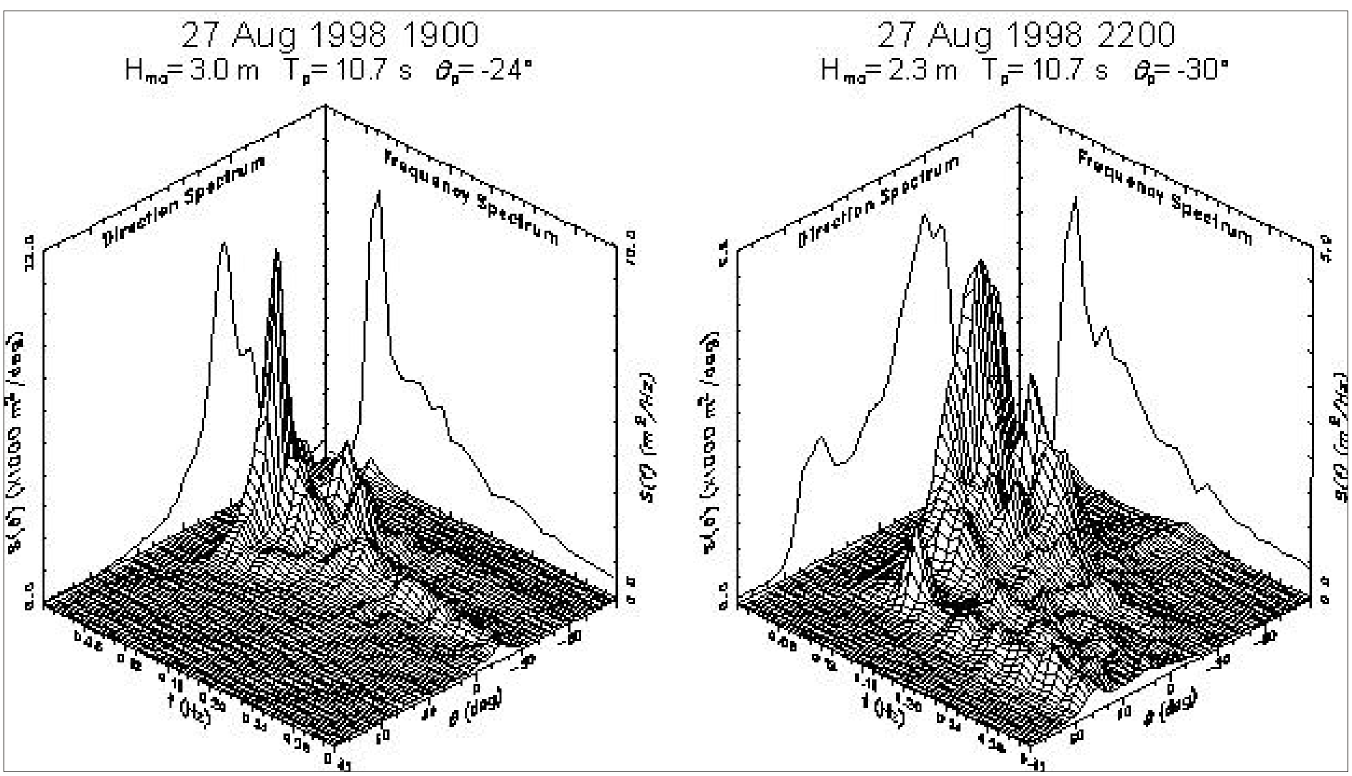

Figure 7. Directional wave spectra collected at the 8-m Directional Wave Array during the passage of Hurricane Bonnie. These data show the significant and rapid changes in the distribution of wave energy reaching the beach

conducted at the FRF. In 1995, NDBC, in cooperation with the FRF, added a permanent Coastal-Marine Automated Network (C-MAN) weather station to the end of the pier as part of a new Ocean Sensor Test Facility for the long-term testing of oceanographic sensors deployed by the Corps or on NDBC's ocean buoys (Woody et al. 1997).

Equally important to the FRF measurement responsibilities is the surveying program using the CRAB to obtain centimeter-accurate measurements through the breaker zone and across the inner shoreface. Four profile lines extending seaward to the 9-m (30-ft) depth contour are surveyed biweekly, and a region 1 km by 1 km centered on the pier is surveyed monthly. The program has benefited from advances in surveying technology through the evolution of four different systems. Early surveys used a surveying level to read a large stadia board mounted on the back of the CRAB. Handwritten notes, weather, biting flies, and reading errors made these data error prone. The level was soon replaced with a Zeiss Elta-2s electronic surveying system, (Birkemeier and Mason 1984). With the Elta-2s, a typical survey of 50 points could be conducted in about 45 min with an accuracy of 3 cm horizontally and vertically.

In 1990, the Elta-2s was replaced with a Geodimeter 140-T self-tracking total station capable of following the CRAB as it moved and acquiring data every second. For the first time, sufficient data points were obtained to fully define the curves and shapes of the nearshore. In fact, some of the earliest evidence of mega-ripples was observed even with the large wheel size of the CRAB. Because the Zeiss and Geodimeter instruments are both range-azimuth systems, their accuracy decreases with distance from the instrument, and they are therefore least accurate at the offshore extent of the surveys, where changes are typically small but can be significant. This problem was resolved in 1996 with the adoption of a Real-Time Kinematic (RTK) GPS system. This system has produced the most consistently accurate data to date and has the added advantage of requiring only a single operator to drive the CRAB and collect the data. By combining the RTK GPS system with a digital echosounder and using the LARC as a platform, the surveys can now be extended into deeper water while maintaining nearly the same accuracy.

The surveys are not frequent enough to capture the dynamic nature of the beach and inner sand bar zone (changes in the foreshore profile of up to 0.8 m have been observed over a single tidal cycle, Holland and Puleo (in preparation)). This region is monitored remotely with video cameras mounted on the observation tower using techniques originally developed by Dr. Robert Holman of Oregon State University. Daily images from a single camera began to be collected in 1986. Today the images from eight cameras are obtained hourly and used to create rectified mosaic images, equivalent to a vertical aerial photograph, for a 2-km (1.2-mile) stretch of coastline, centered on the research pier.

Experiments

To fully utilize the unique potential of the facility and to obtain as many benefits to the Corps and the nation as possible, non-Corps use of the facility and its data has always been encouraged. This policy has led to one of the most productive accomplishments of the FRF, serving as a site for cooperative experiments where resources (funds, labor, instruments, and data) are pooled to investigate complex coastal processes. A sequence of such studies has been conducted at the FRF resulting in a wealth of new coastal knowledge. In addition, these experiments have also created a core group of sponsors (U.S. Army Corps of Engineers, Office of Naval Research, and the U.S. Geological Survey) and researchers who have helped to establish the FRF as a premier research facility.

In l978, DUCK-X brought together 24 participants to evaluate the use of remote sensing for coastal studies, particularly the capabilities of the SEASAT-A satellite. Ground truth data from the FRF proved extremely useful in verifying synthetic aperture radar images sent from the satellite. The Atlantic Remote Sensing Land and Ocean Experiment (ARSLOE) followed in October l980, and included 3l U.S. participants and four foreign researchers. In addition to evaluating remote sensing techniques, wave transformation theories were tested and directional wave measuring systems evaluated (Baer and Vincent 1983).

In the fall of l98l, A Shoreface EXperiment (ASEX) brought several investigators to the FRF to determine the spatial and temporal variability in sediment characteristics, and to relate changes in these characteristics to hydrodynamic processes. This was the first experiment to make extensive use of the CRAB both to survey several cross-shore profiles and to collect a unique series of cross-shore vibracores. Though ASEX included only limited monitoring of morphology and surf zone dynamics, the observations foreshadowed the focus of the following experiments: the complex interaction between hydrodynamics and sediment related processes including morphology change. ASEX was the first of many Duck experiments that Dr. Asbury Sallenger (U.S. Geological Survey) participated in. ASEX was unique in being the only experiment held south of the pier.

It was during ASEX that plans developed for DUCK82 held in the fall of l982 (Mason et al. 1985). FRF scientists and researchers from the U.S. Geological Survey, and Oregon State University conducted a comprehensive month-long study of nearshore processes and morphological change to test models of crescentic sandbar generation (Bowen and Inman 1971). Movie cameras, current meters and wave gauges on the pier, a mobile-instrumented sled and the CRAB were used to collect wave, current, and bathymetric data. It was during DUCK82 that Dr. Robert Holman from Oregon State University began his long relationship with the FRF, bringing his remote sensing techniques and students to Duck.

The DUCK82 experiment began to define the format and logistics of the experiments that followed. In each, the CRAB was used to water-jet precisely located long pipes or pipe frames into the bottom to support the instruments which were cabled back to collecting systems on shore. Typically the number of instruments was thought to be sufficient, based on the understanding of the dominant processes at the time. As the understanding of the processes improved, the number of instrument locations or nodes and the number of instruments at each node increased (Table 1). Instruments were deployed during the mild conditions of late summer in order to be ready to measure the changes caused by the first fall storms of September or October. Instruments in the surf zone require a high level of attention and maintenance. Therefore, the experiments generally lasted only a few weeks to two months to obtain observations under a range of conditions including storms and to have sufficient time to remove the instruments before winter weather set in. Surveys by the CRAB provided frequent updates of the morphology surrounding the instruments. As the experiments became larger and more complex, one key to their success was the developing experience being gained by the FRF and by repeating participants.

Table 1. Instrument Nodes During the Duck Experiments

Experiment	Instrument Nodes[1]
ASEX	0, instrumented sled
DUCK82	7, instrumented sled
DUCK85	17
SUPERDUCK	30, instrumented sled
DELILAH	19, instrumented sled
DUCK94	41, instrumented sled
SandyDuck	105, instrumented sled

[1] Nodes held one or multiple instruments

The DUCK82 experiment was also a landmark in revealing both the importance of sandbar morphology to nearshore dynamics and the incredible speed and complexity at which sandbars evolve during a storm. Because of the circulation associated with the development of migrating rip channels, adjacent profile lines showed opposite trends with offshore bar migration on one, and accretion on the other. Since the cross-shore focus of DUCK82 did not fully resolve this complexity, the DUCK85 experiment was planned with more frequent surveys and a larger array of instruments. DUCK85 differed somewhat by having a separate mild wave phase in September focussing on sediment-transport measurements (Figure 8), and a storm wave phase in October that provided some of the best quantitative data on the rapid changes that occur during storms (Mason et al. 1987). In fact, the CRAB surveys during DUCK85 uniquely captured the initial, and subtle, development of a rip current through a linear sand bar (Howd and Birkemeier 1987). DUCK85 and the experiments that followed provided training opportunities for Corps office staff. During DUCK85, more than 15 District engineers and scientists

Figure 8. DUCK85 sediment transport experiment, directed by Dr. Nicholas Kraus (CHL). The researchers are tending sediment traps facing into the longshore current which is being measured by the two current meters located to their right. Further to the right, the line of photopoles was observed by movie cameras to measure wave conditions

participated for 2 weeks each. For the surveyors and CRAB operators, DUCK85 was also noteworthy as the first and only experiment where the CRAB was operated through the night. It was quickly learned that the added data did not justify the extraordinary demand on the drivers.

DUCK85 was designed as a preliminary experiment to *SUPERDUCK* in 1986, which again included a morphologic and sediment transport component, and a hydrodynamic component, this time including a 509-m (1670-ft) longshore linear array of electromagnetic current meters (Crowson et al. 1988; Birkemeier et al. 1989). The primary purpose of this array had been to measure the dynamics of edge waves on a barred beach profile, a natural extension of edge wave work on unbarred California beaches (Oltman-Shay and Guza 1987). While edge waves were indeed observed, the most startling result of SUPERDUCK was the discovery of shear waves, large fluctuations in what should have been steady longshore currents (Oltman-Shay, Howd, and Birkemeier 1989). SUPERDUCK also saw the first appearance of Dr. Edward Thornton of the Naval Postgraduate School, an FRF experiment regular, collecting data from his first mobile instrumented sled.

The 1990 DELILAH experiment was essentially an experiment of opportunity, providing an inshore companion to SAMSON, a land and ocean experiment into the causes and importance of ocean bottom microseisms. Planning was compressed into the available 9-month preparation period and the focus was placed on hydrodynamics of the newly discovered shear waves and their relationship to the longshore current profile. Cross-shore and longshore arrays measured waves, currents, and swash dynamics (Birkemeier et al. 1997). These measurements also confirmed that, on a barred beach, the peak in the longshore current occurs over the nearshore trough, not over the bar crest as was predicted by theory at the time. The importance of large mega-ripples to sediment movement was also observed. DELILAH saw Dr. Robert Guza of the Scripps Institution of Oceanography, and Dr. Steven Elgar, now at the Woods Hole Oceanographic Institute, join the ranks of experiment regulars.

The hydrodynamic success of DELILAH, and the need for more detailed information about sediment transport and morphologic evolution led to a plan for two additional field experiments with added components to resolve sediment transport and morphologic evolution at bed form scales from ripples to nearshore bars. The first, DUCK94 (Birkemeier and Thornton 1994), was intended as a test run for the new instrumentation, more formal organization, and more complicated logistics to be exercised during the second experiment, SandyDuck '97. DUCK94 was held during August and October 1994 to take advantage of the synergy offered by the National Science Foundation's Coastal Ocean Processes (CoOP) experiment (Butman 1994), being conducted at the FRF during that time. DUCK94 also saw the first participation by the Canadian research group of Drs. Tony Bowen and Alex Hay and their introduction of scanning sonars technologies to bed form studies. During these two experiments, hundreds of sensors and instruments were deployed in the surf zone, from instrumented sleds pulled offshore, from the pier, and from the observation tower. The centerpiece of DUCK94 was a primary cross-shore array of instruments that included wave gauges, current meters, and acoustic altimeters to measure real-time bed level changes (Figure 9). Additional instruments measured suspended sediments, bottom bedforms, and other parameters (Birkemeier, Long, and Hathaway 1997). The success of the DUCK94 array led to the larger spatial array deployed during SandyDuck (see Table 1). Both experiments benefited from the involvement of a large segment of the North American nearshore research community in the initial planning of the objectives and the complex logistics required to define requirements and resource use (CRAB, boats, computers, office space, etc.). In turn, SandyDuck '97 became the largest coastal field experiment ever with participants from 18 universities; six Federal agencies; two private companies, and three foreign countries, conducting 30 separate experiments. Results of SandyDuck '97 are just now reaching publication.

One little recognized but important benefit of these experiments was the opportunity for interaction among the participants. The experiments brought together researchers that typically meet only at conferences perhaps once or twice a year. For an extended period of 1 to 6 months, these scientists and engineers, together with their students and technical support staff, shared space, resources, and ideas. In addition to deploying instruments and collecting data, meetings and seminars were held; hypotheses were proposed and discussed; abstracts and papers were written; and science was advanced. DUCK94 was so intense and interesting an experience, that it was highlighted in a chapter by Dean (1999). SandyDuck '97 received national recognition by being featured on the Cable News Network (CNN), the Weather Channel, and in USA Today.

SandyDuck was followed by SHOWEX, the Shoaling Waves Experiment, in the fall of 1999. SHOWEX was sponsored by the Office of Naval Research and designed to improve the scientific understanding of the properties and evolution of surface gravity waves typical of inner continental shelves up to the edge of the surf zone. The FRF provided logistic support for the shore-based operations including several surf zone components.

