PRELIMINARY SIDESCAN-SONAR INVESTIGATION OF SHORE-DEFENSE STRUCTURES ALONG CHICAGO'S NORTHSIDE LAKE FRONT: WILSON AVENUE GROIN TO OHIO STREET BEACH

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Conversion Factors: U.S. Customary to Metric (SI)
Units of Measurement

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<th>to obtain</th>
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Chrzastowski, Michael J.


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View looking south along the seven-tier, Type B revetment between the entrances to Belmont and Diversey Harbors. In the foreground, capstone displacement has occurred along the lower two or three tiers. In the distance, the deterioration is more advanced; the lowest tier capstones have been displaced lakeward and rest below water level. (Photographed by Dann Blackwood, U.S. Geological Survey, Branch of Atlantic Marine Geology, 1987.)
ABSTRACT
Sidescan sonar was used to evaluate shore-defense structures along 5.5 miles of Chicago's northside lake front from Wilson Avenue groin to Ohio Street Beach. The findings of this preliminary study indicate no apparent structural problems occur where steel sheetpile has been used for the exterior: the Wilson Avenue groin, the Montrose and Diversey Harbor jetties, the submerged bulkhead at North Avenue/Fullerton Beach, the North Avenue groin, and the revetment between North Avenue and the Ohio Street Beach. Structures that have deteriorated are stepped quarry-stone revetments with capstones overlying either a rock-filled wood crib or a quarry-stone mound. Above water, deterioration is expressed as capstones displaced from their original horizontal and stepped configuration. These revetments extend from the landward end of Wilson Avenue groin to Fullerton Parkway.

No lake-bottom erosion or undermining is responsible for the capstone displacement, nor is displacement related to any shift or removal of toe protection. Sonographs show that toe protection is in place in front of all shoreline revetments and along a limited extent of the groins, jetties, and the submerged bulkhead at North Avenue/Fullerton Beach.

For the revetments with wood cribs, the structural problems are associated with breaks or gaps between the top of these wood structures and the top of the toe protection. Through these openings, rock fill is dispersed lakeward, primarily by wave surge. Capstones are subsequently displaced as they lose their underlying support. The most severe capstone displacement occurs along a revetment that has no wood support structures: capstones overlie rock fill, which in turn overlies a quarry-stone mound. Capstone displacement along this revetment emphasizes that a principal factor in revetment deterioration is not the loss of wood support, but rather the size (primarily cobbles and small boulders) and weight (1 to 50 pounds) of the subcapstone rock fill, and the ability of local wave energy to shift and erode this material, if it has a lakeward exposure.

Overall deterioration of the revetments is related to a combination of factors, including design, construction materials, structural age, and the effects of wave surge and lake-level fluctuations. The processes leading to damage and failure are long term, and thus the age of these structures—50 to 80 or more years old—is a key factor in their deterioration.

ACKNOWLEDGMENTS
During this cooperative study, the U.S. Geological Survey and the Illinois State Geological Survey were aided by the Chicago Department of Water, the Chicago Police Department, and the Chicago Park District; the Park District Lifeguard Rescue Unit provided special logistic help. Other assistance was provided by the Chicago District Office of the U.S. Army Corps of Engineers and the Chicago Yacht Club. We especially thank the Chicago Yacht Club for its donation of mooring space for the U.S. Geological Survey Research Vessel NEECHO.

Shipboard data acquisition was assisted by David Mason, Thomas O'Brien, Kenneth Parolski, and A. Richard Tagg of the U.S. Geological Survey. Matthew Riggs of the Illinois State Geological Survey helped process the sidescan sonar records. Principal funding for this study was provided by the U.S. Geological Survey, and supplemented by funding from the Illinois State Geological Survey and the Illinois Department of Transportation, Division of Water Resources.
Figure 1 Study area map showing the extent of landfill along Chicago's north-side lake front.
INTRODUCTION

Chicago's Lake Michigan shoreline is dominated by parkland, beaches, and small boat harbors. Although largely designed and built for aesthetics and recreation, the city's lake front was also developed for shore protection. Extensive landfilling and construction of revetments, bulkheads, jetties, groins, and breakwaters began in the mid- to late-1800s and were mostly completed by the 1940s. About 53 percent of the 27 miles of Chicago's shoreline consists of such shore-defense structures of various designs.

Over the years, these structures were given minimal maintenance. They have deteriorated because of wave action, freeze-thaw cycles, lake-level fluctuations, impact of wave-thrusted ice, and long-term weathering of wood support pilings and sheetings. In many places, segments of the shore-defense structures have collapsed lakeward, and wave erosion threatens the fine-grained landfill materials these structures were built to hold and protect. In the fall and winter of 1986-87, record-high lake levels—about 3 feet above the long-term winter average—accelerated this deterioration. Waves and wave surge impacted the structures above their lake-level design elevation, while waves overtopping the structures caused moderate-to-severe erosion of fill material behind the structures.

Planning to mend, rebuild, and extend structures requires data concerning their present above- and below-water condition. Most important, structural problems that cannot be observed above water must be identified, and the causes and style of structural failure must be understood. Some underwater sites have been investigated by SCUBA-equipped divers. But better suited for extensive examination is sidescan sonar, a geophysical tool for underwater imaging. Sidescan sonar uses transmitted and reflected sound to produce an image of underwater features.

Reports of previous studies using sidescan sonar along the Illinois lake shore are rare. Berkson and others (1975) have used sidescan sonar records to describe the lake bottom 4 miles off the Chicago lake front. Subsequent to the collection and processing of data from this Chicago northside study, a publication appeared with the results of a sidescan sonar investigation along the offshore wood-crib breakwaters at Calumet Harbor on the Illinois-Indiana border (Moran, 1987). No previous sidescan sonar surveys of shore-defense structures have been conducted along the Chicago lake front.

During the summer and fall 1987, the U.S. Geological Survey (USGS) and the Illinois State Geological Survey (ISGS) cooperated in a study along Chicago's northside lake front from Wilson Ave groin to Ohio Street Beach (fig. 1). Researchers collected data concerning lake-bottom morphology and sediment thickness, and inspected various shore-defense structures both above and below water level. Below-water conditions were interpreted from sonar-generated images (sonographs) produced by 100-kiloHertz (kHz) sidescan sonar operated from a research vessel tracking parallel to the shore. This report focuses on shore-defense structures and summarizes above- and below-water observations made during 1987. Findings are preliminary. In the summer 1988, the USGS and ISGS will study the entire Chicago lake front using a 500-kHz sidescan sonar system. The higher frequency system will provide higher resolution sonographs and thus more detailed information on the underwater condition of the shore structures.
Nearshore bathymetry along the lake front study area; 5-foot contour intervals based on ISGS fathometer survey during summer 1987 (Chrzastowski, in review).
STUDY AREA
From the Wilson Avenue groin south to Ohio Street Beach (fig. 1), the study area covered 5.5 miles or approximately 20 percent of Chicago's total shoreline. The shoreline—all parkland managed by the Chicago Park District—forms the edge of land created by various landfill and shore-development projects. The area's three sand beaches are manmade: North Avenue/Fullerton, Oak Street, and Ohio Street Beaches account for about 1.2 miles of shoreline. North Avenue/Fullerton Beach is distinctive because it is a perched beach held by a submerged, offshore, steel sheetpile bulkhead. The remaining 4.3 miles of the study area is armored with bulkheads and revetments that provide a hardened shoreline protecting fill materials behind them. Additional shore-defense structures are the groins at Wilson and North Avenues. These elongate, hooked structures extending from the mainland were built to retain sand at the downdrift ends of Montrose-Wilson and North Avenue/Fullerton Beaches.

