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Periodic Inspections of Coastal Structures with Stone Armor

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) provides information on the long-term structural performance of selected stone-armored navigation structures to their environment. Coastal structures at St. Paul Harbor, AK, and Burns Harbor, IN, are discussed herein. The response of concrete-armored coastal structures to their environment will be presented in a subsequent CHETN.

OVERVIEW: In the "Periodic Inspections" work unit of the Monitoring Completed Navigation Projects (MCNP) Program, selected coastal navigation structures are periodically monitored to gain an understanding of their long-term structural response. Periodic data sets are evaluated to improve knowledge in design, construction, and maintenance of both existing and proposed coastal navigation projects, and will help avoid repeating past designs that have failed and/or resulted in high maintenance costs. Relatively low-cost remote sensing tools and techniques, with limited ground truthing surveys, are the primary inspection tools used in the periodic monitoring efforts. Most periodic inspections consist of capturing above-water conditions of the structures at periodic intervals using high-resolution aerial photography. Structural changes (primary armor unit movement) are quantified through photogrammetric techniques. When a coastal structure is photographed at low tide, an accurate permanent record of all visible armor units is obtained. Through the use of stereoscopic, photogrammetric instruments in conjunction with stereopair photographs, details of structure geometry can be defined at a point in time. By direct comparison of photographs taken at different times, as well as the photogrammetric data resolved from each set of photographs, geometric changes (i.e., armor unit movement and/or breakage) on the structure can be defined as a function of time. Thus, periodic inspections of the structures capture permanent data that can be compared and analyzed to determine if structure changes are occurring that indicate possible failure modes and the need to monitor the structure(s) more closely. Normally, base conditions are established and documented in the initial effort, and the site is reinspected periodically to obtain long-term structural performance data. Also, periodic monitoring usually includes detailed broken armor unit surveys. Base level conditions were initially established for both the St. Paul Harbor, AK, and Burns Harbor, IN, breakwaters. Both structures also have been revisited through the "Periodic Inspections" work unit of the MCNP Program. Monitoring included limited ground surveys for control and a photogrammetric survey of the above-water armor layers. Precise positions of armor units were analyzed, and contour maps of the breakwaters as well as cross sections, point plot maps, and orthophotos of the structures were developed. In addition, a database of broken armor stones was established. Results of the inspections are summarized herein.

ST. PAUL HARBOR BREAKWATER , AK: St. Paul Harbor is located in a cove on the southern tip of St. Paul Island. The island is part of the Pribilof chain in the eastern Bering Sea. Construction of the current harbor was completed in 1989. It is protected by a 548.6-m- (1,800-ft-) long main breakwater and a 295.7-m- (970-ft-) long detached structure. The project was monitored under the

MCNP Program during the period July 1993 through June 1996 (Bottin and Eisses 1997). The outer 320 m (1,050 ft) of the main breakwater was monitored during this effort. Base conditions were established in 1993/1994 with additional surveys in 1996. The structure was also revisited in 2000 under the "Periodic Inspections" work unit (Bottin and Jeffries 2001).

Figure 1. View of St. Paul Harbor breakwater trunk

The main breakwater has a crest elevation (el) of +37[1] from its origin to a point approximately 15.2 m (50 ft) north of the northernmost dock (sta 15+10). The remaining portion of the structure has a crest el +30. Armor stone used on the breakwater trunk was 16,329.3 kg (18 tons), and 21,772.4-kg (24-ton) armor stone was used on the head. The slope of the trunk is 1V:2H with a 1V:3H slope around the breakwater head.