In addition to the major experiments, the FRF has also hosted a large number of smaller specialty experiments for users who benefit from the logistic support, field expertise of the staff, and available data. These studies, which have usually been supported by the Navy or Army, have covered a wide range of topics. These include atmospheric aerosols; mine detection and countermeasures; remote sensing ground truth; surveying techniques; ocean wave reflectance; wave growth and transformation; dune and marsh vegetation studies; and radar

Figure 9. DUCK94 primary cross-shore instrument array being serviced. Unlike during DUCK85 (Figure 8), to provide continuous coverage even during storms, sediment-transport measurements during DUCK94 and SandyDuck were made with in situ instruments

detection of waves and currents. These studies are always interesting because they present new challenges, broaden the FRF's logistic experience, and often introduce new state-of-the-art field instrumentation.

Impact on Research

The Field Research Facility has played a significant role in the advancement of nearshore science as evidenced by the number of publications pertaining to research conducted there. A recent compilation of bibliographic references indicates that more publications have been written describing observations obtained at Duck than for any other coastal facility worldwide. In addition to the hundreds of conference presentations given, approximately 150 journal articles, 108 reports, and 84 conference Proceedings papers have been published, and using FRF data by more than 200 authors representing 42 separate organizations and 16 different nationalities. Topics covered include acoustics, sandbar systems, beach cusps, bed forms, bottom boundary layers, coastal structures, directional spectra, edge waves, experiment summaries, equipment descriptions, facility guides, infragravity motions, morphodynamics, sediment transport, shear waves, surface gravity waves, swash processes, and wind-driven flows. A listing of these publications is available online at http://frf.usace.army.mil/biblio/pubs2.stm.

Many of these publications serve as primary references in the topics of nearshore oceanography and coastal engineering (several papers have been cited more than 40 times). Others stand as creative or innovative applications of technology towards resolving difficult research questions. For example, there have been a number of publications (including Birkemeier 1984; Lippmann and Holman 1993; Larson and Kraus 1994; Plant et al. 1999) pertaining to nearshore profile evolution data collected by the CRAB (Figure 10). Another significant series of publications relating to shear waves (Figure 11) can be traced to their observation by Oltman-Shay et al. (1989) during SUPERDUCK. Shear waves are generated by a shear instability of the mean longshore current. Similarly, over a dozen articles have been published establishing the usefulness of video (Figure 12) for making long-term, spatially extensive measurements of sand bar behavior (starting with Lippmann and Holman 1990) and beach profiles (e.g., Holman et al. 1991; Plant and Holman 1997; Stockdon and Holman

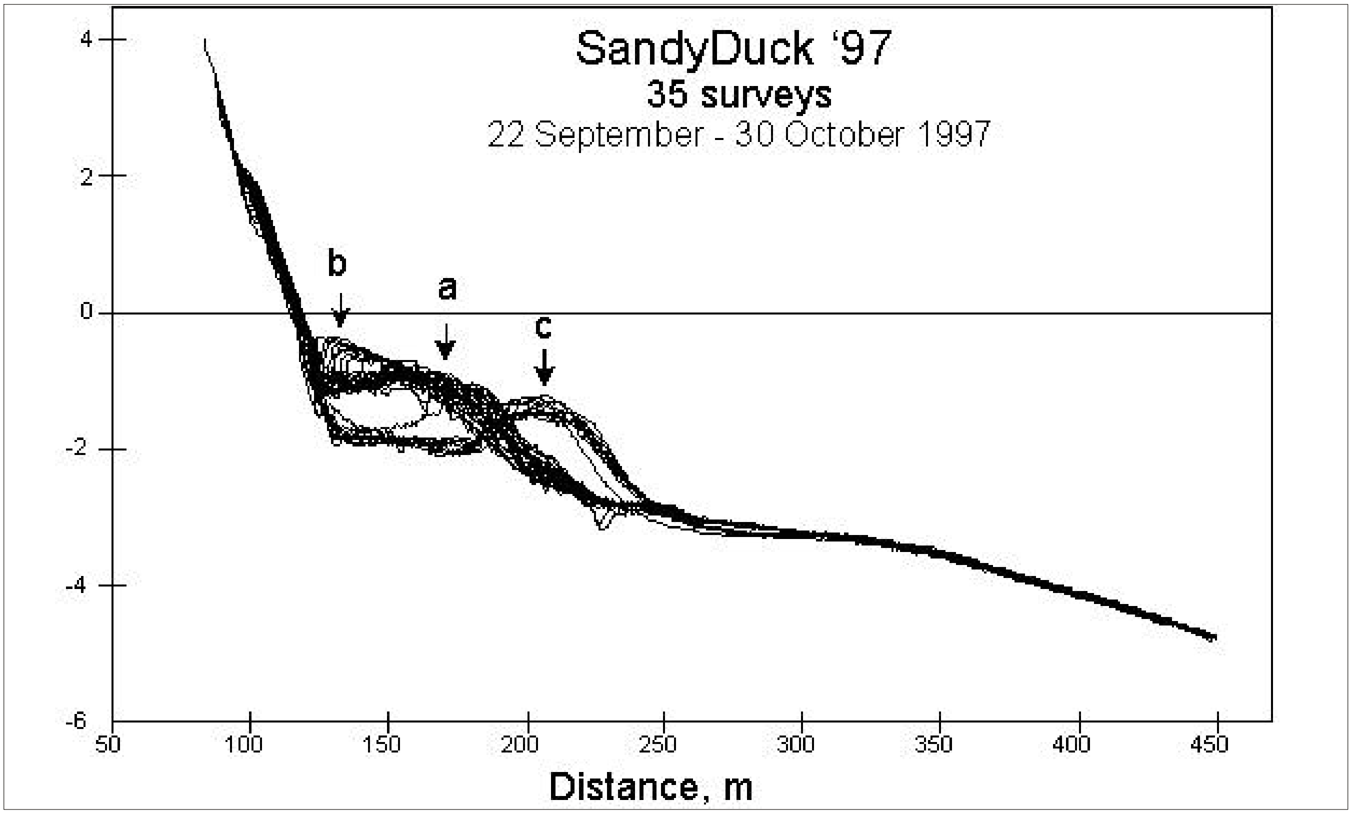

Figure 10. Envelope of cross-section surveys during the SandyDuck experiment showing large variations of bottom topography. During this period the sand bar was initially at location a, migrated onshore to location b, then moved offshore to location c during a passing storm

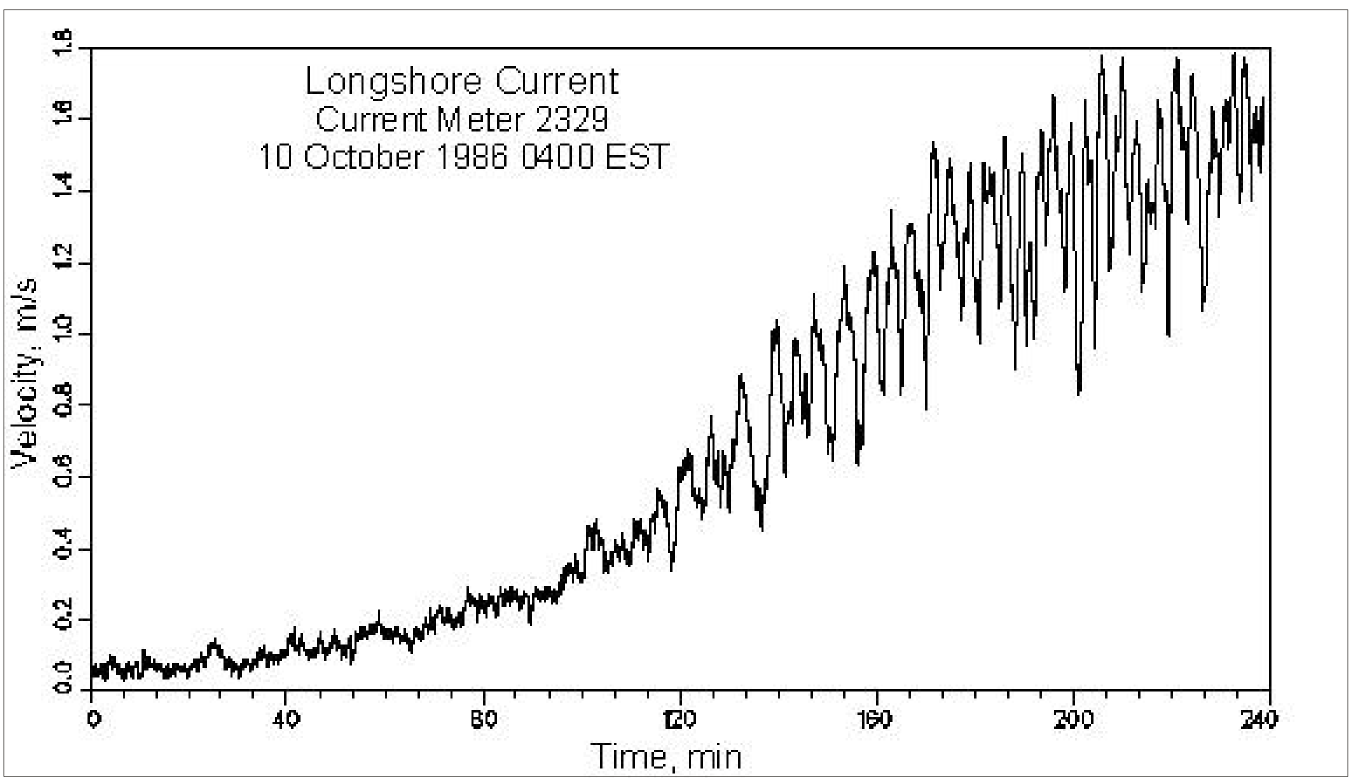

Figure 11. Evidence of shear waves found in 1986 during the SUPERDUCK experiment. Note the development of large-amplitude long-period wave forms after about 120 min, when the longshore velocity increased above 4 m/sec (after Hathaway et al. 1998)

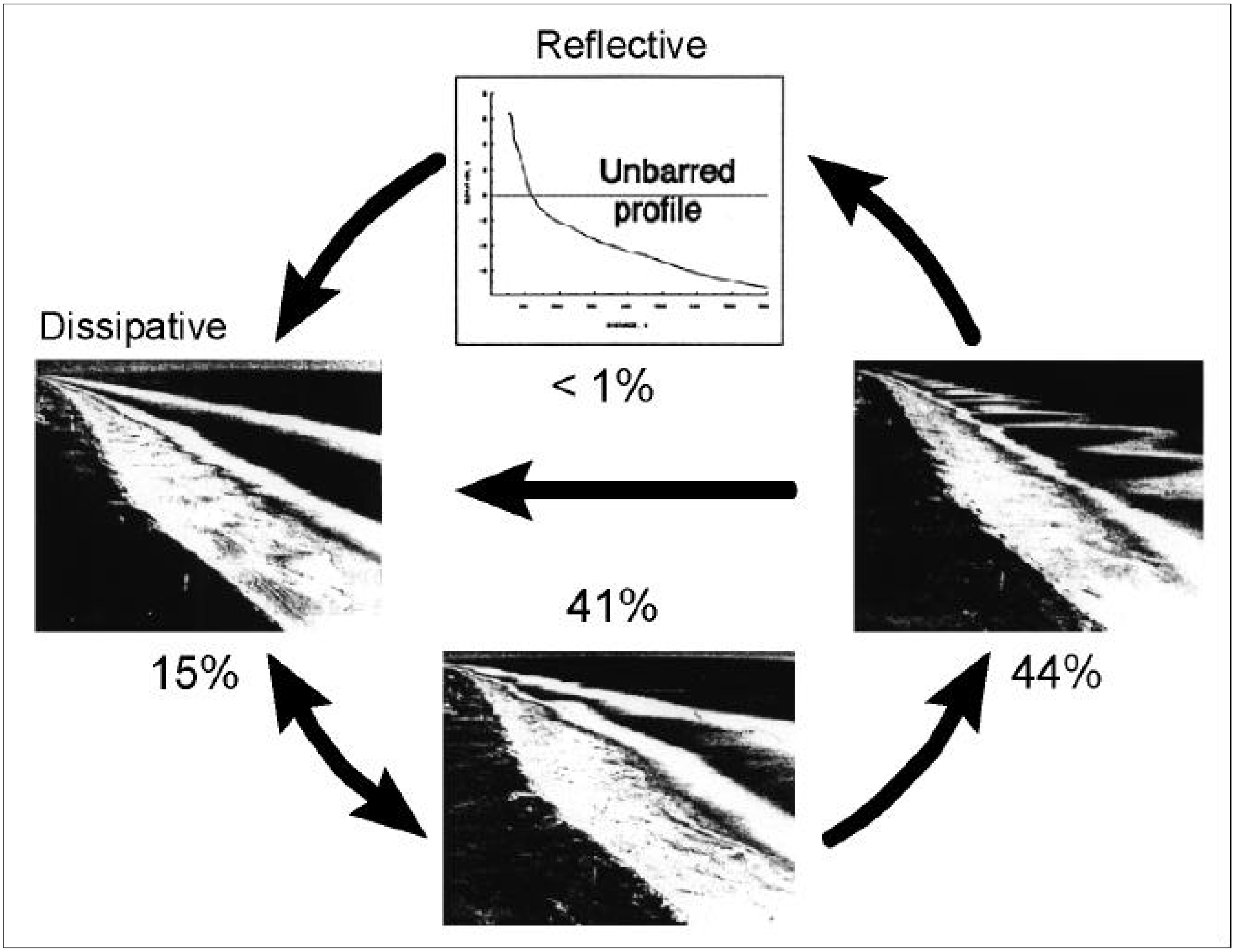

Figure 12. Diagram of beach states using time exposure video images modified from Lippmann and Holman (1990). Numbers indicate the percent of time that the nearshore morphology is unbarred, linear, mildly crescentic, or crescentic

2000). Other authors developed novel methods for using sonars to accurately monitor bottom bed forms (Gallagher et al. 1998b; Thornton et al. 1998).

The Duck location has served as an ideal site for the extension of these findings to other locales worldwide. The variability in waves, currents, and morphology at Duck has allowed hypotheses developed using data from the FRF to be validated elsewhere. For example, the fact that Duck experiences both reflective and dissipative conditions allowed the establishment of a relative scaling for infragravity motions with respect to offshore incident wave conditions (e.g., Holman and Sallenger 1985; Howd et al. 1991; Holland and Holman 1999). Interpretation of the extensive data collected during FRF experiments has also spurred the development and validation of models for alongshore momentum balances (Feddersen et al. 1998; Lentz et al. 1999), sand bar generation and migration (Sallenger et al. 1985; Holman and Sallenger 1993; Thornton et al. 1996; Gallagher et al. 1998a), wave energy transformation (Lippmann, Brookins, and Thornton 1996; Elgar et al. 1997), and the vertical structure of cross-shore currents (Haines and Sallenger 1994; Faria et al. 2000). There is little doubt that the existence of the FRF has resulted in publications that have extended our understanding of the complex interactions between hydrodynamic and morphodynamic processes.

Importantly, this research is leading to improved technology, procedures, and models for use by the Corps. For example, FRF data were used in the development and validation of the SBEACH (Larson and Kraus 1989) profile change model and GENESIS (Hanson and Kraus 1989) a shoreline change model. Corps Districts use software and survey procedures developed or tested at the FRF. Wave observations have contributed to more realistic wave modeling. Instrument tests and evaluations conducted at the FRF have led to more robust and reliable gauging at remote Corps sites. Video techniques developed at the FRF are being used in innovative ways to address unique Corps problems. Continued use of the Duck data set will raise the level of sophistication of the next generation of Corps nearshore numerical models.

