PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
TECHNICAL UNIVERSITY OF NORWAY

SHORE PROTECTION STUDY FOR A SECTION OF U. S. INTERSTATE HIGHWAY 35 IN DULUTH, MINNESOTA[1]

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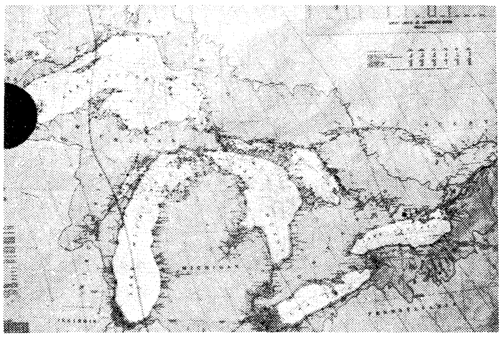
This paper will describe a study of alternative methods of storm protection for a major highway proposed along an urban shoreline under sub-arctic conditions which are rare in the United States. The study involved extensive hydrologic investigations, including hindcasting, wave refraction studies and tests of bottom stability. It also included large-scale model testing of alternative shore protection methods. The study concluded by recommending a permeable, vertical crib wall topped by a curved metal wave reflector as the best means of shore protection. Model tests showed that this design would allow less spray fallout on the highway than other designs tested--including the rubble mound--that it was less affected by ice formation and ice pile-up, and that its cost was significantly less.

The highway section is still in the planning stage, so that the findings reached in this study remain hypothetical. They are presented, nevertheless, in the hope that some of the procudures and findings may be of value in solving other shore protection problems under similar conditions.

The 41,000-mile Interstate and National Defense Highway System has become the most important intercity transportation network in the United States. Connection with this system is economically vital to any growing urban center. Interstate Highway 35 to the Duluth, Minnesota, area was part of the initial Interstate network approved in 1955, but the design for a segment of this road within the City of Duluth was delayed by a storm protection problem unique in the interstate system.

Duluth stands at the western end of Lake Superior at the terminus of a broad reach of the lake called the "Duluth pocket." This area has been subjected to many intensive storms causing considerable property damage and loss of life. Storms from the northeast and east-northeast have the greatest potential for damage because of the "fetch" distances. In storms from these directions, the wind builds up waves for as much as 350 miles across open water and drives them ashore at Duluth. Ice formation and ice floes are accompanying hazards for more than half of each year.



Highway operating requirements compound the problem. Closing of an Interstate highway cannot be tolerated for any extended period of time. Relatively small amounts of spray and ice can create unsafe driving conditions, however, and a highway alignment along the lakeshore must consider this.

In 1958, Howard, Needles, Tammen & Bergendoff, consulting engineers, prepared a study of possible locations for Route 35 through Duluth for the Minnesota Department of Highways. The report evaluated eight routes for the approach into the vicinity of the central business district. The recommended location extends into the lake and parallels the shore for approximately 4,700 feet. This route was chosen to provide proper access to the central business district.[1]

Duluth is contained on the west by steep foothills of the Mesabi Range. A route into these hills would limit the usefulness of the Interstate highway to the city.

Duluth itself occupies the land between the lake and the hills, leaving no possible routes for a major highway. A lakeside alignment was the only alternative which would serve Duluth's transportation needs without disrupting the city.

The master plan for the Duluth roadway calls for lowering the highway profile to pass beneath an existing road. This is the most desirable alignment, allowing the lakeward access ramps to act as spray buffers for the main roadway. Construction costs are also lower for a sunken roadway because the original grade of the Duluth, Mesabi and Iron Range Railway can be used. Further north, the main roadway rises to the level of the top of the seawall and an unobstructed view of the lake is possible.

The Problem and the Studies

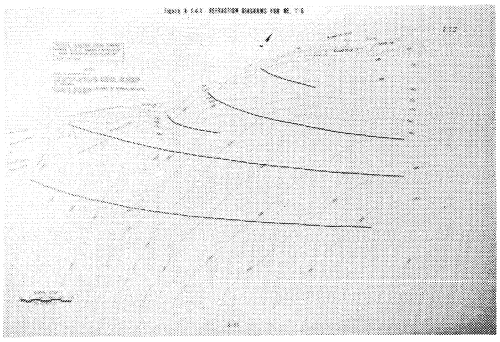
The question, however, was whether adequate storm protection could be provided along a lakeshore alignment without obstructing the view and without prohibitive cost. In October, 1966, Howard, Needles, Tammen and Bergendoff was engaged by the Minnesota Department of Highways to determine the nature and extent of shore protection works necessary to guard this roadway from the elements.[2]

To deal with this problem, the following steps were taken:

1. A "hindcast" study of the history of wave action on the shore to determine the maximum wave height that must be considered in designing the seawall.
2. An analysis of surveys of hydrographic data showing annual changes in the lake bottom profile and the types of sands deposited there.
3. Tracer studies to determine the extent of drift of underwater sands and to estimate the amount and type of fill required to stabilize the lake bottom.
4. Consideration of four types of protective structures (vertical permeable, vertical impermeable, sloping permeable, and sloping impermeable) for their capacity to absorb splash and spray, and for the influence of ice on oversplash and general stability.
5. Analysis of construction and maintenance costs.