The generalized nearshore bathymetry of the study area is shown with a 5-foot contour interval in figure 2; this bathymetry is based on nearshore hydrographic mapping by the ISGS during summer and fall 1987 (Chrzastowski, 1988). The lake bottom slopes up to the present shoreline only at the three beaches. Adjacent to the various shore structures, lakeward of boulders placed at the toe of these structures, the average water depth below Lake Michigan Low Water Datum (LWD) is about 15 feet. The maximum water depth ranges from 18 to 20 feet below LWD along the lakeward side of the Wilson Avenue groin. LWD for Lake Michigan equals 576.80 feet above mean sea level, referenced to the International Great Lakes Datum (IGLD).

Montrose, Belmont, and Diversey Harbors are recreational small-boat harbors formed by constructing embayments within the lake-front landfill. Shore-defense structures along the harbor shorelines were not examined in this study; however, the underwater condition of the lakeward side of jetties at the entrances to Montrose and Diversey Harbors was examined with sidescan sonar. The Belmont Harbor entrance has no jetties.

PROCEDURES AND METHODS
The sidescan sonar survey, directed by J. S. Schlee (USGS), was conducted from the 38-foot USGS research vessel NEECO. Different segments of the shoreline were surveyed on September 3, 4, and 11, 1987. In October and November 1987, for the above-water survey of the area, M. J. Chrzastowski (ISGS) described, measured, and photographed shore structures. Subsequently, he interpreted the sidescan sonographs.

Sidescan sonar operation
Sonar systems are based on the transmission of a sound signal through water and the measurement of the travel time between the signal's emission and reception after reflecting off an object. A fathometer or fishfinder is a simple sonar system in which the sound signal has a conical beam directed below a transducer. Sidescan sonar has a beam with a fan-shaped signal directed below and to the side of a transducer, which is usually mounted in a torpedo-shaped device called a towfish and towed behind or alongside a survey boat.

As the boat and towed transducer advance, a transmitted signal intercepts features along the lake bottom, and sound scatters back to the transducer. Travel time is greater for signals from features at greater distance from the transducer. The echoes are converted to an electrical pulse, which is transmitted to a sonar recorder that marks a graphic strip chart along adjacent scan lines. Each line represents the intersection of the sound beam with the lake bottom and objects along the bottom, and shows the relative position of
these objects. The assemblage of scan lines, which forms a graphic image of underwater features, is called a sonograph (Williams, 1982; Mazel, 1985).

Data collection
This survey used a Klein Associates Hyroscan System Model 531T recorder and a 100-kHz towfish transducer. The towfish was submerged 3 to 5 feet below water level and pulled behind the NEECHO, traveling at a speed of 2 to 3 knots. The boat tracked about 100 feet offshore, parallel to the shore structures. The 100-kHz system provided sonographs with good resolution, but not always with the highest definition of detail. For example, along some shoreline reaches, identifying the individual wood pilings or the corrugated pattern of the steel sheetpiles was difficult.

For the entire survey, the sidescan sonar range setting was 50 meters (164 feet). The position of the boat was controlled by electronic range-range navigation using a Motorola Mini-Ranger Falcon IV System with transponders at established triangulation stations on land and on water-intake cribs located about 2.5 miles offshore from the study area.

Complementing the sidescan sonar survey was the collection of nearshore bathymetric data during the summer and fall 1987 (Chrzastowski, in review; Schlee et al., in review). A Ross Straightline fathometer was used with a 100-kHz and 22-degree conic signal. Sounding lines were aligned east-west at 300-foot spacing and extended to about 2,000 feet offshore. All recorded depths were corrected to LWD. Bathymetric data were also collected with a Raytheon DE719 fathometer and a Raytheon SSD100 digitizer onboard the NEECHO during the sidescan sonar survey.

Interpretation of sonographs
Figure 3a shows a survey vessel conducting a hypothetical sidescan sonar survey along a shore-defense structure; figure 3b represents the resulting sonograph from this survey; and figure 3c shows the sonograph interpretation. (Photographs of actual sonographs collected in this study are included in a subsequent section of this report.) Because a sonograph is sound-generated, dark images correspond to objects that are hard and strong reflectors of incident sound signals. Light images occur if objects absorb or scatter most of the incident sound signal. A white area represents an area on the lake bottom with no signal return because it was not reached by the transmitted signal.

The sonograph provides a plan view of underwater features. Objects protruding from the lake bottom can be identified by a sonar reflection associated with a white area that is an acoustic shadow caused by a gap between sound signals reflected off the top of the object and the lake bottom behind the object. Similarly, depressions in the lake bottom produce white areas due to the absence of sound signals from the side of the depression toward the towfish.

Interpretation of several specific sonograph images was important in this examination of the shore-defense structures. For example, the contrast between smooth, light areas and mottled, coarse-textured, elongate dark areas is the basis for distinguishing the sandy lake bottom from the rock used as toe protection for the structures (fig. 1). Variation in the mottled texture across the toe protection indicates relative size of the material. Dark, angular, discontinuous linear reflectors within the toe protection show where revetment capstones have fallen lakeward. Localized underwater breaks in bulkheads and associated underwater cavities in the fill material are identified by a landward offset of the otherwise laterally continuous reflector along the bulkhead line (fig. 1). Associated with such bulkhead breaks may be textural contrasts across the toe protection caused by rock fill eroded from the structure and dispersed across the larger material used as toe protection.
Figure 3  Sidescan sonar field relationships (A) compared to the resulting sonograph (B) and the interpreted sonograph (C).
The width, height, and distance between objects on the lake bottom can be determined from sonographs, but certain geometric corrections are necessary. Range-scale marks along the sonograph provide a scale of horizontal distance from the sonar's outgoing pulse. On the sonograph, however, distances from the outgoing pulse to objects on the lake bottom are slant-range distances. Figure 4 shows the relationship of horizontal and slant-range distances and the corrections necessary to calculate the width of the toe protection at the base of a lake-front revetment. This determination of width was made along all the toe protection in this study area. From scale marks on the sonograph, the horizontal distance to the bulkhead was measured (H) as well as water depth below the towfish (Z) and slant-range distance to the lakeward edge of the toe protection (S). The horizontal distance from the towfish to the edge of the toe protection (X) was determined using the Pythagorean theorem (fig. 4). The width of the tow protection was then calculated by subtracting this horizontal distance (X) from the horizontal distance to the bulkhead (H).

Because the boat speed and graphic recorder speed were not synchronized, the sonographs collected in this study are compressed in the shore-parallel direction, and thus the shore-parallel scale distances are greater than the shore-perpendicular distances.
DESIGN OF SHORE-DEFENSE STRUCTURES
Along Chicago’s entire lake front, 21 different engineering designs have been employed for various shore-defense structures. Construction materials vary as widely, including wood pilings and planks, quarry blocks, quarry-run riprap, steel sheetpile, and concrete. Within the study area, five structural designs have been used to provide (1) a bulkhead to hold and protect fill material, (2) a hard shoreline to intercept wave impact, and (3) an aesthetically pleasing recreational area.