A final, increasingly valuable aspect of FRF activities is the ongoing collection of long-time series of beach variability at a representative nearshore site. Only in the last decade has the existence and importance of interannual beach changes become apparent (Wijnberg and Terwindt 1995; Plant et al. 1999). Bathymetry and wave records from the FRF are one of only three long data records worldwide (Aarninkhof and Holman 1999; Wijnberg and Terwindt 1995) with which these phenomena can be studied.

Data Access

FRF data have always been accessible. For many years, the data were published in series of monthly preliminary data summaries and annual reports (Leffler et al. 1998). Association of the FRF with universities had an added benefit in 1994 when researchers from the Scripps Institution of Oceanography created the first FRF Web site to distribute information and data during DUCK94. The Web site quickly became the principle mechanism for distributing observations and video imagery in real time, along with historic data. Most FRF data are now available online including the major data sets from DELILAH and DUCK94. Printable versions of the monthly reports, climatalogical summaries of FRF data, descriptions of instruments, and information about the facilities, vehicles and equipment are also available. The FRF Web site (http://frf.usace.army.mil) has been very successful and currently averages 5,700 users per month.

The Web site also serves the public providing real-time ocean conditions and a "virtual" tour of the facility. Many visitors get an up-close look at the FRF by taking one of the well-attended summer tours or visiting with a group. The FRF is also a popular stop for coastal field trips along the Outer Banks for everyone from third graders to graduate students and science teachers.

Future Activities

Mason (1979) compiled a list of 29 potential studies to be conducted at the FRF. Many of these have now been accomplished, some more than once. Relevant among the remaining studies is the movement of nearshore placed material for beach nourishment, an experiment that is presently being discussed. Many topics not on the original list are now feasible to study owing to new instruments and technologies. Some subjects are wave breaking, sediment transport (to include size fractional rates), and the influence of currents combined with waves. Contributing technologies include acoustic current meters, digital video cameras, small rotary side-scan sonars, bottom-mounted acoustic altimeters, and new sediment transport sensors. High-resolution and spatially extensive remote sensing techniques are being developed which require verification with good ground truth data. These techniques, combined with the expertise of the FRF, will also be useful as the Corps' research program shifts to focus on questions related to the regional management of sediment.

The role of the FRF continues to evolve. It will be part of the new Integrated Ocean Observing System developing under the auspices of the National Oceanographic Partnership Program (http://www.nopp.org) and the Ocean.US office (http://www.ocean.us.net). This program is helping to integrate the ocean research interests of 14 Federal agencies and recognizes the value of data from facilities like the FRF to support the general knowledge of the ocean along with providing the wide spatial observations required for regional and global ocean models. The 23-year-long FRF data set will allow new, climatic change questions to be addressed and the interannual variability in coastal dynamics and morphology to be studied. The national value of sites such as the FRF is being recognized (Woods Hole Oceanographic Institution 2000) and a new consortium of East Coast facilities is developing to share data and resources.

Epilogue

This paper has reviewed the capabilities and progress of the Field Research Facility, established by the U.S. Army Corps of Engineers in 1977 to support their coastal research requirements. Through the unique combination of facilities, vehicles, long-term measurements, staff expertise, and a large and energetic community of users, the original objectives of the FRF creators have been exceeded. If anything, the first 23 years of the FRF have shown that, although much has been explained, even more remains to be learned. Our experience has been that improvements in observations usually challenge our existing understanding and raises new questions to be answered. The process of discovery is incremental, not easily rushed, and is continuing in Duck, NC at the U.S. Army Corps of Engineers' Field Research Facility.

Acknowledgements

Preparation of this paper was supported by the Field Research Facility Measurement and Analysis Work Unit of the U.S. Army Corps of Engineers' Coastal Field Data Collection Program. Preparation of the research summary and the list of FRF citations was supported by the Office of Naval Research through base funding of the Naval Research Laboratory. Mr. Curt Mason, the first Chief of the FRF, is recognized for his vision and guidance in developing the facility and its research program. Permission to publish this information was granted by the Chief of Engineers.

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Inlet Entrance Hydrodynamics, Grays Harbor, Washington

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Abstract

An extensive field data collection effort was undertaken during the fall of 1999 to examine wave propagation and currents through an inlet entrance. These data support a circulation and wave model for Grays Harbor, WA, a jettied entrance with a large tidal prism. Both the field data and model results show wave attenuation in the inlet entrance, flood currents strongest on the north side of the inlet, and ebb currents more uniformly distributed. The influence of the tidal current and water level on wave transformation was also examined. Ebb current produces the greatest change at the inlet entrance, increasing wave heights by as much as 0.5-1.5 m. Flood current increases wave height at the seaward end of the entrance due to the ebb shoal redirecting flow offshore, but reduces wave height in the inlet throat. Water level has a minimal impact on wave height in the inlet entrance, but does control wave height in the back bay.

Introduction

Grays Harbor is one of the largest inlets in the United States with a spring tidal prism of 5.5 x 10^8 m^3. Approximately 160 km^2 of 240 km^2 of bay area is emergent at low tide, indicative of expansive tidal flats. The entrance channel is approximately 9-12 m deep relative to mean lower low water, and the Federal navigation channel maintained on the south side of the inlet entrance is 12-13 m deep. As part of a U.S. Army Corps of Engineers navigation study, data were collected at seven locations extending from seaward of Grays Harbor and through the entrance to record surface wave propagation and current through the inlet (Figure 1). These measurements capture tidal flow and change of water level by tide and wind, as well as wave diffraction into the bay, processes that transport sediment into the navigation channel and over oyster-grounds leasing areas. Numerical models of waves and currents have been established for the entrance and bay at Grays Harbor as part of this study. This paper describes wave and current measurements and model simulations conducted to examine surface wave propagation through the inlet, including the modification of the waves by the tidal current and water level.

Field Data Collection

The data-collection program consisted of bathymetry surveys in the offshore and along maintained and natural channels; a Light Detection and Ranging (LIDAR) survey and controlled aerial photography of land and tidal flats during lower tide in the bay; measurement of water level at five locations around the bay periphery, wind and barometric pressure at a nearshore tower; and waves, water level, tidal current through the water column, and suspended sediment concentration at seven bottom-residing tripods. The tripod deployment interval of mid-September to mid-November 1999 spanned two lunar months (Hericks and Simpson 2000).

The tripods were deployed along or near the navigation channel (Figure 1). Stations 1 through 6 extend from the entrance, through the inlet, and into the bay. Each tripod was configured with a SonTek Hydra, functioning as a directional wave gauge and an up-looking 1,500-kHz Acoustic-Doppler Profiler (Figure 2). The Hydras contained a down-looking Acoustic-Doppler Velocimeter Ocean Probe, a high-resolution Resonant Pressure Transducer, and two optical backscatterence sensors. This instrument suite documented the waves, current near the bottom, and water level; the current through the water column in 0.5-m bins; and the suspended-sediment concentration through the inlet entrance. Station 0 (the seaward-most location) was configured with an Ocean Probe and an RDI Sentinel ADCP with directional wave-spectra firmware to determine if comparable data are derived from the two different measurement methods.

Numerical Simulations

The field-data collection supports both circulation and wave numerical models for Grays Harbor. The ADvanced CIRCulation (ADCIRC) long-wave hydrodynamic model can define the circulation and water level associated with both tide and wind (Luettich, Westerink, and Scheffner 1992). A two-dimensional

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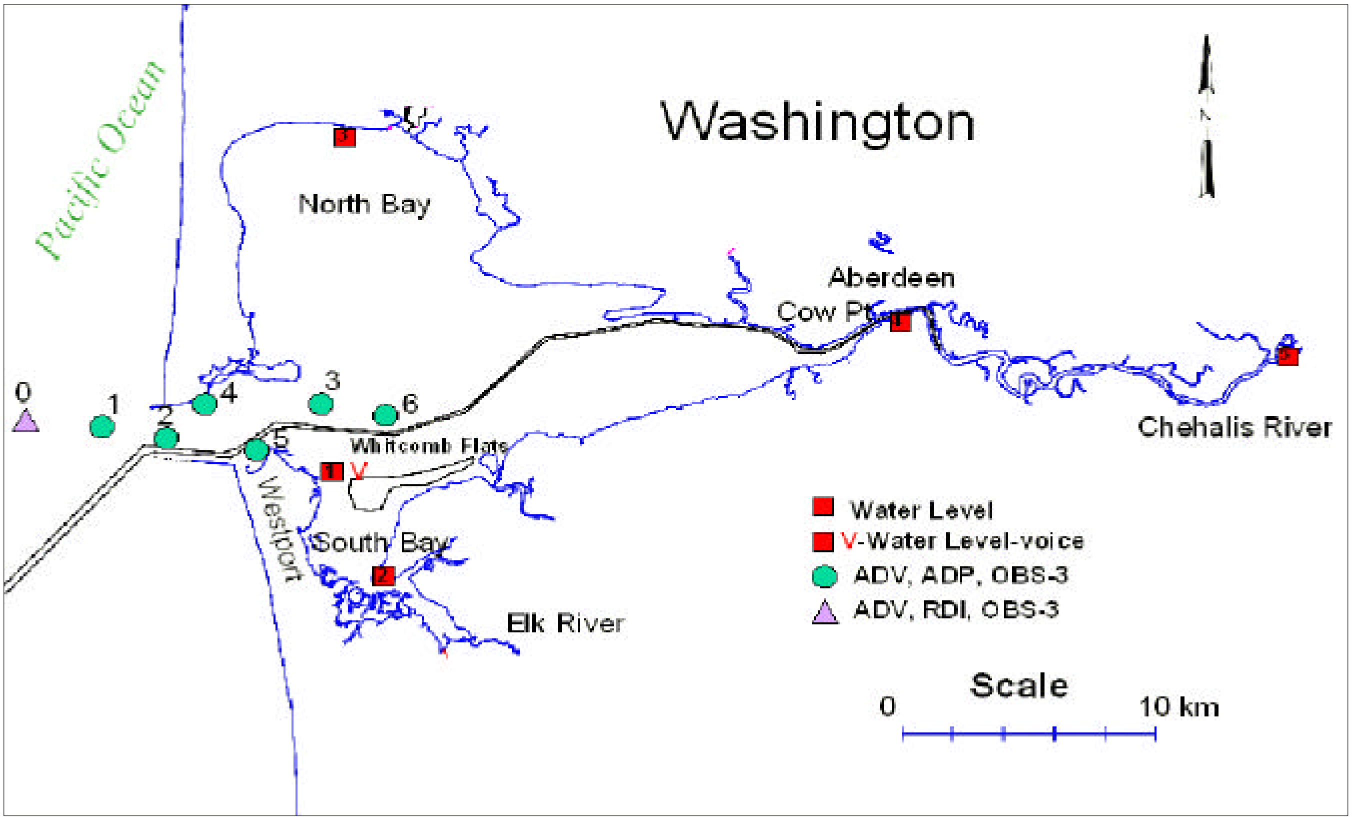

Figure 1. Grays Harbor, WA, location map and field-data collection schematic

(depth-averaged) version of ADCIRC was applied. The Corps' Coastal Inlets Research Program (CIRP) has enhanced ADCIRC to include flooding and drying, and it has exercised the model in shallow water estuarine conditions such as at Willapa Bay, WA and as a reconnaissance-level study at Grays Harbor, WA. The reconnaissance-level application of the ADCIRC model at Grays Harbor was enhanced and refined with field data collected in the Corps' navigation study.

The steady-state spectral wave model STWAVE has been modified in the CIRP to represent the wave-current interaction including the wave-action equation, current-induced breaking, and wave blocking by a current (Smith, Resio, and Zundel 1999). Communication between ADCIRC and STWAVE is necessary in this study for computing wave-generated currents through the transfer of the radiation stresses from STWAVE to ADCIRC and the transfer of tide-, wind-, and wave-generated currents from ADCIRC to STWAVE. In addition to improved wave modeling in the presence of a strong current, STWAVE will give reliable estimates of sea-state in the channel. It can also quantify storm wave conditions as a function of the wind. The CIRP is presently upgrading STWAVE to include diffraction through a gap, as found at the Grays Harbor jetties that open to the bay.

Tidal Circulation Modeling

A finite-element grid was developed for the ADCIRC model to simulate water-surface elevation and circulation as a function of tidal and wind forcing over the entire Grays Harbor region (Figure 3). The ADCIRC grid contains 31,838 elements and 16,916 nodes, with the finest resolution along the Federal navigation channel. The shoreline north of Grays Harbor (known as Ocean Shores) also shows fine grid resolution and is part of another coastal study. The ADCIRC model was driven with the Le Provost et al (1994) tidal constituent database for the field-data collection time period (September to November 1999).

Figure 4 is a time-series of water surface elevation from the field data collection time period and computations at South Bay and Aberdeen (see Figure 1 for locations). Model results correspond to the field data both in amplitude and phase at both the southern and eastern ends of the bay. Figure 5 is a time-series of current speed from the field data collection time period and computations at Inlet stations 2 and 4. Computations correspond to the field data in amplitude with slight phase differences, attributable to bathymetric inaccuracies. Ebb and flood current data and model results show the strongest flood currents are on the north side of the inlet. Ebb currents are more uniformly distributed (Figure 6).

Wave Propagation Modeling

A computational grid for the region shown in Figure 7 was developed for the Steady-State Spectral Wave Model (STWAVE), which computes nearshore wind-wave growth and propagation (Resio 1987, 1988a, 1988b; Davis 1992). (This