The initial photogrammetric survey of May 1994 revealed low areas along much of the breakwater. Breakwater topography indicated only about 5 percent of the higher portion of the structure (sta 7+50-15+10) was at its design el +37, and 9 percent of the lower portion (sta 15+10-18+00) was at its design el +30. For the higher portion of the structure, the elevation of about 24 percent of the

[1] Elevations (el) cited herein for St. Paul Harbor are in feet referenced to mean lower low water (mllw) datum (to convert feet to meters, multiply number of feet by 0.3048).

length of the breakwater was within 0.3048 m (1 ft) of its design elevation, or between el +36 and el +37; and approximately 66 percent of the structure was between el +35 and el +37, or within 0.6096 m (2 ft) of its design elevation. About 29 percent of the structure length was below el +35. Most of the low area (that below el +35) was concentrated between stas 13+70 and 15+10. For the lower portion of the structure, the elevation of about 50 percent of the length of the breakwater was within 0.3048 m (1 ft) of its design elevation, or between el +29 and el +30; and approximately 89 percent of the structure was within 0.6096 m (2 ft) of its design elevation, or between el +28 and el +30. Only 2 percent of the structure length was below el +28. The initial broken armor unit survey of the St. Paul Harbor breakwater extension occurred during July 1993. The survey revealed 73 broken or cracked armor stones above the waterline. Of the 73 stones, 7 stones were located on the crest, 31 on the seaward slope, and 35 on the harbor side.

The May 1996 photogrammetric survey of the breakwater revealed very slight change in breakwater elevation relative to the 1994 survey. Contours showing the difference in elevations, indicated essentially no change along the crown of the structure. In the vicinity of sta 9+50, a change up to 0.9144 m (3 ft) occurred along the waterline on the sea side of the structure. In this area, however, emergency repairs were made in 1995. Other changes (between 0.3048 and 0.9144 m (1 and 3 ft)) generally occurred on the harbor side of the breakwater. The data indicated essentially no settlement of the structure between 1994 and 1996. Examination of cross section data revealed similar sections for both 1994 and 1996. A broken armor unit survey conducted during June 1996 revealed 230 broken/cracked armor stones on the main breakwater (versus 73 in July 1993). Of the 230 stones, 54 were located on the crest, 105 on the seaward slope, and 71 on the harbor-side slope. Broken stones, generally, were evenly distributed along the length of the structure. The survey indicated that 49 percent of the broken stones were located on the shoreward half of the breakwater extension, and 51 percent on the outer half.

Examination of breakwater topography for the June 2000 photogrammetric survey indicated that essentially no change had occurred in the crest elevation of the breakwater since 1996. Maps developed depicting changes in contours between 1996 and 2000 revealed some areas in the breakwater where voids or subsidence (on the order of 1.5 m (5 ft)) had occurred. Decreases in breakwater elevation were noted along areas on both the seaward and shoreward slopes. Difference contour maps also revealed voids in several areas where single armor stones had been displaced. In addition, breakwater cross sections developed revealed low areas in the structure at some locations. The overall shape and elevation of the breakwater appeared similar, but voids were noted in the 2000 survey that had not been present previously. A broken armor unit survey conducted during July 2000 revealed 221 broken or cracked armor stones above the waterline. Twenty-four new broken stones were noted since the June 1996 inspection, and 33 broken stones documented during the previous inspection could not be found. They could have been moved away by wave and/or ice action. Just fragments of most these stones remained. Of the 221 broken stones identified in the 2000 inspection, 56 were located along the breakwater crest, 96 on the sea-side slope, and 69 on the harbor-side slope. In general, broken stones were evenly distributed along the length of the structure with 54 percent located on the shoreward half of the breakwater extension and 46 percent on the outer half. An obvious void observed during the broken armor unit survey was in a stretch along the waterline on the sea-side slope between stas 8+80 and 9+70 where core stone was exposed in one area. The rate of breakage appeared to have declined at St. Paul breakwater. Only 24 new broken armor stones were observed in the 4-year period between 1996 and 2000 as opposed to 157 broken stones that occurred during the original 3-year monitoring period between 1993 and 1996.

To minimize further breakwater damage and reduce overtopping of the main breakwater, the construction of three submerged reef breakwaters seaward of the structure was completed by the U.S. Army Engineer District, Alaska, during the 2001 construction season. In addition, the void area between stas 8+80 and 9+70 was repaired. The 2000 periodic inspection of the breakwater extension not only determined changes in the armor unit field since previous studies, but established new base conditions since construction of the reef breakwaters. Subsequent inspections will evaluate the effectiveness and analyze the performance of the improved project.