On Chicago Park District engineering drawings, shore-defense structural designs are identified with alphabetic and alphanumeric designations (Chicago Park District, 1944). The five designs in the study area are Types A, B, C, D1, and E (fig. 5). Type B is distinctive because it is the only structure in the study area with no wood or steel support system, and its foundation consists of a mound of quarry stone. Although steel sheetpile has been used along jetties and groins in the study area, the Type E structure is the only shore-defense structure in the study area with a steel sheetpile lakeward face.

Figure 6 shows the shoreline reaches where the five different structures are located. Protecting the longest reach is the Type D1 structure, extending 1.3 miles between the entrances of Montrose and Belmont Harbors.

The designation of a structure as a bulkhead, seawall, or revetment depends to a large degree on its function. Bulkheads and seawalls generally are vertical or near-vertical structures that hold fill material; whereas revetments, which are built along upland areas, generally are stepped or sloping structures that do not hold fill. The five types of shore structures in the study area are bulkheads in the cross section below water, but revetment-like above water (fig. 5). In this report, for brevity and consistency, the entire structure above and below water is referred to as a revetment.

Types A, C, D1, and E revetments share a basic design. At the foundation and lakeward edge is a rock-filled crib built of a shore-parallel, double row of wood pilings spaced 12 to 20 feet apart. The 8- to 10-inch wood pilings are spaced 2 to 4 feet apart and support horizontal timbers (wales); the wales hold wood sheeting that is three planks thick (Wakefield Sheeting). The Type C structure along the Montrose “peninsula” exhibits a variation on this design; it has no wood-plank sheeting and only closely spaced pilings. For all of the cribs, steel tie rods span the crib walls; in some cases, a line of pilings runs between the crib walls, dividing the crib into compartments 20 to 40 feet long. The cribs are filled with 1- to 50-pound quarry-run riprap mixed with brick, concrete, and stone debris varying from cobble to boulder size (table 1).

The crib pilings are generally cut at an elevation 1.8 feet above LWD, which is about 0.4 foot above the yearly mean lake level. Superimposed on the crib and extending landwards and upwards is the above-water part of the revetment. In the case of the Types A and E structures, this above-water area is a sloped, concrete surface referred to as a "paved beach." Along the Types B, C, and D1 structures, the section above water consists of several tiers of dolomite quarry-block capstones. These 3.6- to 8-ton capstones are commonly 4 by 4 by 5 feet (table 1). The crib rock fill provides support for the overlying capstones, which are stepped and five to eight tiers high, depending on the structure type. Joints between the capstones are filled with cement and sand mortar. The elevation at the top of the uppermost capstone ranges from 11.3 to 14.3 feet above LWD.
CHARACTERISTICS OF TOE PROTECTION

Toe protection refers to the rock piled against the base of a structure to prevent scour caused by waves reflected off the structure. Absence of toe protection in a setting of moderate to high wave energy commonly will result in the undermining and possible collapse of a structure. In the study area, toe protection is a wedge of quarry boulders piled highest and thickest directly against the structure. Along the northern reach of the Type D1 structure, the toe protection is visible in several places where it rises to the level of the revetment’s lowest tier.

In the fathometer traces, toe protection is identified by a steeply inclined bottom profile positioned against the structures. On the sonographs, toe protection is identified as a strongly reflective, mottled and coarse-grained belt-like pattern along the structures; it
Figure 6  Map showing reaches defended by shore-defense structures with different designs (modified from Chicago Park District, 1944, 1947, 1987).
Table 1 Physical characteristics of three stone types used in the shore structures

<table>
<thead>
<tr>
<th>Stone designation</th>
<th>Use in structure</th>
<th>Weight</th>
<th>Average size</th>
<th>Description</th>
</tr>
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<tr>
<td>A-stone</td>
<td>Capstones</td>
<td>3.6-8.0 tons</td>
<td>4x4x5 ft</td>
<td>Dolomite quarry blocks; some limestone and sandstone blocks</td>
</tr>
<tr>
<td>B-stone</td>
<td>Toe protection</td>
<td>500-1,600 lbs</td>
<td>Boulders (&gt;10 inch diameter)&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Dolomite quarry-run riprap; some limestone and sandstone</td>
</tr>
<tr>
<td>C-stone</td>
<td>Crib fill</td>
<td>1-50 lbs</td>
<td>Cobble (2.5-10 inch diameter); boulder (&gt;10 inch diameter)&lt;sup&gt;4&lt;/sup&gt;</td>
<td>Dolomite, limestone, and sandstone quarry-run riprap with concrete, brick, and stone demolition debris</td>
</tr>
</tbody>
</table>

1 After U.S. Army Corps of Engineers, 1986.
2 Size classification of boulder and cobble based on the Wentworth scale (1922) with conversion of size classes from metric to U.S. customary units.
3 Toe protection boulders are generally in the range of 2 to 4 feet in diameter. The largest boulder observed is 6 feet in diameter.
4 Large cobbles and small boulders (<2-foot diameter) are the most common crib fill.

contrasts strongly with the adjacent smooth, weakly reflective sand or mud bottom. As shown by fathometer and sonar records, toe protection is laterally continuous in front of all five different shore-defense structures in the study area. The only shore structures without toe protection are the jetties at the entrance to Montrose Harbor.

The thickness, slope, and offshore width of toe protection varies among the structures, and to some degree, along the same structure. Table 2 summarizes various toe-protection characteristics by type of structure. Rock that fronts the Type B revetment is treated here as toe protection, although it is actually the submerged part of the stone mound that forms the foundation for the revetment capstones (fig. 5). Measurements of width, depth, and thickness were made from a combination of sonographs and fathometer records. Average toe-protection width in the study area is 46 feet. The maximum mean widths occur off the Wilson Avenue groin (72 feet) and the Type B revetment (67 feet). The minimum mean width (25 feet) is adjacent to the submerged bulkhead at North Avenue/Fullerton Beach. Compared to the other structures, the toe protection of the Type E revetment is anomalous; its maximum thickness is only 3 feet (mean), and its slope is most gradual (1:16 mean). For all the others, maximum thickness averages 10 feet, and the mean slope ranges from 1:3 to 1:7.