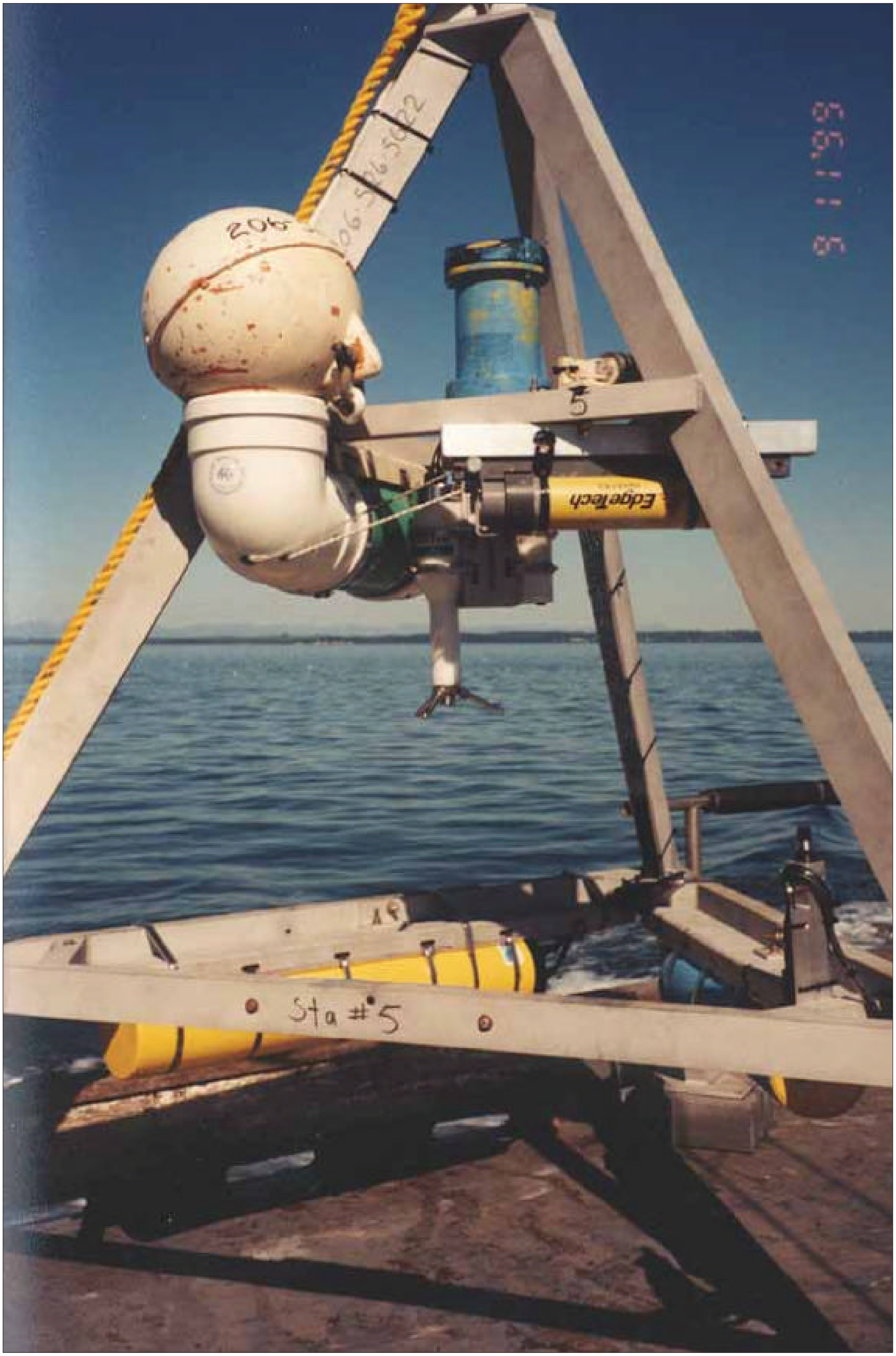

Figure 2. Instrument tripod

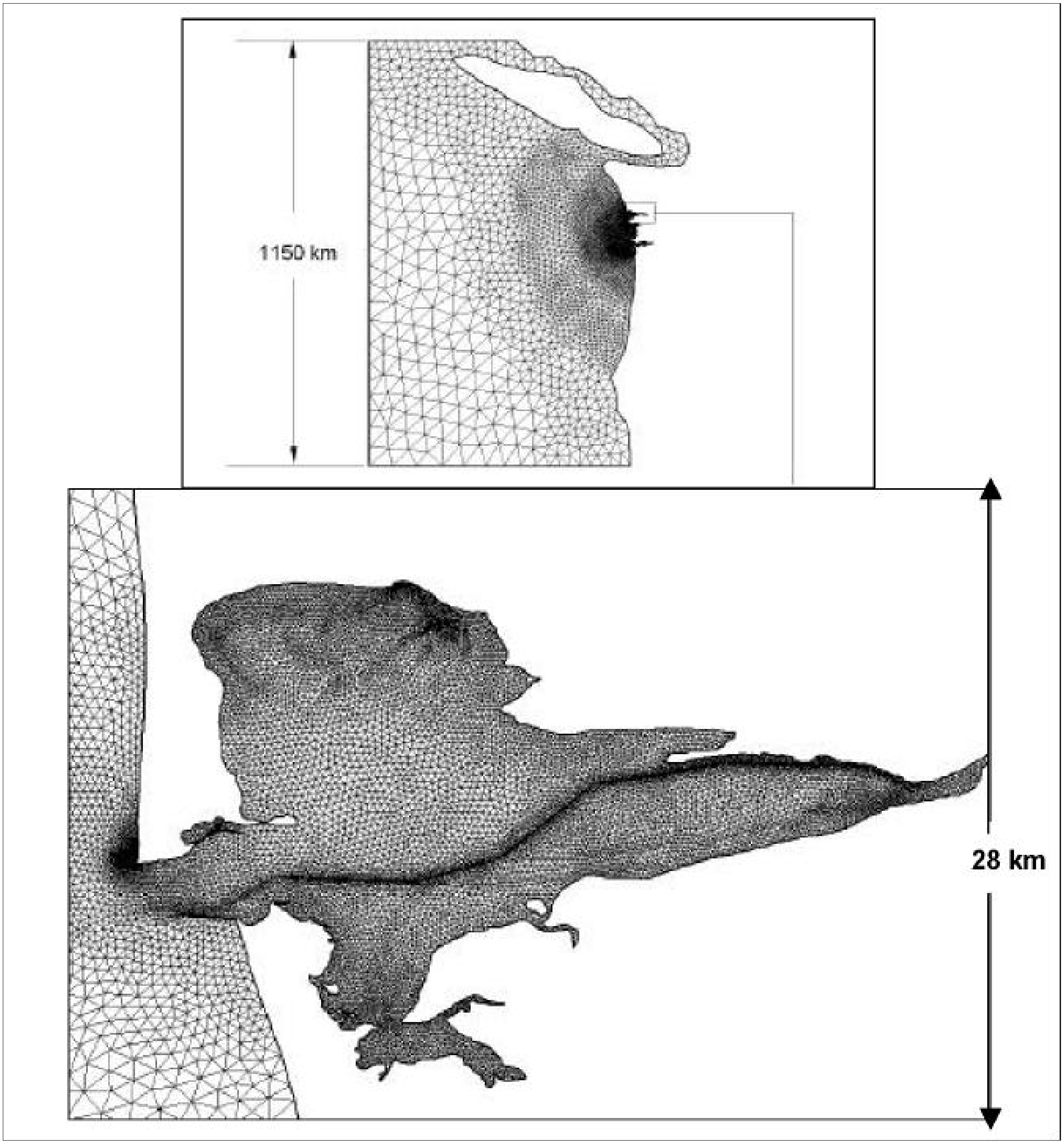

Figure 3. ADCIRC computation grid and details of Grays Harbor, WA

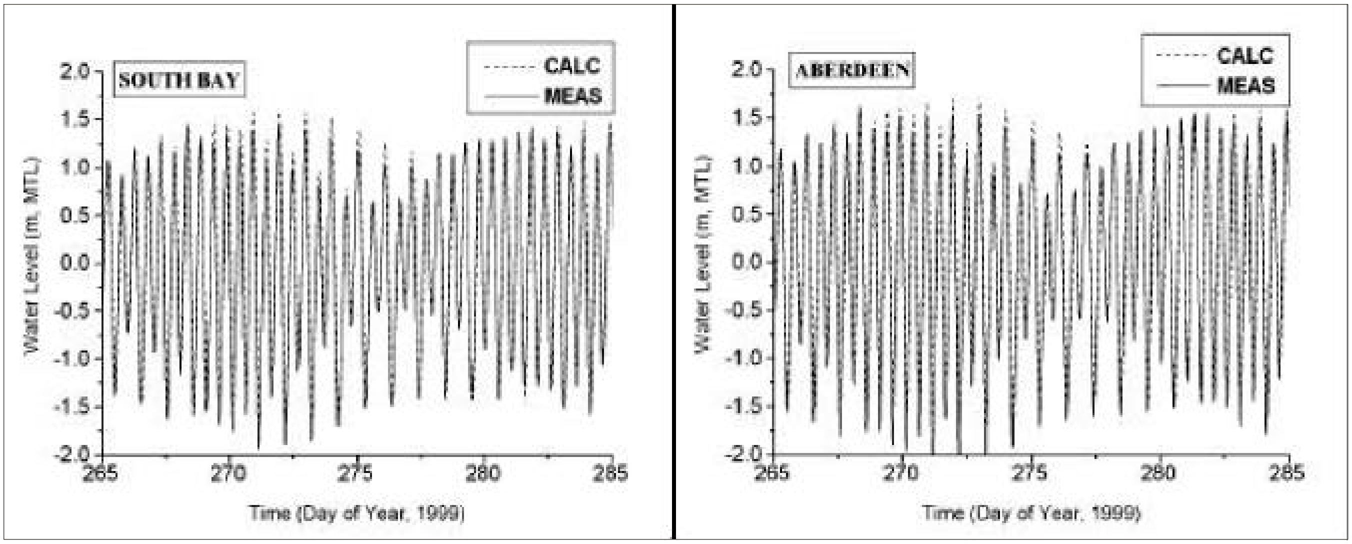

Figure 4. Measured water levels and ADCIRC model results at bay stations 2 and 4

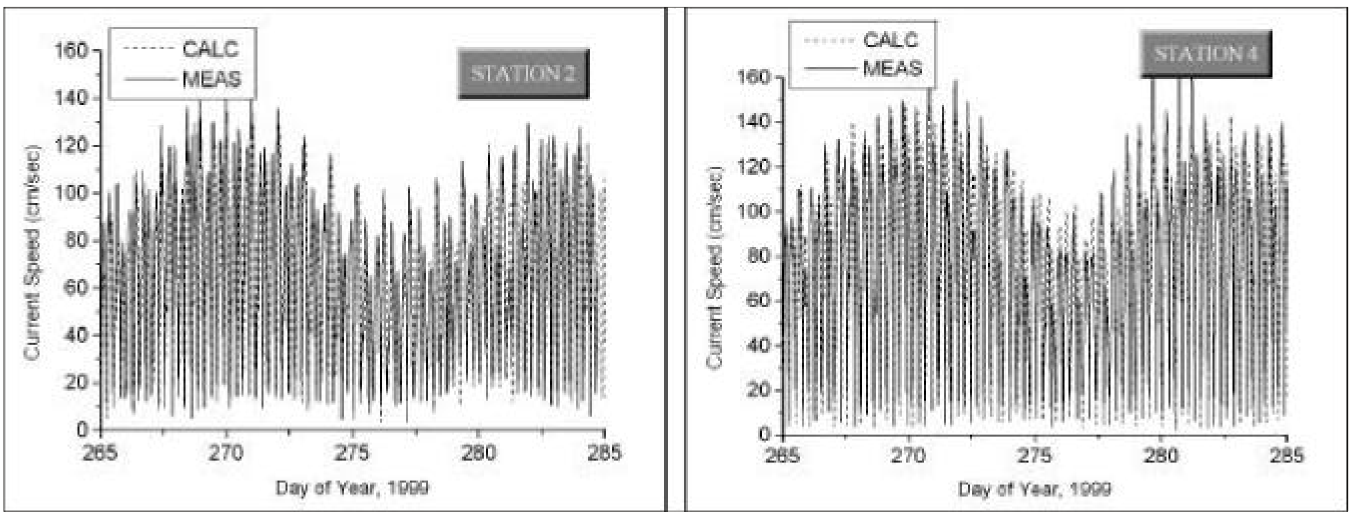

Figure 5. Measured currents and ADCIRC model results at inlet stations 2 and 4

application did not consider wind-wave growth because the 9-km fetch had a limited effect on wave height, typically less than 15 percent.) Bathymetric data were obtained from the U.S. Army Engineer District, Seattle, 1999 annual survey and from the GEOphysical DAta System GEODAS database of Hydrographic Survey Data (National Geophysical Data Center of National Oceanic and Atmospheric Administration (NOAA)). The vertical datum was adjusted from mean lower low water to mean tide level with the Westport (Figure 1) tidal benchmark adjustment of 1.5 m. Tidal elevation data were added to the mean tide level bathymetry for each simulation where the influence of tide level was considered. The grid orientation is 10 deg west of north to align the longshore axis with the offshore bathymetric contours (Figure 7). The STWAVE grid had 341 cells in the cross-shore direction and 588 cells in the longshore direction with a cell size of 50 x 50 m.

STWAVE simulations of the first month (11 September –14 October) of the 2-month period of field-data collection (11 September through 17 November 1999) were accomplished by driving the model with the Grays Harbor Coastal Data Information Program (CDIP) buoy wave spectra at 3-hr intervals. The CDIP buoy is located at 46° 51.47’ north latitude and 124° 14.64’ west longitude, approximately 9 km southwest of the entrance to Grays Harbor in a depth of 40-42 m. One-dimensional frequency spectra from the CDIP datawell buoy at Grays Harbor (03601) were obtained from the CDIP Web site. A theoretical directional spread was applied to the frequency spectra to create 2-D spectra for input to the STWAVE model. The two-dimensional spectra were rotated 10 deg west of north to correspond with the grid orientation. Tide elevation data from water level station 1 were used to modify depth for each 3–hr time period to account for water level (and depth) fluctuations of the tide.

Model validation with the field data shows good correlation. A preliminary comparison of wave height at seven wave gauge locations

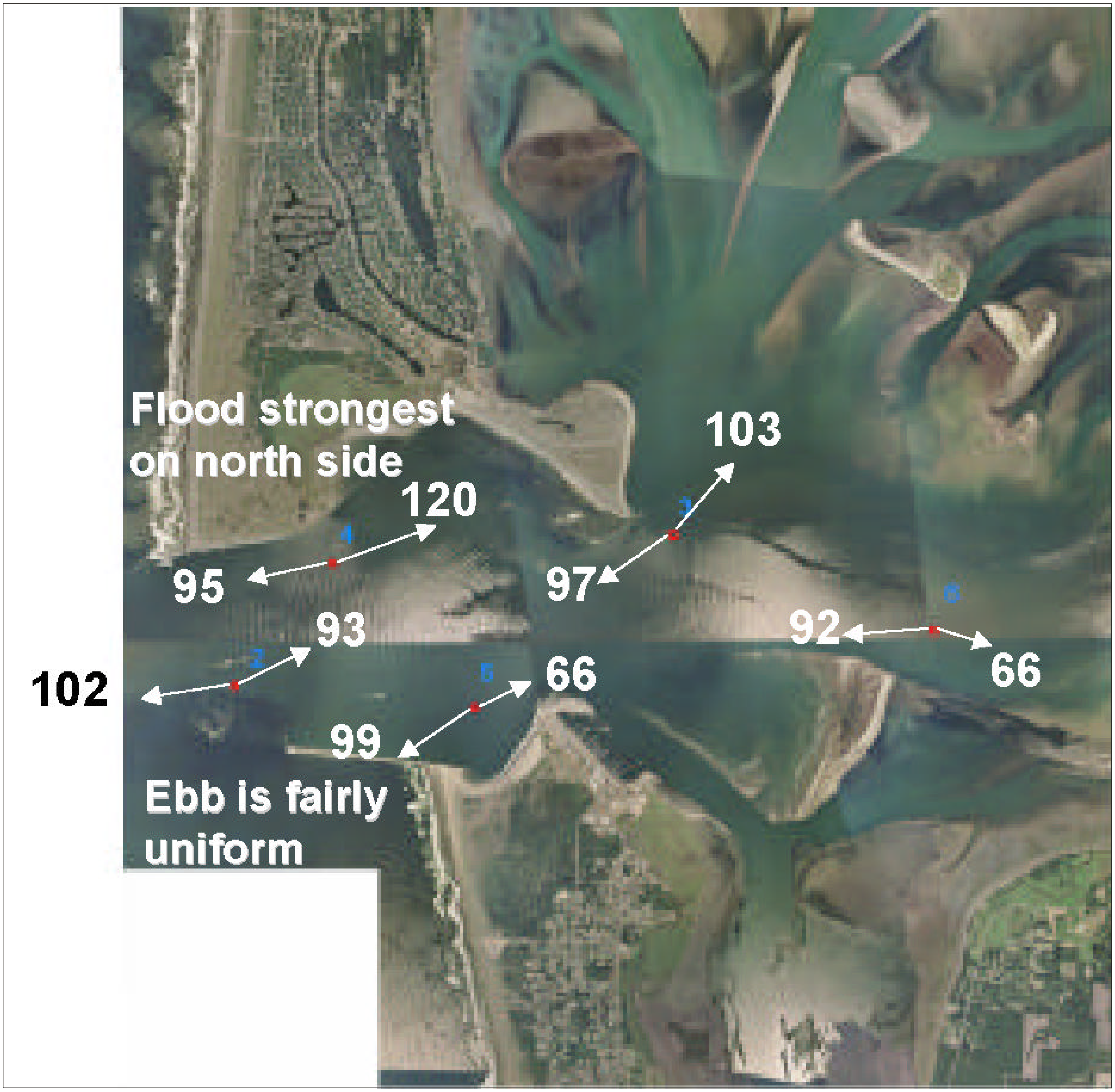

Figure 6. Average peak ebb and flood currents (cm/sec) for first month of field-data collection

(stations 0 through 6 in Figure 1) to the model results at these locations is given in Figure 8. Wave attenuation from station 0, to station 2, to station 3, to station 6 is clearly evident. The maximum wave height at stations 0 through 2 is over 4 m. Wave heights at stations 4 and 5 (in the inlet throat) do not exceed 2.8 m during this same time period. Wave height at station 3 does not exceed 1.2 m and at station 6 (most bayward) does not exceed 0.4 m. All stations show some evidence of tidal influence, with the most predominant influence at the interior stations (stations 3 and 6). The difference between measured and calculated wave height shows that model results are typically within 0.5 m of the measurements.