BURNS HARBOR BREAKWATER, IN: Burns Harbor is located on the southern shoreline of Lake Michigan. It is protected by north and west breakwaters that have an aggregate length of 1,780 m (5,840 ft). Construction of the breakwaters was completed in 1968. The project was monitored under the MCNP Program during the period 1985 through 1989 (McGehee et al. 1997); however, no quantifiable data relative to armor-stone positions were obtained during this effort. Base conditions were established in 1994/1995 for the 1,414.3-m- (4,640-ft-) long north breakwater under the "Periodic Inspections" work unit (Bottin and Matthews 1996). The structure was revisited in 1999 (Bottin and Tibbetts 2000).

The north breakwater was constructed with a multilayered design and random placement of the armor-stone cover layer. The design crest elevation of the breakwater was el +14. [1] Armor stones consisted of rectangular-cut Indiana Bedford limestone blocks ranging from 9,071.8 to 13,607.8 kg (10 to 15 tons) on the trunk and 13,607.8 to 18,143.7 kg (15 to 20 tons) on the head. Side slopes were 1V:1.5H. After completion of construction, extensive breakwater damage occurred, and maintenance of the crest elevation and structure cross section required the addition of large amounts of stone.

The initial photogrammetric survey of November 1994 revealed low areas along much of the breakwater. Breakwater topography indicated that, cumulatively, about 344.4 m (1,130 ft), or 24 percent, of the total breakwater length was below its design crest el +14. Most of the low areas ranged from el +12 to el +14. Only about 65.5 m (215 ft) cumulative length of the breakwater (4.6 percent) was below el + 12. Topography and cross-section data also revealed that the design width of el +17 was not maintained in many areas. In addition, on some portions of the structure, the slope of the harbor side of the breakwater was much steeper than the original 1V:1.5H design. The initial broken armor unit survey of the Burns Harbor north breakwater was conducted during July 1995. The survey revealed a total of 165 broken or cracked armor stones above the waterline. Of the 165 stones, 26 (16 percent) were located on the breakwater crest, 95 (57 percent) on the lake-side slope, and 44 (27 percent) on the harbor-side slope. No broken armor stones were observed around the head. Broken stones occurred along the entire breakwater, however in general, higher concentrations were found along the easternmost portion of the structure. About 50 percent of the broken units were located on the eastern one-third of the breakwater.

Examination of breakwater topography for the July 1999 photogrammetric survey indicated continued loss of structure elevation. Cumulatively, about 646.2 m (2,120 ft), or 46 percent, of the total length of the breakwater was below its design el +14 (versus 24 percent in the previous survey of 1994). About 152.4 m (500 ft) cumulative length of the breakwater (11 percent) was below

[1] Elevations (el) cited herein for Burns Harbor are in feet referenced to low water datum (lwd) (to convert feet to meters, multiply number of feet by 0.3048).