In table 2, the toe protection’s minimum depth below LWD is the depth of the top of these boulders where they rest against the structure. This is a measure of the underwater exposure of the structure’s wood bulkhead or steel sheet pile between LWD and the toe.
Table 2  Characteristics of the toe protection for study area revetments, jetties, and submerged bulkhead of the perched beach

<table>
<thead>
<tr>
<th>Structure</th>
<th>Width (ft)</th>
<th>Maximum thickness (ft)</th>
<th>Slope (rise:run)</th>
<th>Minimum depth below LWD (nearest .5 ft)</th>
<th>LWD depth along edge of toe protection (nearest .5 ft)</th>
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<tr>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Range</td>
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<td>8-13</td>
<td>--</td>
<td>3-11</td>
<td>14.5-20.5</td>
</tr>
<tr>
<td>Mean</td>
<td>54</td>
<td>10</td>
<td>1:5</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>Type B</td>
<td></td>
<td></td>
<td></td>
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<td>Range</td>
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<td>10-13</td>
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<td>12</td>
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<td>12.5</td>
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<tr>
<td>Type C</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Range</td>
<td>27-49</td>
<td>7-12</td>
<td>--</td>
<td>7.5-13</td>
<td>16-21</td>
</tr>
<tr>
<td>Mean</td>
<td>38</td>
<td>10</td>
<td>1:4</td>
<td>9</td>
<td>18</td>
</tr>
<tr>
<td>Type D1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>23-46</td>
<td>7-12</td>
<td>--</td>
<td>(-3)-8.5</td>
<td>10-15.5</td>
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<tr>
<td>Mean</td>
<td>32</td>
<td>10</td>
<td>1:3</td>
<td>1</td>
<td>11.5</td>
</tr>
<tr>
<td>Type E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>44-68</td>
<td>2-3</td>
<td>--</td>
<td>9.5-11</td>
<td>11-13</td>
</tr>
<tr>
<td>Mean</td>
<td>50</td>
<td>3</td>
<td>1:16</td>
<td>10</td>
<td>12</td>
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<tr>
<td>Wilson Ave grön--east side</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>68-81</td>
<td>11-12</td>
<td>--</td>
<td>7.5-11</td>
<td>20-21</td>
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<tr>
<td>Mean</td>
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<td>11</td>
<td>1:7</td>
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<tr>
<td>Diversey Harbor--east jetty</td>
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<tr>
<td>Range</td>
<td>15-60</td>
<td>9-10</td>
<td>--</td>
<td>7-8</td>
<td>17-18</td>
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<tr>
<td>Mean</td>
<td>29</td>
<td>10</td>
<td>1:3</td>
<td>8</td>
<td>18</td>
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<tr>
<td>North Ave/Fullerton Beach submerged bulkhead -- lakeward side</td>
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<td></td>
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<tr>
<td>Range</td>
<td>22-29</td>
<td>5-10</td>
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<td>5.5-8</td>
<td>11.5-15.5</td>
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<tr>
<td>Mean</td>
<td>25</td>
<td>8</td>
<td>1:3</td>
<td>6.5</td>
<td>13.5</td>
</tr>
</tbody>
</table>

1. Maximum thickness calculated by the difference between the minimum water depth over the toe protection and the lake-bottom depth at the edge of the toe protection.
2. Negative numbers indicate elevation above low water datum (LWD).
3. Rock that fronts the revetment is here treated as toe protection, although it is in fact part of the stone mound that is the revetment foundation.
4. Measurements for the Type C revetment along the Montrose Peninsula only; does not include the Type C revetment near the entrances to Belmont and Diversey Harbors.
5. Measurements only for the Type E structure north of Oak Street Beach.
6. Measurements for toe protection between the second and third groins counting from the north.
The least underwater exposure occurs along the wood bulkhead of the Type D1 revetment, which has some sections with toe protection rising above LWD. The other structures average 8 to 10 feet of underwater exposure. In table 2, the depth along the edge of the toe protection indicates the approximate depth of water where the structure was built. The Type D1 revetment was built in the least mean depth (11.5 feet); the Wilson Avenue groin was built in the greatest mean depth (20.5 feet).

EXAMINATION OF SHORE-DEFENSE STRUCTURES
Wilson Avenue groin
A 2,300-foot long, 23-foot wide, hooked structure functions as a large groin holding sand at the downdrift end of the Montrose-Wilson Beach. The structure has an exterior of steel sheetpiling and a reinforced concrete cap forming a walkway 7.1 feet above LWD. Along the concrete walkway are small areas of cracked and pitted concrete; but in general, the concrete surface is in good condition.

Only the east (lakeward) side of the structure was examined with sidescan sonar. The steel sheetpiling is laterally continuous and has no offsets or unusual features. Toe protection, which is laterally continuous along the sheetpiling, has a rather uniform width and no anomalous narrow areas; no lake-bottom depressions suggestive of scour or undermining lie along its lakeward edge. In total, the entire east side of the Wilson Avenue groin appears to be free of underwater structural problems.

Revetment along Montrose "peninsula"
The revetment defending the east side of the Montrose "peninsula" is five tiers; on the south, it is four tiers. Starting at the south end of the Wilson Avenue groin, the five-tier structure extends for about 2,000 feet south and west. From this point to the Montrose Harbor entrance (1,465 feet), the structure is only four tiers. Although designated a Type C revetment, it has a design variation from that shown in figure 5. The lakeward edge of the rock-filled crib consists of closely spaced wood pilings without any associated wood-plank sheeting. The rock fill within the crib is thus held and protected solely by these pilings. Along the entire revetment, missing pilings are rare; and above water, the piling line is more than 95 percent complete. The pilings are typically 8 inches in diameter, but they have likely diminished in diameter since originally emplaced. Gaps of 2 to 6 inches are common between adjacent pilings, but larger gaps of 8 to 10 inches also occur.

On the peninsula’s eastside exposure, extreme damage has occurred along 245 feet of shoreline. Most capstones along the lower two to three tiers have subsided in place or tilted about 30 to 40 degrees lakeward. The line of pilings is generally complete; but where the worst structural damage has occurred, the pile line has a 7-foot void. In this area of severe damage, three of five tiers of capstones are out of place; some capstones have possibly fallen lakeward through the break in the piling line. Exposures of the rock fill show that it is cobble- and boulder-size quarry rock and demolition debris. Much is rounded and abraded, indicating long-continued movement due to wave surge.

Sonographs along this stretch of damaged revetment indicate that the toe protection has a more irregular surface than that elsewhere on the peninsula. This condition is interpreted as representing a thick blanket of debris eroded from the rock-filled crib. Numerous large sonar targets also appear across this debris field. Some may be displaced capstones; but most are likely to be larger cobbles and boulders removed from the revetment crib, as well as concrete blocks related to revetment repairs and remedial action. The sonographs provide no information about the underwater face of this revetment because the severe damage has led to remedial action and the placement of
concrete blocks, 5 to 6 feet on a side, atop the toe protection and against the revetment piling line. These concrete blocks probably are barriers to any additional loss of rock fill; however, wave surge at the level of the revetment tiers can shift and displace rock fill exposed under tilted and offset capstones, and thus cause additional capstone displacement.

Along the south side of the peninsula, the principal structural problem is a nearly uninterrupted lakeward shift and tilt of the revetment capstones. Generally, just the lower one or two tiers are affected, but in several locations all four tiers are displaced. The maximum amount of lakeward tilt varies from about 20 to 40 degrees. Although in places, the shifting of the lowest tier of capstones has pushed pilings lakeward, the line of pilings is generally unbroken. Along most of the revetment, wave surge can be heard moving in the crib rock beneath the capstones.

Sonographs show that toe protection is in place; no scour or undermining occurs along its lakeward edge. An essentially continuous sonar reflector along the structure indicates that any underwater breaks in the pilings must be limited in extent and few in number. Dispersed across the upper half of the toe protection is finer grained material interpreted to be rock fill removed from the lakeward side of the crib. This rock fill has apparently been removed by waves surging through the gaps between the closely spaced pilings.

Several factors account for the fact that revetment damage is more severe along the east side than along the south side of the Montrose peninsula. The eastern exposure permits the shoreline to be hit by waves from the northeast quadrant, the main direction for most damaging waves. Furthermore, the revetment is in deeper water along the east side, where wood pilings have more underwater exposure above the toe protection. Greater exposure increases the deterioration and loss of pilings, and thereby, the loss of crib rock fill.