Impacts of Currents and Water Level on Wave Transformation

Climatological conditions were determined from the CDIP buoy data (August 1993 through November 1999). The wave climate was divided into 6 height, 5 period, and 6 significant angle bands to drive the STWAVE model, for a total of 180 STWAVE simulations (Table 1). Wave conditions were first run at

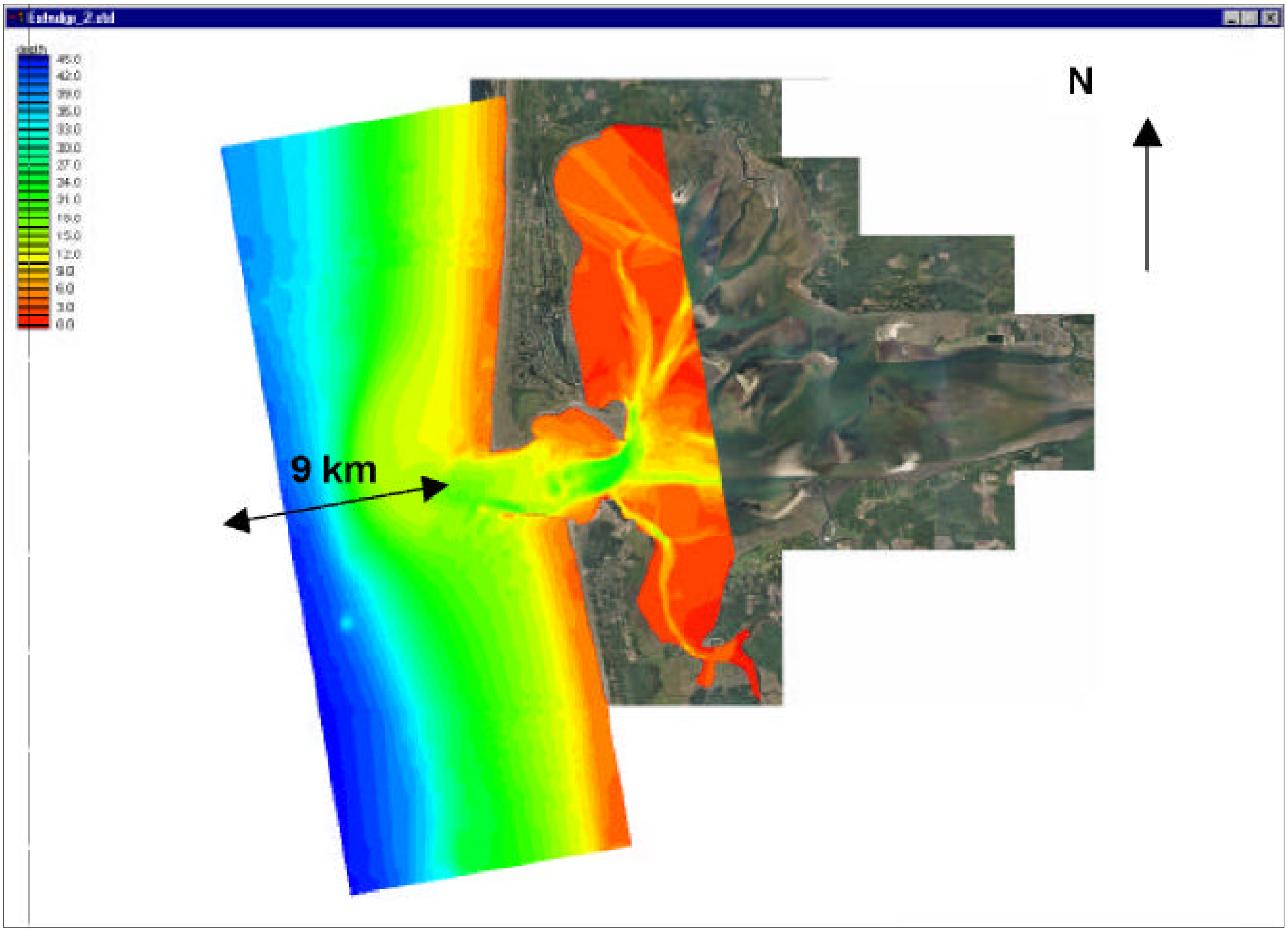

Figure 7. STWAVE model domain used in navigation study

Table 1. Wave Conditions from Grays Harbor Wave Climate (1993-1999)			
Significant Wave Height, m	**Peak Period, sec**	**Wave Direction, Deg from North**	**Compass Direction**
0.5	6	202.5	SSW
1.5	8	225.0	SW
2.5	12	247.5	WSW
3.5	16	270.0	W
5.0	20	292.5	WNW
6.5		315.0	NW

mean tide level (mtl) with no current. These base condition results were monitored at all inlet data-collection locations (Figure 1). The majority (45.1 percent) of the waves are in the 1-2 m range and result in waves at the entrance to Grays Harbor of approximately 0.5 to 2 m. Wave heights in the 2-3 m range at the CDIP buoy have a 24.7 percent occurrence, producing waves of 0.5-3 m at Grays Harbor entrance. The largest waves (>6.5 m) have a probability of occurrence of less than 1 percent, but result in wave heights of 1-8 m in the inlet entrance. Wave heights at tripod station 3 (bayward side of the inlet entrance) have an 80 percent probability of being less than 1 m.

The climatology simulations were then made at different tide stages and currents. Conditions were selected based on analysis of data, which showed that slack currents in the inlet occur near the time of mean high water and mean low water and maximum currents occur near the time of mtl. Ebb and flood currents were obtained from an

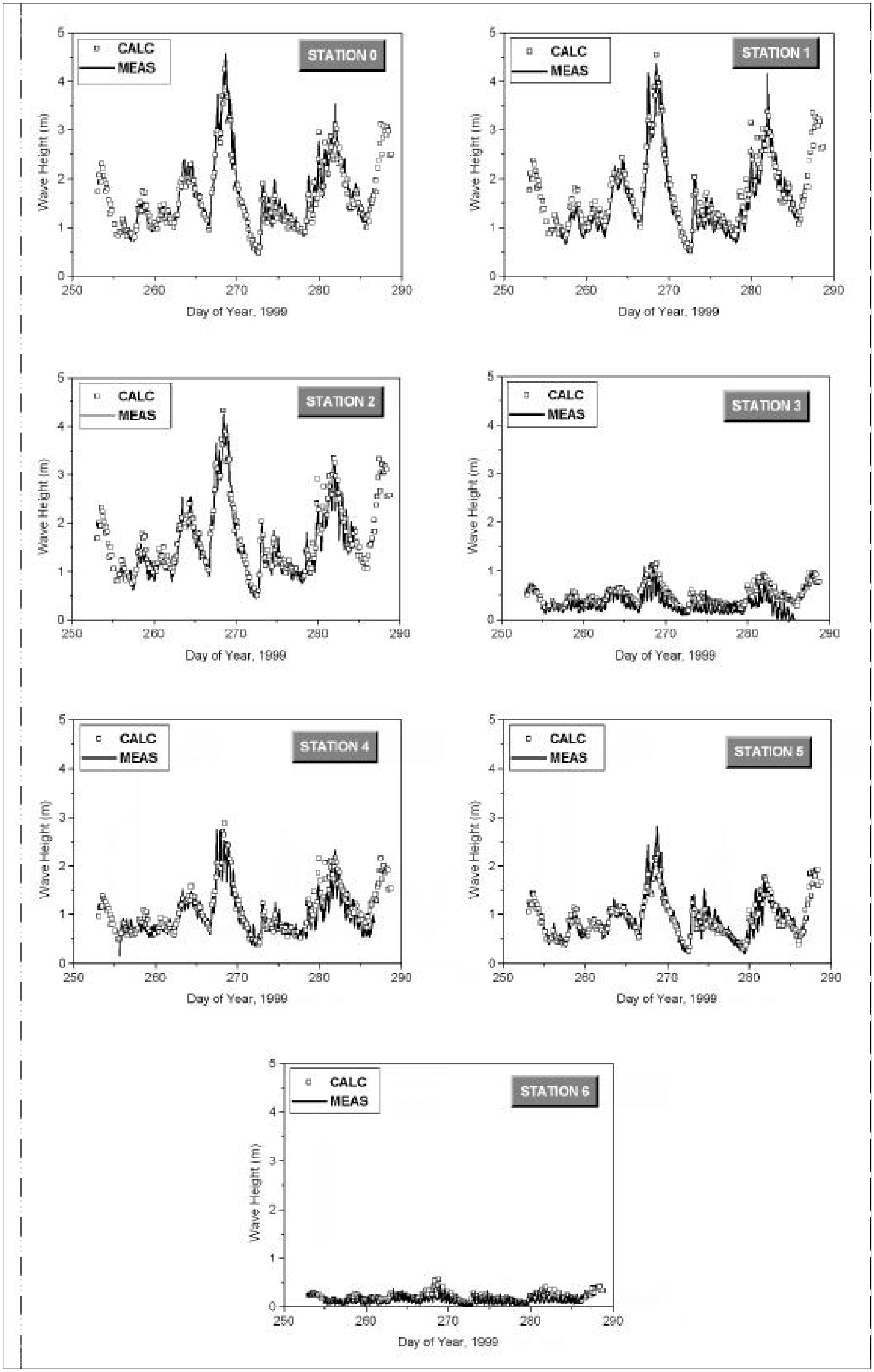

Figure 8. Measured wave height and STWAVE model results

ADCIRC simulation and interpolated onto the STWAVE grid. Peak currents, on the order of 0.8-0.9 m/sec, were selected for a typical mean tide cycle and do not represent maximum conditions that can occur at Grays Harbor. (The maximum current at the entrance during the first deployment period was 1.7 m/sec.) The tide range was approximately 2.1-2.2 m, which is equivalent to the mean tide range, whereas the spring tide range is on the order of 3 m. These simulations demonstrate the influence of water level and current on waves in the Grays Harbor entrance. Figures 9 and 10 show differences in wave height at station 2 for the various currents and water levels versus wave heights with no current or water level variation. Water level has minimal influence on wave height in the inlet entrance under most conditions. Flood currents increase wave height at station 1 (due to the ebb shoal bathymetry redirecting flow offshore), but reduce wave height at stations 2 and 3. Ebb currents cause a significant increase in wave height at all stations for most wave conditions.

Conclusions

An extensive hydrodynamic study of Grays Harbor, WA was conducted including data collection in fall 1999 and numerical model simulations. The measurements show considerable wave attenuation through the inlet throat (factor of 10 decrease), flood currents strongest on the north side of the inlet, and ebb currents more uniformly distributed. The numerical models include wave and tidal circulation simulations and the effects of tidal currents and change in water level on waves in an inlet entrance. Ebb currents have the greatest influence and increase wave height 0.5-1.5 m. Flood currents increase wave height at the seaward end of the entrance due to a local bathymetry-induced flow reversal and reduce wave height (flatten waves) further inside the inlet entrance. Water level has a minimal impact on waves in the inlet entrance, but does control wave transformation in the back bay. Examination of the effect of tidal currents on wave transformation and the modification of the current through wave radiation stresses will be examined in the next stage of dynamic linking of models through the CIRP steering module.

Acknowledgements

This work was performed as part of a mission-support activity for the U.S. Army Engineer District, Seattle. Permission was granted by Headquarters, USACE, to publish this information. The cooperation of

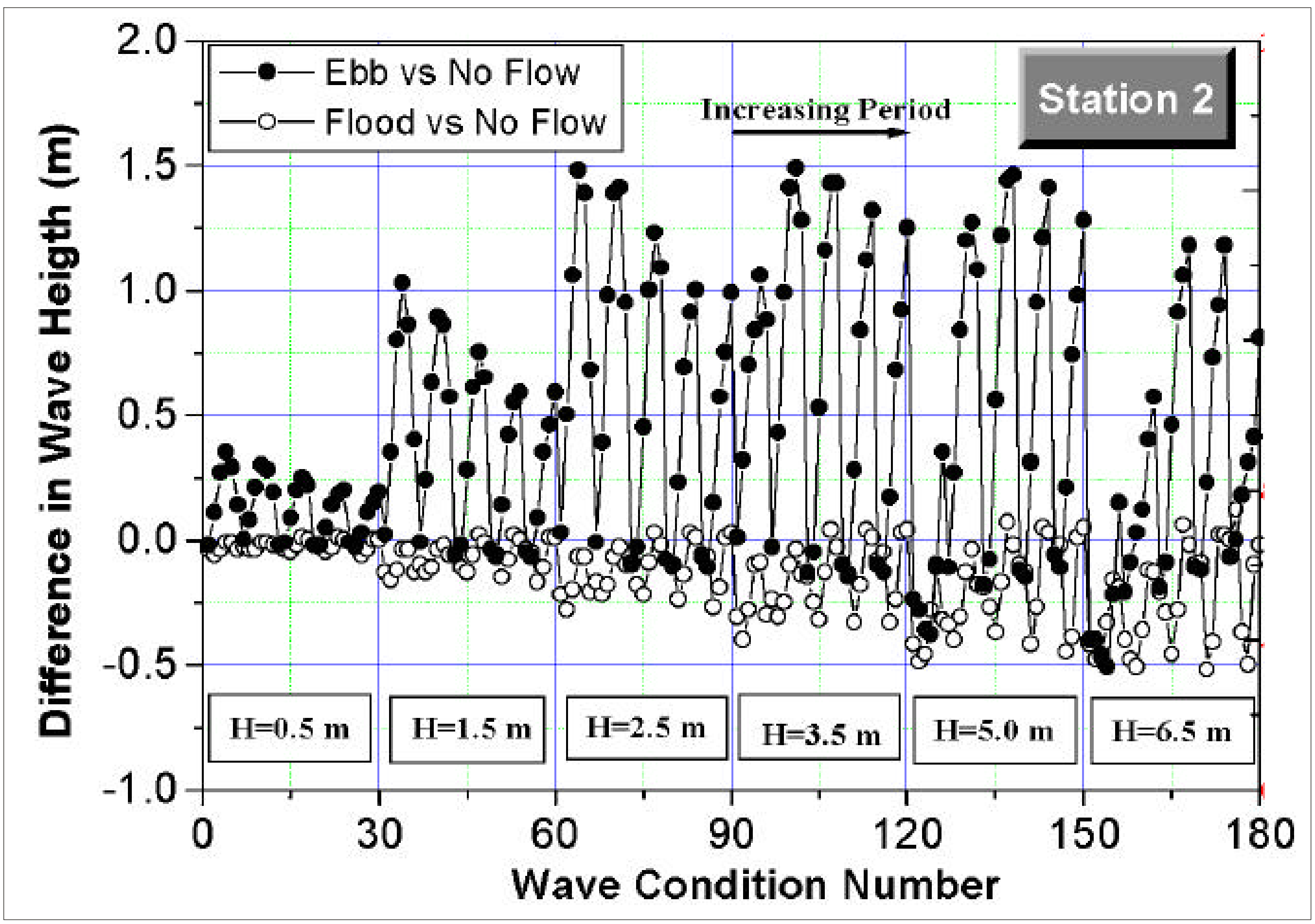

Figure 9. Influence of current on wave height. Each group of 30 wave conditions includes 5 wave periods and 6 wave directions