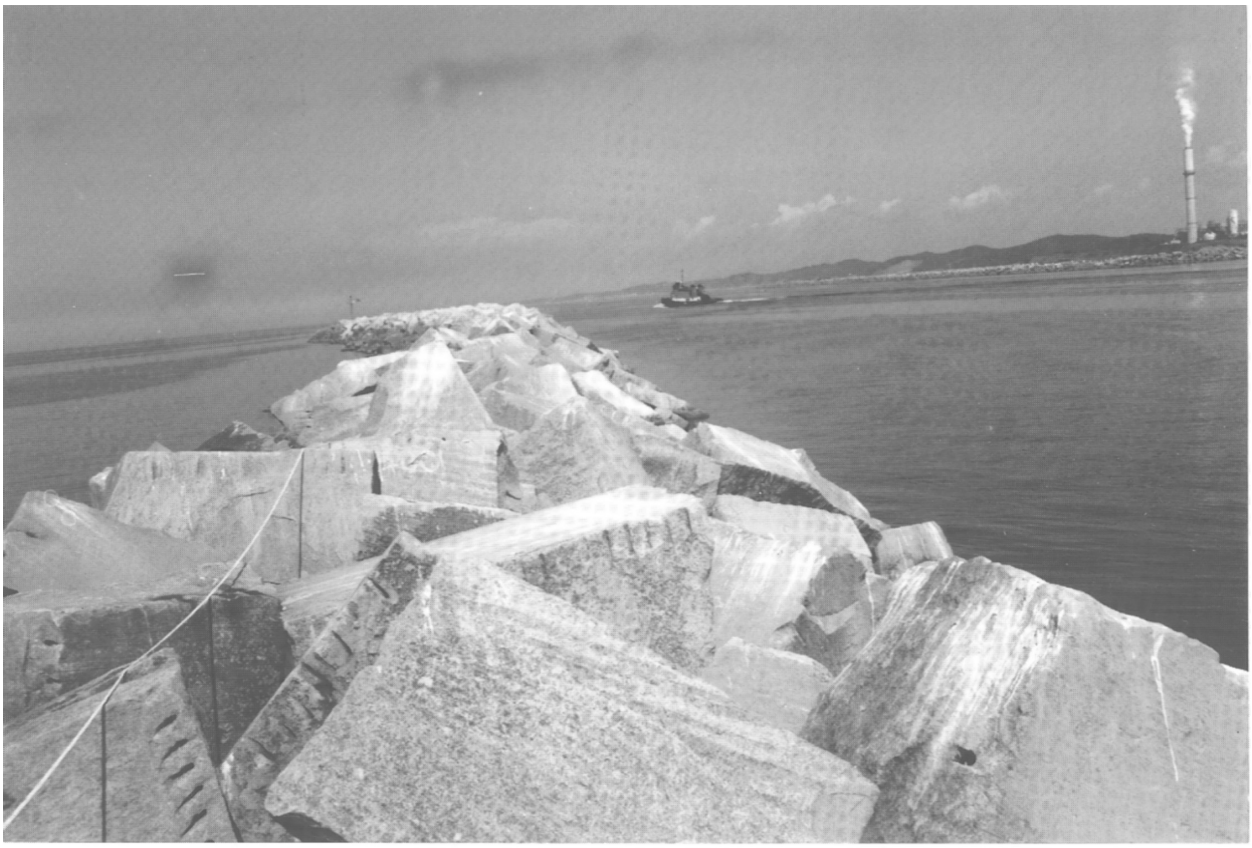

Figure 2. View of Burns Harbor north breakwater trunk

el +12 in July 1999 versus 65.5 m (215 ft) (4.6 percent) in July 1994. In July 1999, concentrations of low areas occurred between stas 8+40-15+65 and 30+70-37+80, however, sporadic areas of low elevation were noted along the length of the structure. Both the 1994 and 1999 surveys revealed the crest width less than the el 17 design and steep slopes (steeper than the 1V:1.5H design) on the harbor side of the structure. A broken armor unit survey conducted during July 1999 revealed 225 broken or cracked armor stones above the waterline (versus 165 in July 1995). Of the 225 stones, 34 were located on the breakwater crest, 96 on the lake-side slope, and 95 on the harbor-side slope. About 42 percent of the broken stones were observed on both the lake- and harbor-side slopes in 1999 versus 57 percent on the lake side and 27 percent on the harbor side in 1995. The survey revealed that between 1995 and 1999 most of the additional breakage occurred on the harbor-side slope. The percent of broken armor units on the breakwater crest remained relatively constant at 15 to 16 percent for both surveys. In 1999, about 44 percent of the broken armor stones were located on the eastern one-third of the breakwater versus 50 percent of the broken stones in 1995.

To minimize further breakwater damage and reduce transmitted wave heights in the harbor, a submerged reef breakwater was constructed lakeward of the north structure during the construction seasons between June 1995 and August 1998 by the U.S. Army Engineer District, Chicago. The 1999 periodic inspection of the breakwater not only determined changes in the armor unit field since the previous survey, but established new base conditions since construction of the submerged reef breakwater. Subsequent inspections will evaluate the effectiveness and analyze the performance of the improved project.

ADDITIONAL INFORMATION: Questions relative to this CHETN may be addressed to Mr. Robert R. Bottin, Jr., Coastal Harbors and Structures Branch, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center at (601-634-3827), FAX (601-634-4827), or e-mail: Ray.R.Bottin@erdc.usace.army.mil. Additional information on the MCNP Program may obtained from: *http://chl.wes.army.mil/research/navigation/mcnp_site/default.htm*.

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