**Montrose Harbor jetties**
The two jetties at the entrance to Montrose Harbor (fig. 7) have vertical exteriors of steel sheetpile with reinforced concrete caps forming walkways 5.3 feet above LWD. The west jetty has a near east-west alignment; it is 160 feet long and 20 feet wide with the shore end meeting the Type D1 revetment. The east jetty has a near north-south alignment; it is 225 feet long and 15 feet wide with the shore end meeting the Type C revetment. Along both jetty walkways, small areas of concrete are cracked or pitted; but in general, the walkways are in good condition.

Only the lakeward side of the jetties was investigated with sidescan sonar. Sonographs indicate that the lakeward-side steel sheetpile of both jetties is continuous with no breaks or offsets. Neither jetty has toe protection. No lake-bottom depressions occur along the lakeward side of the jetties, and thus scouring by waves and wave-induced currents is not a problem. However, distinct elongate lake-bottom depressions extend off the end of both jetties parallel to the jetty axes (fig. 7). The west depression is centered on the jetty end and extends into the harbor entrance; the east depression is positioned off the southeast corner of the jetty and extends southward. From their general appearance on the sonograph, the surface area of the west jetty depression is about 1.5 times larger than the east depression.

Length and width of the depressions were not determined, but leadline soundings were taken within the jetty-end depressions and 15 feet back from the jetty ends on both the lakeward and harbor sides (table 3). These data indicate that the depressions are about 2 to 4 feet deeper than the lake bottom on the jetty harbor side, and about 6 feet deeper than the lake bottom on the jetty lakeward side. The depressions correspond to the deepest water adjacent to any structures in the study area.
Table 3  Leadline depth measurements at the outer end of the Montrose Harbor jetties

<table>
<thead>
<tr>
<th></th>
<th>Depth in ft below low water datum (LWD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>West jetty</td>
</tr>
<tr>
<td>Jetty end depression</td>
<td>29.0</td>
</tr>
<tr>
<td>Jetty lakeward side</td>
<td>22.8</td>
</tr>
<tr>
<td>15 ft back from jetty end</td>
<td>26.9</td>
</tr>
</tbody>
</table>

Available data are insufficient to determine whether these depressions are growing larger. These features may be as old as the jetties and represent a lake-bottom configuration in equilibrium with the wave and current forces interacting with the jetties. They may or may not represent potential structural problems for the jetties. Underwater investigation by divers may be warranted.

Revetment between Montrose and Belmont Harbors
The Type D1 revetment (fig. 5) extends about 1.3 miles from the west jetty at the entrance to Montrose Harbor to the peninsula along the north side of the Belmont Harbor entrance. For its entire length, the revetment is six tiers. The lowest tier is a broad promenade three capstones wide with the stones superimposed on the rock-filled crib. The crib bulkhead is built of wood sheeting that is three planks thick and held by horizontal timbers (wales) attached to 8-inch-diameter pilings spaced about 2 feet apart. The pilings are along the lakeward face of the bulkhead.

Toe protection is above or just below LWD along most of the revetment. As a result, most of the lakeward face of the bulkhead is covered by rock and has little or no underwater exposure. Locally, toe protection is visible along the revetment front and consists of dolomite boulders, measuring 2 to 6 feet long axis. Sonographs show that toe protection is laterally continuous along the revetment, has a rather uniform width, and includes some of the largest toe-protection boulders in the study area. Along the lakeward edge of the toe protection, sonographs indicate no lake-bottom scour or undermining.
A unique feature associated with this revetment is a line of steel I-beams about 15 feet offshore from the line of wood pilings. The I-beams extend from the Montrose Harbor west jetty southward to about 450 feet north of Belmont Harbor entrance. Driven into the lake at the outer edge of the toe protection with a slight landward inclination, the I-beams are generally spaced 16 to 28 feet apart. After the revetment was constructed, these steel I-beams were added as a remedial action to provide structural support.

From the west jetty of Montrose Harbor southward for about 1500 feet, few capstones are out of original position. The few capstones that have tilted or settled are stones that form the lower tier promenade. Along this reach, the upper part of the three-plank sheeting is intact, and toe protection extends up to or slightly below the top of the sheeting. Gaps between the lower tier capstones reveal that the crib rock fill is primarily cobbled-size material. Settling and shifting of this fill is probably responsible for the few tilted and downdropped capstones.
Figure 7  Sonograph of the lakeward side of steel sheetpile jetties at the Montrose Harbor entrance. Significant characteristics are the lake-bottom depressions at the ends of the jetties and the absence of toe protection. Distortion of the jetty orientation is caused by survey boat and sidescan sonar towfish turning past the harbor entrance.
The revetment in front of the southern part of Waveland Golf Course has been modified with riprap, which covers the lower three of six tiers. The riprap consists of 2- to 6-foot long-axis dolomite boulders. They extend onto the toe protection, but none extend out to the steel I-beams. The structural problems that prompted this addition of riprap are not detectable above water, and none are indicated by the sonographs.

From the south end of Waveland Golf Course and continuing south, 1200 feet of revetment fronts the Addison Drive parking area. The northern 700 feet of revetment maintains the original design, but the southern 500-foot section has been modified with riprap. Along the unmodified revetment, some capstones remain in their original position; some are tilted and offset. The sections in good condition always correspond to three-plank wood sheeting and wood pilings that are intact, and to toe protection that extends upward to within one foot of the top of the bulkhead. Capstones that are displaced belong to one or more of the three lower tiers in the promenade. Wood pilings generally are present along these areas; but breaks in the wood-plank sheeting are visible below water level, and toe protection is low at these breaks. Capstones are shifted or tilted in a lakeward direction, and in two cases, capstones from the first row have fallen lakeward and rest atop the toe protection. The bulkhead breaks clearly correspond to places where rock fill has been removed from the crib and dispersed onto the toe protection; however, no distinct debris fans can be identified in the sonographs.

Along the Addison Drive parking area, the most severe structural problems occur opposite the juncture of the drive and the parking area. All six revetment tiers have been affected. Capstones of the upper four tiers are tilted lakeward; capstones of the lower two tiers are tilted or settled in place. These structural problems correspond to a major break in both the wood-plank sheeting and wood pilings, and a lower height of toe protection causing greater underwater exposure. Sonographs show a debris fan dispersed across the toe protection, extending about 5 feet beyond the local lakeward edge of the toe protection.

The southern 500 feet of revetment along the parking area has riprap consisting of 2- to 6-foot dolomite boulders blanketing the lower three tiers. The riprap extends onto the toe protection, although not as far offshore as the line of steel I-beams. The structural problems that warranted the addition of riprap are not indicated by sonographs or above-water observations.

Southward from the Addison Drive parking area, the condition of the revetment is quite variable. Several long reaches have no structural problems; several have problems limited to the lowest tier where capstones have shifted or tilted; and several have major capstone displacement involving five of the six tiers. Wherever structural problems occur, they are almost always associated with visible breaks in the wood-plank sheeting. Capstones in several localities have subsided and tilted sufficiently to expose the underlying crib fill. Much of this material has been rounded and abraded by wave surge. In a few places, all cobble-size fill has been removed, leaving cavities under capstones held up by a few boulders.