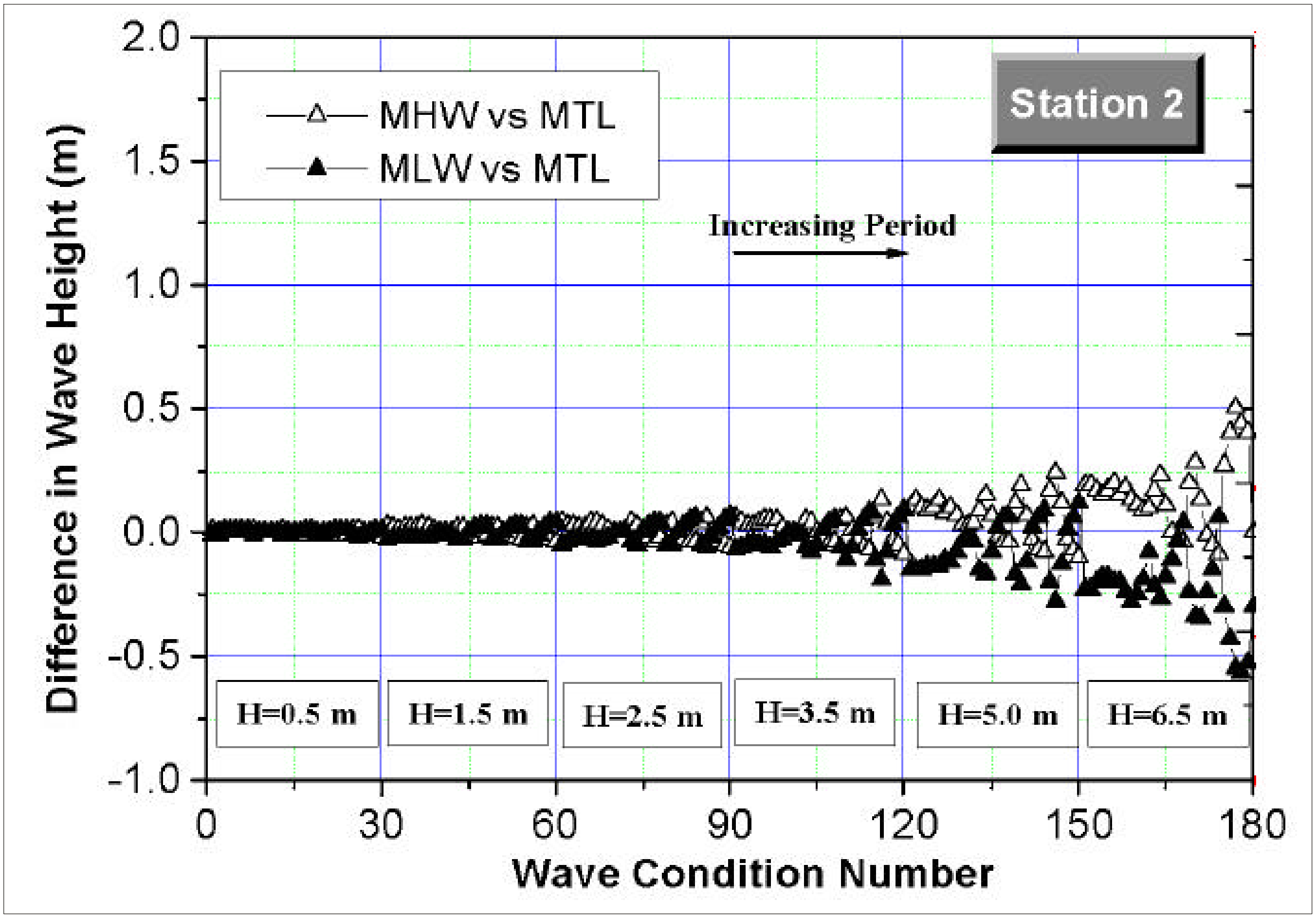

Figure 10. Influence of water level on wave height. Each group of 30 wave conditions includes 5 wave periods and 6 wave directions

instrument manufacturers named in this work is acknowledged, but no endorsement of equipment is implied.

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Developing a Lock Operation Strategy for Pool Lowering

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Abstract

The pool lowering capability of Locks and Dam 1, Mississippi River, can be increased if the lock filling and emptying system is used as a discharge outlet. However, the steady-state conditions of passing flow through the lock system and the conditions during the acceleration to steady state can include excessively low pressures downstream of the filling and emptying valves. A lock valve operation scheme that provided acceptable flow conditions in the lock system was developed using a numerical flow model of the lock filling and emptying systems coupled with commercial optimization software. The flow model was validated with field data obtained at the Lock 1 prototype. The resulting modeling system determined the optimum valve operations to obtain steady-state conditions and provided the head-discharge relationship for the lock.

Introduction

A valve operation scheme is developed for passing flow through the filling and emptying system of Lock 1, Mississippi River. The Locks and Dam 1 project is located at Mississippi River mile 847.6 above the mouth of the Ohio River between the cities of St. Paul and Minneapolis, MN. The original lock and dam was opened to navigation in 1917. The dam is a 175-m overflow structure having a privately owned hydro power station. Construction of a new lock was completed in 1930. A second lock, landward from the first, was completed in 1932. The lock chamber is 17.1 m wide by 121.9 m long and has a design lift of 11.6 m. Rehabilitation of the landward lock, the subject of this study, was completed in 1981. Details of the filling and emptying system are provided on the plan and elevation drawing of Figure 1. The need to provide a means of pool lowering has led to the idea of using the lock culvert system as a pool outflow structure. The questions to be answered are what is the best manner in which to operate the valve and what is the head-discharge relationship for the lock system.

The purpose of this study is to develop a lock operation scheme for

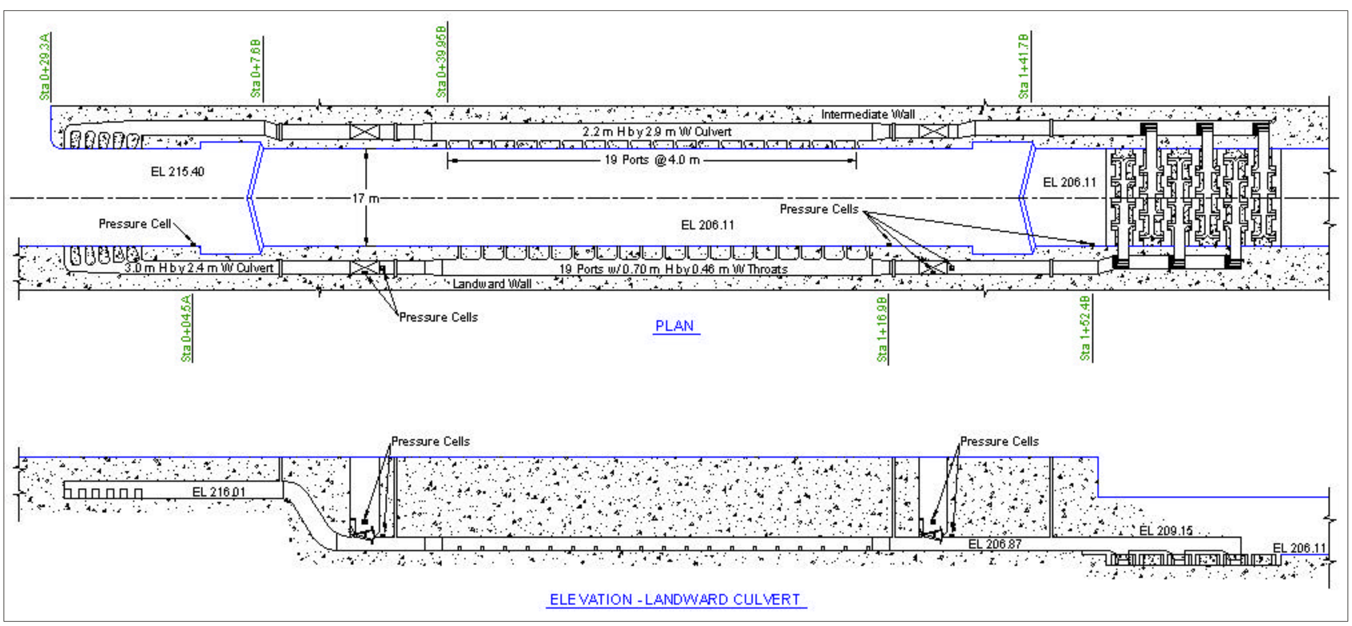

Figure 1. Plan and profile of landward lock, Lock and Dam 1, Mississippi River

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pool lowering. Project personnel want the option of using the lock's filling and emptying system during emergencies which require rapid pool lowering. Guidelines and operation procedures are needed to provide lock operators instruction for lock valve operation during an emergency. An earlier hydraulic model study (Ables 1979) found that low pressures exist in the lock culvert during the unsteady flow of lock operations, which might induce cavitation in the culvert system. The objective of the present study is to compute a head-discharge relation for the culvert system and to develop a safe operation procedure that avoids excessively low pressures and that swiftly reaches steady state. First, a numerical model of the filling and emptying system was constructed. The numerical model provided information for simulations of different head and tailwater conditions. The computed discharge and pressures were validated with prototype data. Information needed for numerical model validation were the temporal variations of the upper and lower pool, the lock chamber water surface, the gate position, and the lock culvert pressures downstream of the filling and emptying valves. The validated model was then coupled with optimization software to determine the best method of using the lock culvert system to pass flow in the event that pool lowering is required. The study determines if the lock system can be used as an outlet structure and the optimum operation scheme for pool lowering. This paper describes the development of the lock model and the determination of the optimum valve operation. The optimization model minimizes the time required to reach steady-state flow while maximizing the minimum cavitation indexes downstream of the operating valves during the transient conditions of steady flow establishment.

Lock System Model

The numerical flow model, LOCKSIM (Schohl 1999) serves as an evaluation tool for lock filling and emptying system designs. LOCKSIM couples the unsteady pressure-flow equations, which are applicable to the conduits within the system; with the free-surface equations describing the approach reservoirs, valve wells, and lock chamber. The model computes pressures and flow distributions throughout a lock system. Discharge and piezometric head in the lock system components are computed by numerically solving partial differential equations for one-dimensional unsteady flow. The relationships between discharge and piezometric head difference for valves and culvert losses are described by algebraic energy equations. The position of a valve is prescribed as a function of simulation time. Functions are also used for manifold components, which simulate combining and dividing flow, to describe the variation of the branch head loss coefficients with the ratios of the individual branch discharges to the combined discharge. Available time-varying numerical results include pressure, hydraulic grade line elevation, and discharge at all computational points. The stage, velocity, depth, top width, and channel area are provided at each computational point within the free-surface components and the velocity, shear stress, and vapor cavity volume are given for each computational point within the closed-conduit components. The minimum pressures and cavitation indices in the wakes of reverse tainter valves are also computed.

This study's principal objective is to construct a model of the Lock 1 system and then develop an operational scheme that would transition the flow from unsteady to steady state for passing discharge through the system. The numerical model reproduced the entire filling and emptying system including the intakes, valves, culverts, lock chamber, and outlets. Field data (Stockstill, Fagerburg, and Waller 2000) were used to quantify loss coefficients of the lock system. Energy loss coefficients were determined for primary components of the system for which there is limited published data. Both the filling components and the emptying components of the lock system were validated with field data. The location of the pressure cells used in the data collection are shown on Figure 1. The pressure cells provided temporal variations of the water surface in the upper and lower approaches, in the lock chamber, and in the valve wells. The pressure cells also measured the soffit pressure downstream of the valves during lock operations.

Model Parameters and Loss Coefficients

The contraction coefficient is a parameter used to calculate the piezometric head at the culvert soffit immediately downstream of the filling and emptying valves and the cavitation index for the low-pressure region downstream of the valves. Published data quantifying the contraction coefficient for reverse tainter valves shows considerable scatter (Engineer Manual 1110-2-1610). The coefficient of contraction for the reverse tainter valves was specified as a fourth-order polynomial function in terms of the relative valve opening. This function is a best fit of the prototype data presented in EM 1110-2-1610 "Hydraulic Design of Lock Culvert Valves" (Schohl 1999). The contraction coefficient for a reverse tainter valve is very sensitive to the shape of the bottom edge of the valve, therefore there is no universal description of contraction coefficients for reverse tainter valves. However, the values used for this study are believed to be adequate for estimating the lowest pressures at partial gate openings.

Field data obtained during lock operations were used to determine energy loss coefficients on the components for which no published data are available. Loss coefficients for many hydraulic components are well established and are readily available in the literature (e.g., Miller 1990; U.S. Army Corps of Engineers 1952). However, lock culvert system components are often unique to a particular project and the loss coefficients have not been determined. The unknown coefficients were determined from field data using the optimization techniques provided in the commercial-software package iSIGHT[1]. This involved linking the numerical model of Lock 1 with iSIGHT. The optimization routine was developed to automatically change the specified coefficients in the model input file, execute the LOCKSIM program, read the flow solution, and compute error indicators. The error indicators were chosen to be the differences in computed and observed operation time, pressure downstream of the valve and the water surface in the valve well at critical times during the operation. The optimization scheme drove these error indicators toward zero by adjusting the specified energy loss coefficients. Techniques of both exploitative and exploratory optimization were used. The exploratory techniques, which are numerical optimization techniques, provided minimization of an objective function, while exploration was used to find optimum solutions throughout the parameter space. The numerical optimization techniques employed were of the direct methods type. Specifically, the method of feasible directions and modified method of feasible directions were used to find local optima. Global optimization was achieved using the explorative techniques of genetic algorithm and adaptive simulated annealing. Model simulation runs were completed in an automatic fashion for both the filling system and the emptying system in order to establish the loss coefficients.

Filling System

Determination of the loss coefficients for filling system components used the field data recorded for a single-valve filling operation (landside culvert). Particular emphasis was the determination of appropriate loss coefficient values for the intakes and the “chute” vertical transition. This transition involves two vertical curves and a 9.1-m drop in culvert elevation immediately upstream of the filling valves. The field data were used to establish the values of these loss coefficients by integration of the numerical model with the optimization software in the manner previously described. The results of the adjusted model are shown on Figure 2. The model reproduces the field data quite well except for the pressures downstream of the filling valve during the first 50 sec of the filling operation. The valve opens about 55 percent during this period. Early in the operation, the computed pressures are significantly higher than the measured values due to the errors in the

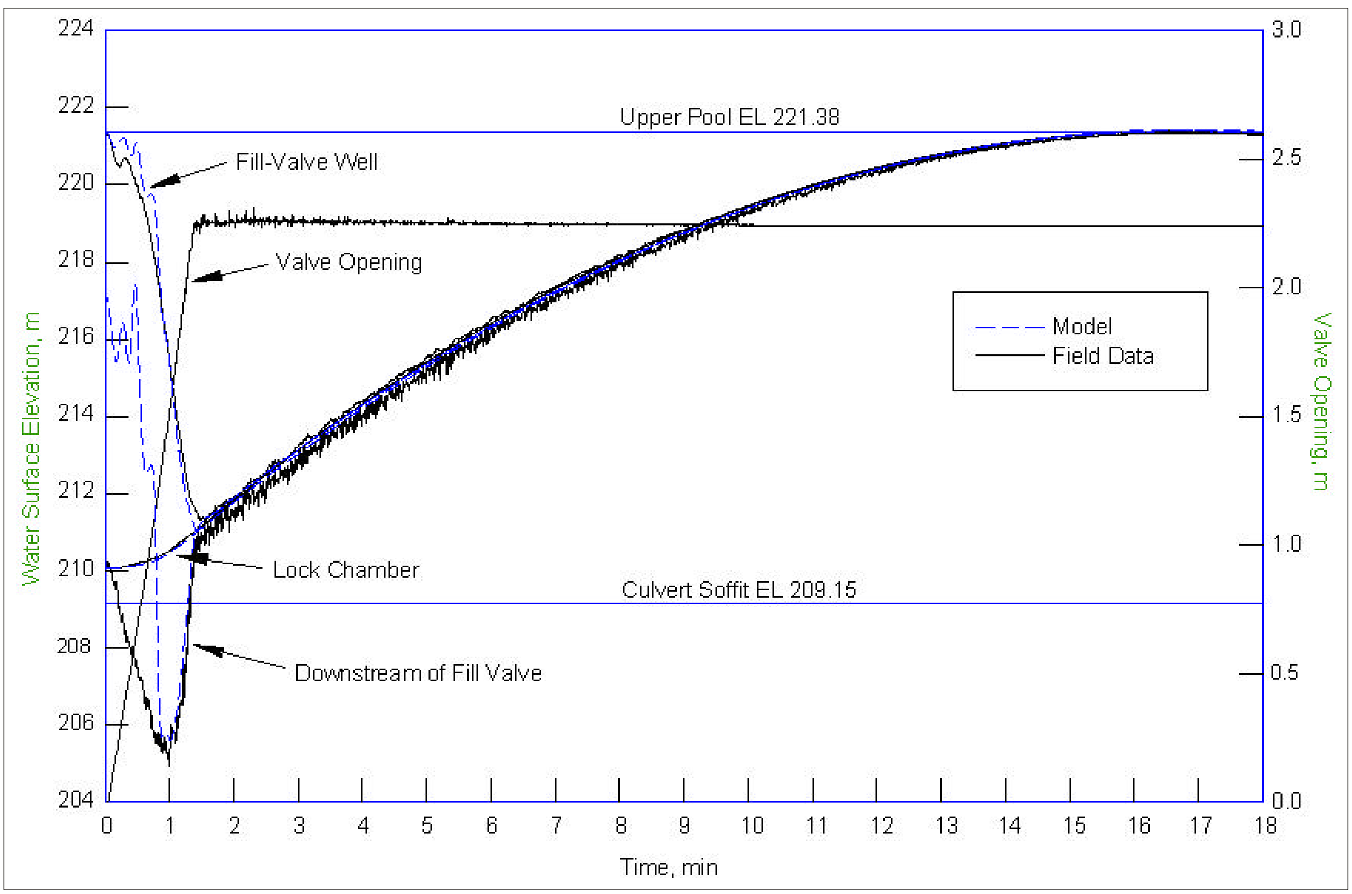

Figure 2. Model validation results for single-valve-filling operation, upper pool 221.4, lower pool 210.1

1 Engineous Software, Inc. No endorsement of this product is made or implied in this paper.

contraction coefficient at small valve openings. However, the contraction coefficient produces accurate estimates of the culvert pressures at the critical period and accurately captures the lowest pressures during the filling operation.

Emptying System

The loss coefficients associated with the emptying system were determined using the data from a single-valve emptying operation. These runs were used to quantify loss coefficients for the sidewall ports acting as intakes and the outlet manifolds. The field data indicated that the emptying valve never reached the full open position (i.e., b/B = 1.0, where b is the valve opening height and B is the culvert height). The data show significant head loss across the valve, when in the full open position. Adjustment of the modeled maximum valve opening led to the conclusion that the emptying valve reaches a maximum opening of 97 percent (b/B = 0.97).

The automatic error-minimization process that couples the lock model with optimization software found the loss coefficients appropriate for the emptying system components. Model results for the adjusted emptying system model are provided in Figure 3. The computed emptying curve and the pressures downstream of the emptying valve matched the field data well during the critical period of low pressure. As with the filling valves, the soffit pressure downstream of the empty valves are higher than those observed in the prototype for valve openings less than 50 percent. The model pressures are in reasonable agreement with the field data at the time in which the pressures are lowest.

Flow Passage Through the Lock System

The steady-state discharge through the lock filling and emptying system is quantified with a discharge coefficient to provide a head-discharge relation in the form:

$$Q = 2C_d A_V \sqrt{2gH} \qquad (1)$$

Here, Q is the discharge through the lock, C_d is the lock discharge coefficient, A_V is the valve area, g is the gravitational acceleration, and H is the lock lift, which is the difference between upper and lower pools. The selection of valve area as representing the flow area is a common choice in lock design and evaluation. Steady-state solutions were computed by simulating 80 min of lock operation beginning with the lock full and both the filling and emptying valves closed. First, the filling valves were fully opened in 83 sec. Then

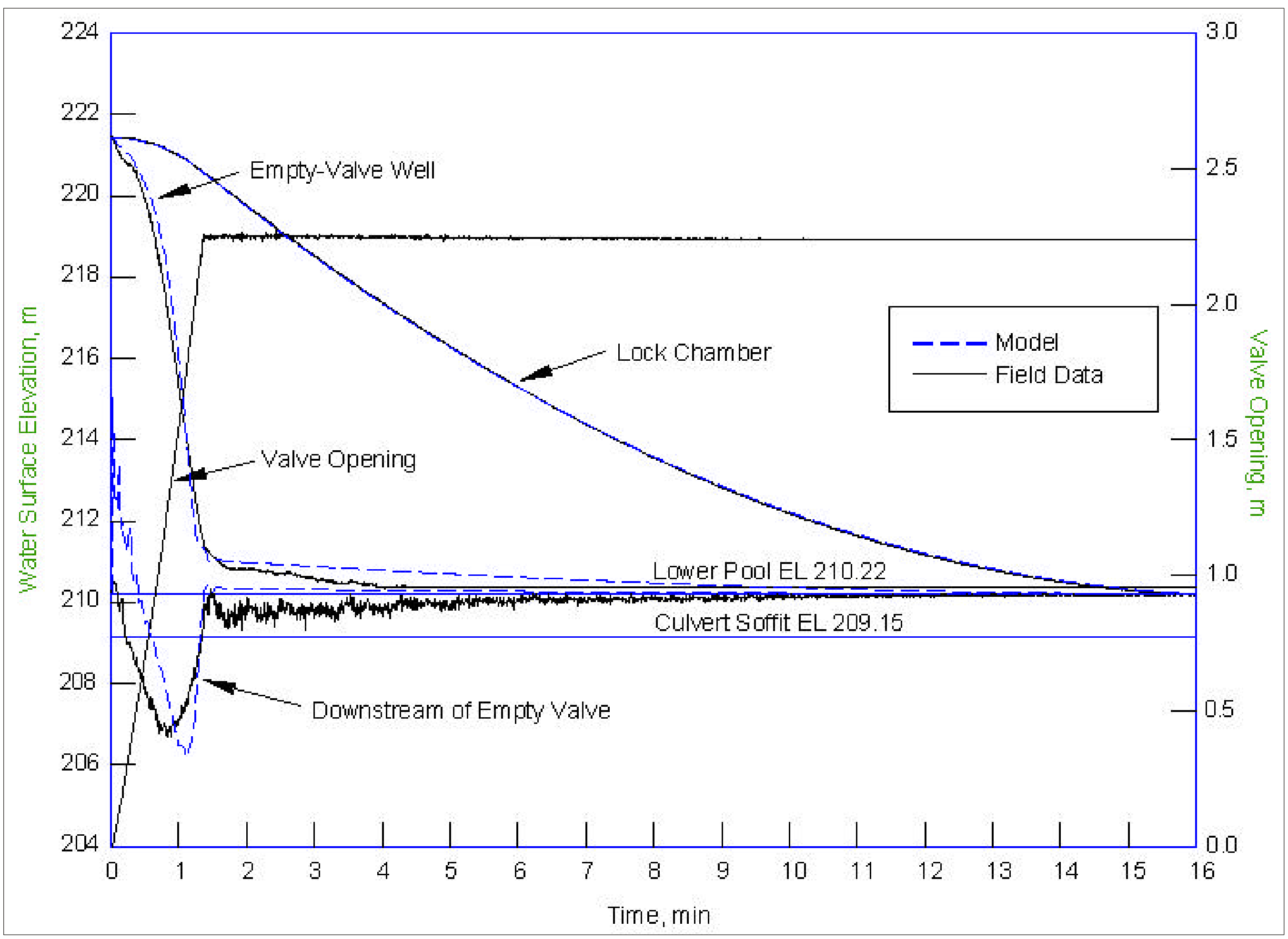

Figure 3. Model validation results for single-valve-emptying operation, upper pool 221.4, lower pool 210.2

the emptying valves were fully opened (actual *b/B* of 97 percent as explained previously) in 480 sec. The field experiments found the 83-sec valve time to be the project's normal valve opening time and the 480-sec valve time was taken from the recommendations of the physical model study. As the chamber water surface fell, the flow evolved to a steady state with flow in the intakes and out the discharge laterals. Steady state was determined by a continuity check of the lock system. When the difference in discharge in and out of the system was insignificant, the model was considered at steady state. The model results at steady state were then used to determine a discharge coefficient for the lock system. A discharge-rating curve for the lock system is provided in Figure 4. The discharge coefficient for the lock system is constant for the heads evaluated. The lock discharge coefficient, which was determined to be 0.55, can be used to compute other head-discharge relations for flow through the lock, within the range of lifts anticipated at the project.

These simulations showed that although the steady-state pressures downstream of the filling and emptying valves were acceptable, pressures downstream of the emptying valves were quite low during valve operation. The lowest pressures occurred when the valve was between 50 percent and 70 percent open. These low pressures could lead to cavitation, the potential of which is quantified using the cavitation index, σ, expressed as:

$$\sigma = \frac{P + (P_a - P_v)}{V^2/2g} \qquad (2)$$

where, P is the gage pressure head at the top of the vena contracta of the jet emerging from the partially open valve, P_a is the atmospheric pressure head, P_v is the vapor pressure head of water, and V is the velocity in the vena contracta of the jet emerging from the partially open valve. A value of 10.15 m was used for the term P_a - P_v. There has been much discussion regarding the cavitation index value that is associated with incipient cavitation in unvented systems. A value of 0.61 has been used by many and this value is substantiated by the prototype study of Bay Springs Lock (McGee 1989). The air vents downstream of the valves at Lock 1 are in questionable condition. Therefore, this study adopted maintaining a cavitation index above 0.61.

Valve Operation Optimization

The optimization software was programmed to run the model from initial conditions of an empty lock chamber with filling and emptying valves closed, to the steady-state condition with the valves fully open. The operation constraints were the maximization of the minimum cavitation index below both the filling and emptying valves during the establishment of steady flow. A rule was imposed that eliminated the consideration of any valve operations that produced minimum cavitation indexes lower than 0.61. Operation rates of both the filling and the

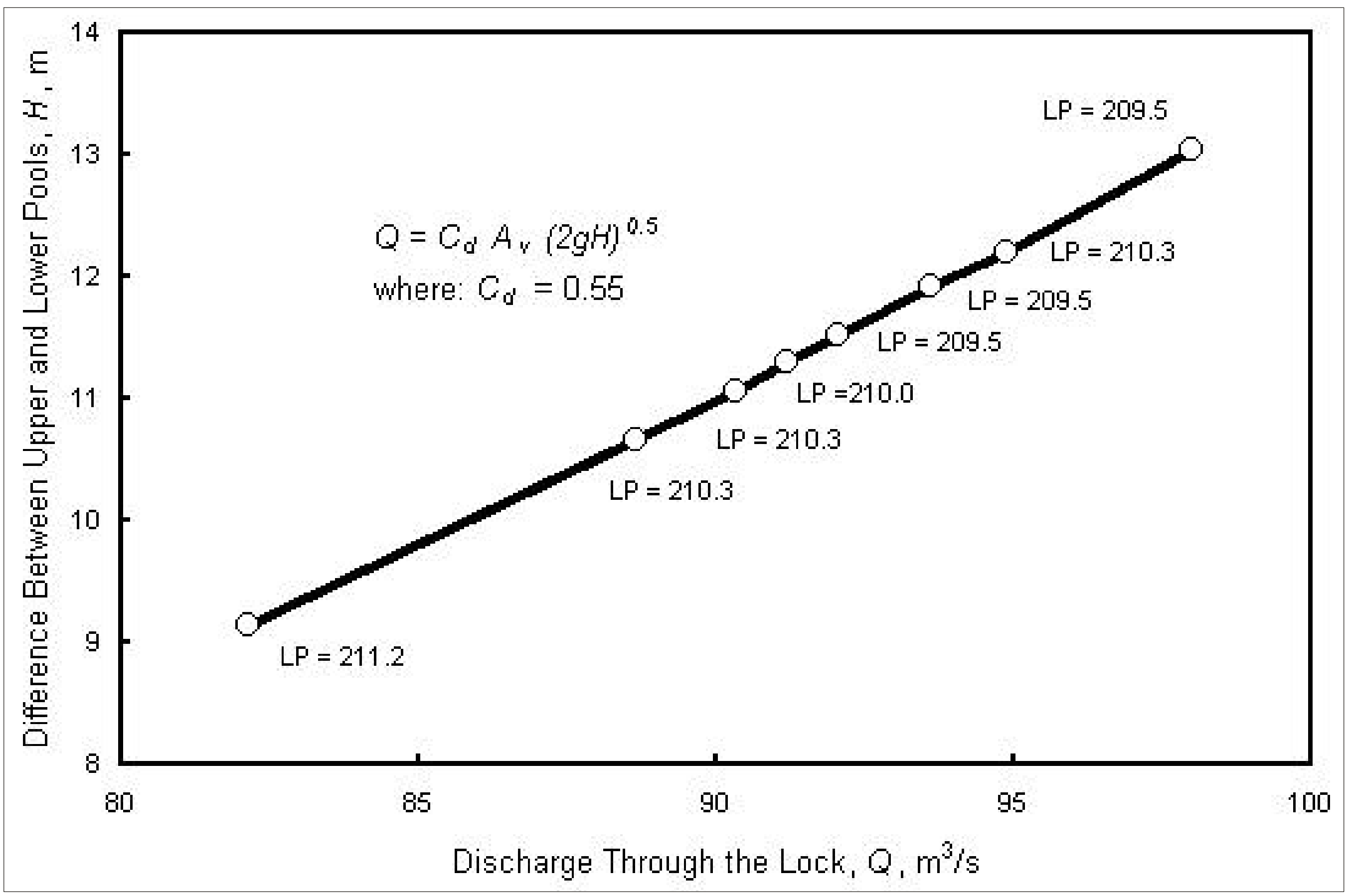

Figure 4. Lock discharge rating curve, all tainter valves fully open and miter gates closed

emptying valves and the lag between initiation of the emptying valve operation were varied. The pool conditions selected for this lock operation optimization was an upper pool elevation (el) 221.4[1] and a lower pool elevation (el) 209.5. A total of 551 lock operation simulations found the optimum valve configuration that included minimization of the time required to reach the steady-state flow condition and that produced acceptable minimum cavitation indexes for both the filling and the emptying valves. The optimum valve schedule used a 591.9-sec filling-valve time, a 160.0-sec emptying-valve time, and a 90.0-sec lag between valve operations. Both exploitative and exploratory optimization techniques were used to globally resolve the objective function, which was maximization of the minimum cavitation index and minimization of the time required to steady state. This valve scheme produced steady-state flow conditions in about 23 min. Timings were rounded to the nearest 0.5 min. This resulted in a filling valve operation time of 10.0 min, a 2.5-min emptying valve opening time, and a lag of 1.5 min between initiation of the filling valve and emptying valve operations (Figure 5). The results of these simulations are shown in Figures 6-8. The steady-state discharge at this head is 93.5 m^3/s (Figure 6) and the lock chamber water surface remains at el 214.4 (Figure 7). The minimum cavitation index downstream of the filling valves was 1.6 and the minimum cavitation index downstream of the emptying valves was 0.71 (Figure 8). This simulation demonstrates an operation schedule that meets the cavitation index guidance for the low tailwater of el 209.5.