The worst structural problems along the entire Type D1 revetment occur at three sites within an 800-foot section of the peninsula north of the entrance to Belmont Harbor. At all three sites, the wood bulkhead is completely gone and the six capstone tiers are in disarray. The largest of the three failures is centered about 200 feet north of the Belmont Harbor entrance and affects about 55 feet of shoreline. Not only is the bulkhead gone, but no toe protection is visible, and capstones of the lower two tiers have subsided to water level or fallen and slid out onto the toe protection (fig. 8). Sonographs show that these revetment breaks are associated with a broad fan of debris blanketing the toe.
Figure 8  Sonograph along the Type D1 revetment north of Belmont Harbor entrance. Three underwater breaks in the wood bulkhead correspond to above-water sites of major capstone displacement. Debris fans of eroded crib rock fill are associated with the bulkhead breaks as well as large, angular sonar reflectors, which are possibly capstones that have fallen lakeward. An extensive debris fan extending lakeward was likely derived from erosion of fill material from the landward side of revetment.
protection and extending as much as 120 feet offshore. Because the debris has spread so far offshore, much of it is considered to be fine-grained fill material eroded from the landward side of the revetment. The offshore deposition probably occurred, to a large degree, during 1986-87 winter storms when substantial wave overtopping and upland erosion affected this site, and wave erosion nearly breached this peninsula.

Causes for the locally severe deterioration are related to two factors: (1) this part of the D1 revetment was built in water deeper than that adjacent to the revetment extension to the north, and (2) the toe protection does not extend as high against the bulkhead as it does to the north. The 6 to 8 feet of below-water exposure has locally accelerated bulkhead deterioration and breakage, which resulted in crib-fill losses and undermined capstones.

This most severe structural damage along the Type D1 revetment corresponds to the part of the revetment that has no steel I-beams in the nearshore. Possibly, the I-beams intercept and break ice that may otherwise ram and break the wood planks of the bulkhead; however, the 16- to 18-foot spacing of the I-beams limits their effectiveness as ice defense. The critical factors in this localized structural failure are considered to be the limited height of the toe protection and the greater underwater exposure of the bulkhead.

Revetment between Belmont and Diversey Harbors
A seven-tiered revetment lies between the entrances to Belmont and Diversey Harbors. Along this reach, the revetment has three different designs: the first 1,000 feet south of the Belmont Harbor entrance is a Type C structure; a Type B structure extends to the shoreline curve into Diversey Harbor; then another Type-C revetment continues southward for about 200 feet along the north side of the harbor entrance. The most severe structural problems occur along the Type B revetment.

For 1,000 feet south of the Belmont Harbor entrance, the Type C revetment has a bulkhead of three-plank wood sheeting held by wood pilings spaced at 3-foot intervals. Sonographs indicate that toe protection is continuous along the revetment, and that no anomalously narrow areas are present. Much of the toe protection is draped by material from an offshore debris mound that possibly derived from a capsized dredge barge (Chrzastowski, 1988). Along the exposed part of the revetment, the upper five tiers remain mostly horizontal; only the lower two tiers are tilted or offset. Capstone displacements correspond to visible breaks in the wood sheeting through which crib rock fill has apparently been removed.

The worst failure has occurred near the juncture of this structure and the Type B structure to the south: the wood planks and pilings are missing, and the lower two capstone tiers have subsided while the upper three tiers have sagged. Although no distinct debris fan shows in the sonographs, capstone displacement indicates that a moderate amount of rock fill has been lost. Capstones have subsided 2.5 to 3 feet at one location along 30 feet of the fourth tier; however, above and below it, the tiers are still in their original position. With no associated break in the wood bulkhead, the subsided capstones likely indicate localized settling and compaction of crib fill.

The transition from the Type C to B revetments can be observed at the water edge where the Type C bulkhead ends and nearshore boulders underlie the Type B capstones. Type B capstones rest atop a broad, quarry-rock mound that provides both support and toe protection (fig. 5).
Structural deterioration of the Type B revetment has been moderate to severe. Numerous 10- to 20-foot sags affect two or more tiers. The largest sag occurs near the north end of the revetment, affecting all seven tiers along an 82-foot reach. This is also the largest sag in the study area—as well as the largest such feature observed along the entire Chicago lake front. The maximum vertical displacement along the sag axis is about 2 feet. Possibly, these sags along the revetment owe their origin to settlement and compaction of underlying rock fill rather than to lakeward loss of fill material.

Severe damage is related mainly to wave-induced removal of rock fill from under capstones. Along much of the revetment, capstones from the lower one or two tiers have been undermined, fallen lakeward, and now rest atop the quarry-rock mound, generally within 5 to 10 feet of the original revetment edge (photo, p. iv). Where rock fill is exposed, cobble-size rock and demolition debris are abundant; much has been rounded and abraded by wave surge. In several locations, enough rock fill has been removed and capstones displaced that wave surge reaches beneath the fourth or fifth tiers of the revetment.

The most severe damage to any section of revetment in the study area has occurred along the shoreline at the north end of the Lincoln Park Gun Club. Capstones of the lower four tiers have tilted and fallen from their original positions, exposing the rock fill underlying the upper tiers. Near the north fence of the Gun Club, a significant volume of rock fill has been removed from beneath the revetment, and the three upper tier capstones form an arch over a cavern. Comparable deterioration may have previously occurred along the southern part of the Gun Club shoreline; but it has either been halted or hidden by riprap that has been placed on the revetment and covers all but the upper three tiers.

Although a considerable volume of fill has been removed under the capstones of the Type B revetment, no debris fans can be identified on the quarry-rock mound. This may be the result of limited resolution of the 100-kHz sidescan sonar used in this survey. It may also be the result of displaced rock dispersing into the interstitial spaces of the larger rock that composes the quarry-rock mound. Sonographs indicate this mound has a rather uniform width along the Type B revetment, and no scour or undermining shows along the lake-bottom edge of the mound.

Lakeward of the Diversey Harbor east jetty, most of the capstones in the Type-C revetment are in their original positions. Capstones that have shifted and tilted are generally associated with breaks in the wood planks of the bulkhead. No sonograph was obtained along this reach.

**Diversey Harbor jetties**
The east and west jetties at the entrance to Diversey Harbor were built within the last 15 years; they are the youngest shore structures in the study area. Only the lakeward side of the east jetty was examined. The jetty is 188 feet long, 16 feet wide, and aligned approximately north to south. It has an exterior of steel sheetpiles and a reinforced concrete cap that forms a walkway 7.1 feet above LWD.

Sonographs indicate that the steel sheetpiles is laterally continuous along the lakeward side; it has no breaks and no apparent structural problems. The toe protection is laterally continuous, has a rather uniform width, and wraps around the end of the jetty. Along the edge of the toe protection, the lake bottom shows no scour or undermining. Overall, no structural problems are apparent either above or below water along the east jetty.
Revetment between Diversey Harbor and Fullerton Parkway
The shoreline between the southside entrance to Diversey Harbor and the shoreline prominence at Fullerton Parkway is defended with the Type-A revetment (fig. 5), which has a 14- to 15-foot-wide timber crib with wood sheeting three planks thick and 8- to 9-inch-diameter wood pilings at 4-foot intervals. Every piling has a steel tie rod that spans the crib. The crib rock fill is capped with three rows of dolomite quarry blocks. Although the blocks were once covered by a concrete veneer, most of it has weathered away. Behind the crib and slightly above the quarry blocks, a concrete "paved beach" slopes upward.

Deterioration is concentrated along the southern half of this revetment and limited to the timber crib along the lakeward edge of the structure. Along this southern reach where capstones have dropped from their original positions, the crib has six separate cavities, each ranging from 25 to 60 feet of shoreline length. Wood pilings are still front of the cavities but the wood-plank sheeting is gone. The tie rods are generally bent and broken free from the lakeward side of the crib. In some places, tie rods still span the crib walls and capstones have toppled in place without dislodging the rods. Leadline soundings in the cavities indicate the capstones have dropped 3 to 6 feet from their original positions. From length, width, and depth measurements at each of these cavities, the estimated losses of crib rock fill range from 67 to 161 cubic yards. For all six cavities, the total loss of rock fill is estimated to be 577 cubic yards.

Sonographs show laterally continuous toe protection along the entire revetment. No anomalously narrow points, and no lake-bottom depressions are apparent. Cavities in the timber crib show clearly because the sonar signal passed through breaks in the wood sheeting and reflected off the landward crib wall (fig. 9). In front of the revetment cavities, sonographs show debris fans of displaced rock fill spread across the toe protection. The fans are elongate, irregular lobes limited to the upper half of the toe protection.

In addition to the six sites of structural failure at the south end of the revetment, one more site occurs at the north end of this reach near the Diversey Harbor entrance where the shoreline bends toward the northeast. Capstone displacement is not as severe, however, as along the southern reach. Both the northern and southern failure sites have a northeast shoreline orientation; therefore, shoreline orientation may be an important contributing factor in structural failure. The remainder of the revetment has an east and southeast orientation with no capstone displacement, although in a few locations the sonographs indicate small debris fans. These fans may correspond to the early stages of bulkhead breaks and crib-fill erosion.

North Avenue/Fullerton Beach submerged bulkhead
This is a perched beach held by a submerged bulkhead of steel sheetpile and concrete-filled steel columns. The top of the steel sheetpile is 2 feet below LWD. Along the southern half of the lakeward side of the bulkhead are 13 emerged steel sheetpile buttresses that project lakeward at about a 45-degree angle to the bulkhead and provide added structural support. Only the lakeward (east) side of the bulkhead was examined in this sidescan sonar survey. The buttresses hindered sonar examination by blocking sonar signals from part of the bulkhead.

The part of the submerged bulkhead that was examined is laterally continuous with no breaks or displacements in the steel sheetpile. The lakeward side of the steel sheetpile buttresses also are laterally continuous with no breaks or displacements. No underwater structural problems were identified along the bulkhead or its buttresses.
Figure 9 Sonograph along the Type A revetment north of Fullerton Parkway. Cavities in the revetment crib are indicated by sonar reflections off the wood bulkhead on the crib landward side. Below the cavities, lobate debris fans blanket the upper half of the toe protection.
Sonographs indicate that toe protection extends for approximately 500 feet between the junctures of the bulkhead and the second and third groins, counting from the north. No other toe protection can be identified along the bulkhead, or along the lakeward side of the buttresses. If toe protection is present along the buttresses, then it is blanketed or buried by sand, and thus cannot be distinguished in the sonar record. Several buttresses have acted as groins, trapping a small wedge of sand on the north side. Off the lakeward end of these buttresses, no lake-bottom depressions nor any other bottom features indicate scour caused by waves and wave-induced currents.

**North Avenue groin**

This hook-shaped groin has a steel sheetpile exterior and a reinforced concrete cap that forms a walkway 7.2 feet above LWD; the structure is 15 feet wide and 1,180 feet long from its outer end to the walkway that backs the sandy stretch of North Avenue Beach. In addition, the groin extends 900 feet farther westward to its junction with the Type-E revetment. The function of this structure is to retain sand at the downdrift end of the North Avenue/Fullerton Beach.

From the tip of the groin to its junction with the Type E revetment, the concrete walkway is in good condition except in a few small areas where pieces of concrete are missing. Sonographs indicate that the below-water steel sheetpile is laterally continuous with no breaks or offsets. Toe protection is apparently absent from the base of the structure, except along the groin end and continuing for 66 feet along the north face (fig. 10). This short length of toe protection has a uniform width of about 17 feet. Fathometer records along the structure indicate that a submerged wedge of sediment has accreted against the east- and southeast-facing sides of the structure. Overall, observations above and below water level indicated no structural problems, nor any lake-bottom scour or undermining adjacent to the structure.

**Revetment between North Avenue and Ohio Street Beach**

The steel sheetpile Type E revetment defends the shoreline from its junction with the landward extension of the North Avenue groin southward to the north side of Oak Street Beach, and from the south side of Oak Street Beach to the west side of Ohio Street Beach.

North of Oak Street Beach, sonographs show a laterally continuous steel sheetpile with no breaks or offsets. Toe protection, which extends along the northern 1,500 feet of the revetment, possibly continues south of this reach; but it may be buried by sand eroded from the Oak Street shoreface and ramped against the steel sheetpile. The toe protection is also laterally continuous and has no anomalously narrow areas. Along its lakeward edge, according to fathometer records, lies a shore-parallel lake-bottom depression that is 1,800 feet long, 50 feet wide, and up to 2 feet deeper than the lake bottom 150 feet farther offshore (Chrzastowski, 1988). It may represent an area of nondeposition influenced by wave energy reflected off the steel sheetpile. Since the toe protection has not been undermined or shifted, the depression presents no apparent threat to the stability of the toe protection or the revetment. Southward, the depression diminishes in size and then ceases to exist near Oak Street Beach.

From Oak Street Beach southward to Ohio Street Beach, a wedge of sand has accumulated against the Type E revetment, limiting its underwater exposure. Whereas, north of Oak Street Beach the revetment has an average 10 to 11 feet exposure below LWD, between Oak Street and Ohio Street Beaches the exposure is typically 3 to 5 feet. Above this sand wedge the sonographs indicate a laterally continuous steel sheetpile with no breaks or offsets. The sand wedge is evidence that scour has not occurred.
Figure 10  Sonograph along the lakeward outer end of the North Avenue groin. Toe protection is limited to the north-facing exposure of the steel sheetpile. No lake-bottom depressions occur along the unprotected east-facing exposure.
No sand wedge has accumulated at the nearshore entrance to Chicago Outer Harbor opposite the nearshore end of the Outer Harbor Breakwater. Toe protection is present and necessary along this reach because of potential lake-bottom scour by wave-induced currents through the restricted harbor entrance. Although averaging 25 feet wide, the toe protection narrows to about 12 feet about 250 feet south of the harbor entrance (fig. 11). As sonographs suggest, a lake-bottom depression is associated with this narrow part of the toe protection and may be caused by scour. Further underwater investigation is warranted.

DISCUSSION AND CONCLUSIONS

Prior to this study, the causes of revetment deterioration along Chicago's near-northside lake front were largely speculative. This sidescan sonar study of shore-defense structures determined that deterioration and capstone displacement along the wood-crib and stone-mound revetments are not related to lake-bottom erosion or scour, or to the absence or shifting of toe protection. Deterioration of the revetments is related to a combination of factors, including design, construction materials, structural age, and the effects of wave surge and lake-level fluctuations.