Summary and Conclusions

This evaluation of the Lock 1 filling and emptying system determined the discharge capacity of the lock system with various valve and pool configurations. The discharge coefficient of the lock system was determined to be 0.55 with the valve fully open. The field data provided the information needed to validate the numerical model. The numerical model results indicate that steady flow through the lock system is best maintained with both the filling and emptying valves fully opened. Valve operation optimization produced a valve schedule that provided acceptable pressures below the valves while establishing the steady state most rapidly (about 23 min). The operation used 10-min filling valves, 2.5-min emptying valves, and a 1.5-min lag between initiation of the filling valve and emptying valve

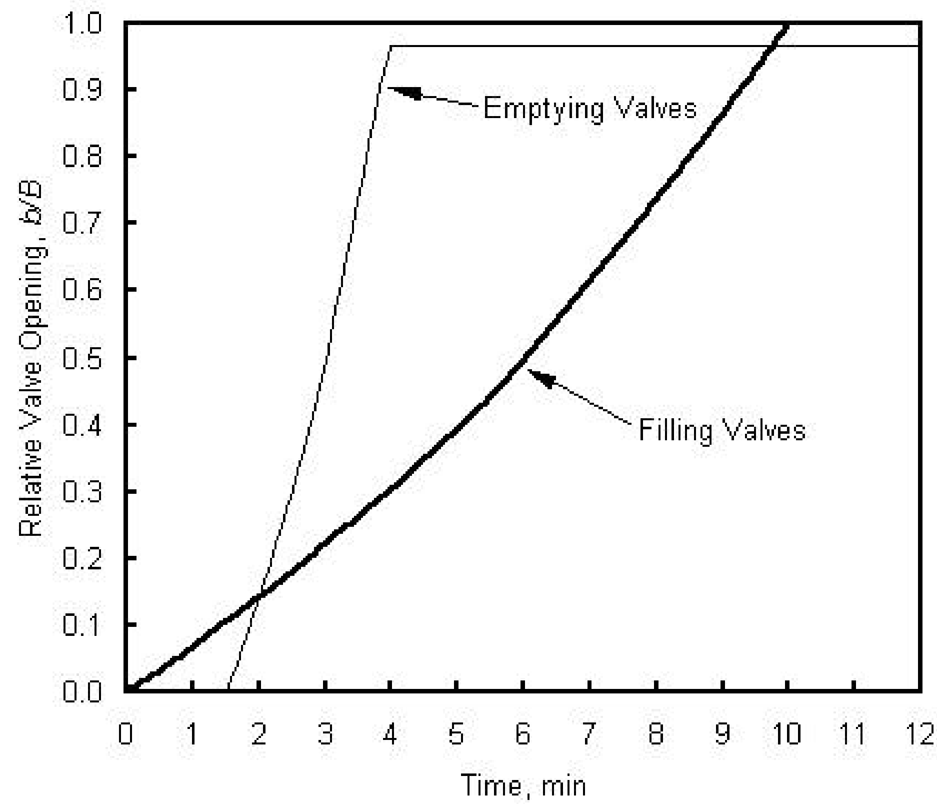

Figure 5. Valve schedule for establishment of steady flow, lock chamber initially empty

1 All elevations (el) cited herein are in meters referenced to the National Geodetic Vertical Datum.

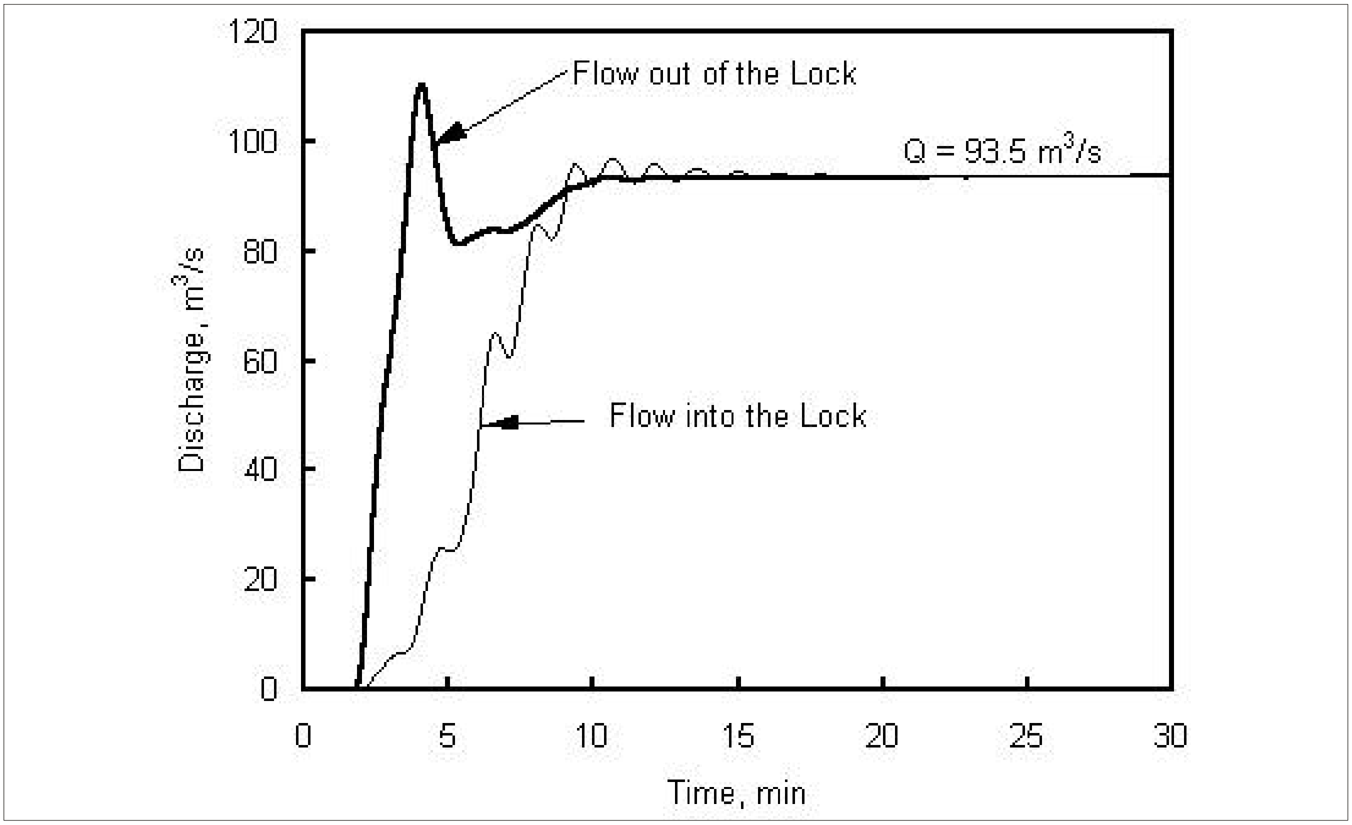

Figure 6. History of discharge, 10-min filling valve, 2.5-min emptying valve, emptying valve begins opening 1.5 min after initiation of filling valve operation, upper pool 221.4, lower pool 209.5

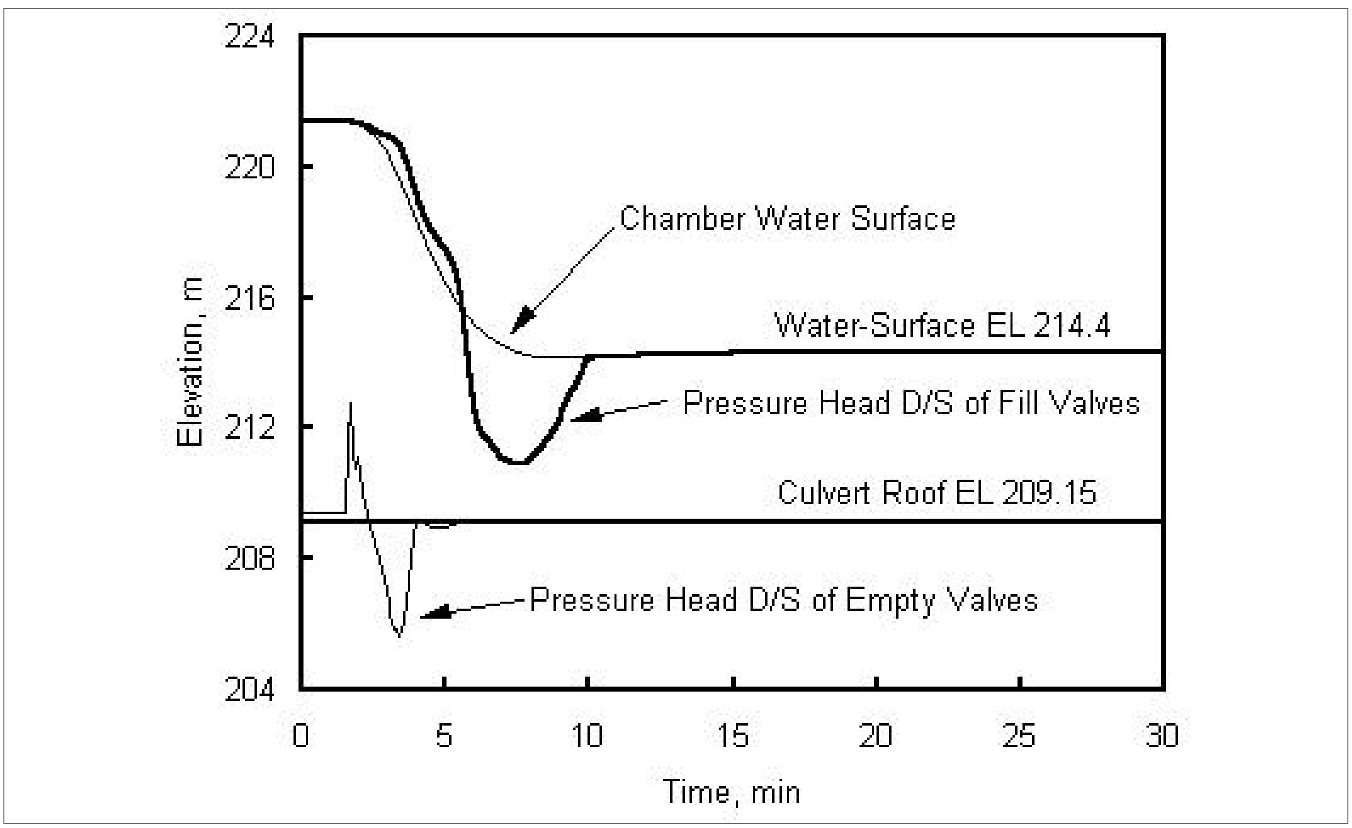

Figure 7. History of pressures and water-surface elevation, 10-min filling valve, 2.5-min emptying valve, emptying valve begins opening 1.5 min after initiation of filling valve operation, upper pool 221.4, lower pool 209.5

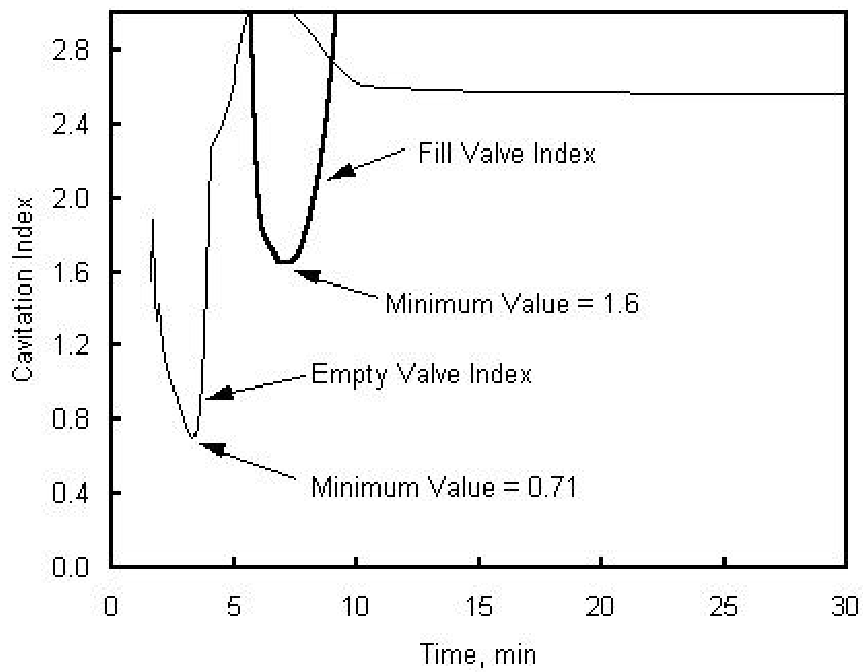

Figure 8. History of cavitation index below valves, 10-min filling valve, 2.5-min emptying valve, emptying valve begins opening 1.5 min after initiation of filling valve operation, upper pool 221.4, lower pool 209.5

operations (Figure 5). Although the optimization was conducted for a single lift of 11.9 m (upper pool el 221.4 and lower pool el 209.5), this is a high lift for this project and the optimum valve configuration is believed to be applicable to other lifts.

Acknowledgments

The field data reported and numerical simulations described were obtained from research sponsored by the U.S. Army Engineer District, St. Paul, by the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Permission was granted by the Chief of Engineers to publish this information. Special gratitude is given to the prototype evaluation team, led by Mr. Timothy Fagerburg and to the Lock 1 staff headed by lockmaster Mr. James Ryan.

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Coastal and Hydraulics News

Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
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This bulletin is prepared in accordance with AR 25-30 as an information dissemination function of the U.S. Army Engineer Research and Development Center (ERDC). The publication is part of the technology transfer mission of the Coastal and Hydraulics Laboratory (CHL) of ERDC under PL 79-166 and PL 99-802. Results from ongoing research programs will be presented. Special emphasis will be placed on articles relating to application of research results or technology to specific project needs.

Contributions of pertinent information are solicited from all sources and will be considered for publication. Communications are welcomed and should be addressed to the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, ATTN: Dr. Lyndell Z. Hales, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, or call (601) 634-3207, FAX (601) 634-4253, Internet: Lyndell.Z.Hales@erdc.usace.army.mil

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