Shore structures that have deteriorated or failed in some locations are the Types A, C, and D1 revetments built with a foundation of rock fill held within a wood bulkhead crib, and the Type B revetment built with capstones and rock fill atop a quarry-stone mound.

Above water, revetment deterioration shows in shifted, tilted, and settled capstones. As indicated by the typical lakeward tilt of capstones, displacement has progressed landward from the lakeward side of the structure. Also, the initial stages and the most severe capstone displacement always occur along the lowest capstone tier.

Below water, sonographs show that toe protection is present in front of all revetments but only present along various sections of the study area groins, jetties, and perched beach submerged bulkhead. The toe protection is a wedge-shaped pile of 50- to 1,600-pound riprap with an average maximum thickness of about 10 feet and an average width of 46 feet.

For revetments with wood support structures, capstone displacement can be traced to the damage and loss of the wood structures between the top of the toe protection and the top of the wood structures. Deterioration along the Type A and D1 revetments, as well as along the Type C revetment near the entrances to Belmont and Diversey Harbors, is related to crib rock-fill removal through such breaks in the wood bulkhead. The Type C revetment along Montrose peninsula is a special case in which crib rock fill is lost through gaps developed between deteriorated pilings that were once tightly spaced. The sonographs associated with sites of displaced capstones show debris fans of rock fill removed from the crib and dispersed across the upper part of the toe protection.

The processes causing the deterioration are long term; thus the age of these structures--50 to 80 or more years old--is a significant factor. As the structures alternately emerged and submerged with seasonal and yearly changes in lake levels, the natural deterioration of the wood-plank sheeting and pilings progressed at varying rates and to varying degrees. After years of exposure to lake processes, such as wave impact, ice ramming, and freeze-thaw action, breaks developed in the wood sheeting and gaps developed between closely spaced pilings. Through these breaks and gaps, the crib rock fill was exposed to wave surge. Wave surge combined with gravity, freeze-thaw cycles, and possibly, ice ramming to produce shifting, abrasion, and lakeward loss of crib rock fill. As a result, the capstones lost support and were displaced from their original horizontal positions.
Figure 11  Sonograph along the steel sheetpile, Type E revetment at the entrance to the Chicago Outer Harbor. Notable is an anomalously narrow place in the toe protection and its possible association with an area of lake-bottom depression.
Figure 12 presents a model depicting this process of rock-fill erosion and capstone displacement along an idealized revetment with a wood crib foundation. The erosion of crib rock fill progresses landward from the lakeward edge of the crib. Thus, the most common capstone displacement is a lakeward tilt; and the initial and most severe displacement is typically along the lowest capstone tiers. Because the lower tier capstones are held by the crib rock fill rather than the wood sheeting or pilings, the capstones often settle behind these wood structures, which are partially intact (fig. 12). This condition is common along the Types A, C, and D1 revetments.

Deterioration, breakage, and loss of the wood sheeting and pilings has been a major factor in the capstone displacement. However, the most extensive and severe displacement in the study area has occurred along the Type B revetment, which has no wood support (fig. 5). As this deterioration along the Type B revetment demonstrates, capstone displacement is not only related to deterioration and loss of wood support, but to size and weight of the rock fill. If this rock fill, consisting of 1- to 50-pound cobbles to small boulders (table 1), is exposed to wave surge, the local wave energy is sufficient to eventually shift much of it and move it lakeward. Evidence that movement has occurred is indicated by the rounded and abraded surfaces of exposed rock fill. Much of the concrete demolition debris used as subcapstone rock fill is rounded and abraded, although most of this material was angular when first placed as fill.

An additional factor leading to capstone displacement is lake-level fluctuation. Water-level changes have allowed wave impact to be expended at different heights along the revetments. For example, in the past 24 years, as recorded by the lake-level gauge at Calumet Harbor, Illinois, the monthly mean lake level has fluctuated as much as 6.39 feet. The record low monthly mean elevation was +575.41 feet (IGLD) in February 1964; the record high monthly mean was +581.80 feet (IGLD) in October 1986 (National Oceanic and Atmospheric Administration, 1964, 1986). High lake levels have likely been a major factor in deterioration along the Type B revetment where wave surge could affect the rock fill underlying the capstones rather than expend energy on the quarry-stone mound that forms the revetment foundation (fig. 13). Considering the Types A, C, and D1 revetments, lower lake levels brought conditions where waves and ice did not move over the bulkheads, but rather impacted these structures in their mid to lower exposures above the toe protection and led to the breakage and loss of wood sheeting.

In the study area, the groins, jetties, and revetments with no apparent structural problems are those with a steel sheetpile exterior: the Wilson Avenue groin, the Montrose and Diversey Harbor jetties, the North Avenue groin, and the Type E revetment between North Avenue and Ohio Street Beach. Advantages of the steel sheetpile include its rigidity, long life, and most importantly, impermeability. Rock fill behind a lakeward face of steel sheetpile cannot be shifted, removed, or otherwise affected by wave surge. Thus, structures with an exterior of steel sheetpile provide the model for improved revetment design.

If the deteriorated revetments are to be rebuilt with steel sheetpile, then the existing toe protection is a barrier to driving sheetpile. This rock must first be removed, or the steel sheetpile must be driven beyond the lakeward edge of the toe protection and backfilled. To prevent scour and undermining, a new belt of toe protection must be placed at the base of this sheetpile.
Wood piling or wood bulkhead deterioration, breakage and loss provides lakeward exposure of the revetment rock fill.

Revetment rock fill is dispersed onto the toe protection by wave surge action as well as gravity and freeze-thaw. Revetment capstones tilt, slide and fall as they lose their underlying support.

**Figure 12** Model representing successive stages leading to capstone displacement along an idealized revetment with a rock-filled crib.
Figure 13  Model for the process of revetment capstone displacement along the Type B revetment built without wood support structures. Sequence shows successive stages of rock fill removal.
In summary:

- The shore-defense structures can be divided into two categories based on construction, which directly corresponds to degree of deterioration. Those with an exterior of steel sheetpile have no apparent structural problems; those without a lakeward face of steel sheetpile have deteriorated due to the lakeward loss of rock fill.

- Toe protection is present along all the revetments but only along a limited extent of the jetties, groins, and the submerged bulkhead of the perched beach. The toe protection is an average maximum of about 10 feet thick and average width of 46 feet. Other than a shallow depression associated with the northern section of the Type E revetment, no lake-bottom scour or undermining occurs along the lakeward edge of the toe protection.

- Revetment capstone displacement occurs as a result of erosion of underlying rock fill. The principal erosion process is wave surge action. The size (cobble to small boulder) and weight (1 to 50 pound) of the rock fill is such that if the rock fill has a lakeward exposure, available wave surge is sufficient to shift, abrade, and remove the rock fill.

- The processes resulting in the revetment deterioration are long term. Thus the advanced age of the structures--50 to 80 or more years old--is a key factor.

The findings from this sidescan sonar study conducted during the summer and fall 1987 are preliminary. During the summer of 1988, this shoreline reach and the remainder of the Chicago lake front will be studied using higher resolution sidescan sonar.
REFERENCES


Chicago Park District, 1944 (revised 1947, 1987), Lake Shore Protection Work Map of Shoreline Bulkhead Types: Chicago Park District map (scale: 1 inch = 0.25 mile).