Hydrologic studies were conducted by Dr. Per Bruun of the National Engineering Science Company. Hindcasting of storm data for a 51-year period--1916-1967--disclosed the prevalent storm directions, magnitudes and critical wave heights and frequencies. Hindcasting, together with model studies and the statistical wave spectrum, indicated there would be most spray during lengthy storms from the northeast or east-northeast in which at least one-third of all breaking waves reached heights of 9 to 10 feet or more. Such storms occur approximately once a year and produce 10 to 20 waves per hour in the 13 to 16 foot range.

Refraction diagrams were used to indicate which sections of the shoreline would be most affected by storms. These diagrams show the degree of bending a wave sustains as it is affected by the bottom slope. The diagram for a northeast wind shows minimum refraction near the Holiday Inn at the western end of the wall. Here the bottom slope is most gentle and wave height is reduced more by bottom friction than in other places.



Because the waves approach in a straighter line with an east-northeast wind, waves are reduced less by refraction than with a northeast wind. The refraction studies showed that no concentration of wave action caused by refraction can be expected along the wall. When wind direction varies from northeast to east-northeast, some waves will crest at a small angle to one another. This may cause waves to break on the wall where waves from one direction only would not produce breakers. Under these conditions the frequency of wave breaking increases but the height of the breaking does not.

The U. S. Army Corps of Engineers' lake survey charts for the Duluth area show that the beach and nearshore profiles are very steep. The analysis of hydrologic characteristics continued with a study of these bottom profiles and their effects on offshore construction.

Detailed studies of the bottom had been conducted in 1955 by the Corps of Engineers and in 1966 by the Minnesota Highway Department.

The changing "steepness characteristic" of the beach profile was computed. Steepness characteristic is the mean depth divided by the width of beach profile. Both the average mean depth and average steepness characteristic increased during the 11-year period between data collections. This is a sign of decreasing stability of the profiles. The evidence suggests that the lake bottom at depths of more than 30 feet becomes more stable as it is filled with material washed out from inside the 20-foot contour line.

Borings were also drilled in the lake bottom parallel to the shoreline. These accurately revealed the location of bedrock support that could be used as a foundation for piles in a crib type seawall.

A tracer study was made to determine which sands were most stable and which were likely to be washed into the lake. Sand thus washed away undermines the protective properties of the wall.

The addition of a seawall also changes wave reflection characteristics that may be observed with tracer studies. When reflection of wave energy increases, the bottom stability decreases due to increased water velocities over the bottom.

Sands of four different colors and two different grain sizes were placed to determine the extent of movement that should be expected from sand fill. These sands were Nevada 47 with a mean diameter of 0.23mm and a finer sand, Nevada 70, with a mean diameter of 0.13mm. These sizes correspond to the grain sizes of sand available for the project from local borrow areas.

Two major storms occurred between placement and collection of the tracer material. A general increase in movement with increasing distance from shore was evident. The bottom profile and tracer studies showed that the coarse sand was relatively stable, but the finer sands were easily washed out.

It was determined that equilibrium could be established if a minimum of 300,000 cubic yards of sand no finer than the coarse test sand were placed in front of the wall upon completion of construction. Obtaining this balance of sand on the lake bottom means insuring the stability of the toe of the wall.

Seawall Design

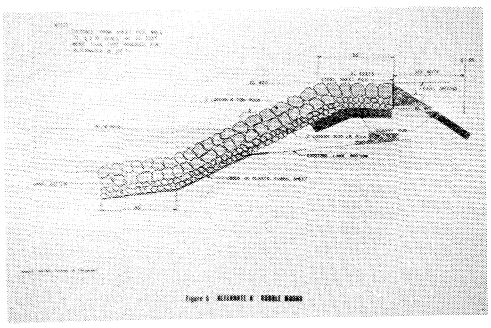
To serve its purpose of dissipating the forces of breaking waves, a seawall must satisfy these criteria:

1. It must maintain the equilibrium of the lake bottom in front of the wall.
2. It must remain structurally sound and stable.
3. It must provide for some wave reflection while preventing up-run, spray and oversplash.

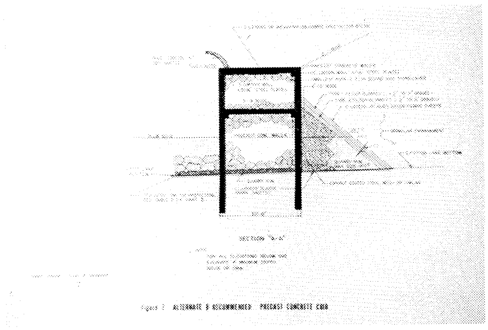
The Duluth wall had to be constructed to emphasize retardation of up-run and spray. In spite of its precarious location, it had to provide stability against overturning, sliding, scouring and ice action.

Seawalls may have vertical or sloping walls and may be of permeable or impermeable construction. Generally, vertical walls should be used where there is little possibility of erosion. Wave reflection and consequent erosion at the base of the wall are the greatest disadvantages of vertical walls. Sloping walls can be used where subsoil is erodible. They may be of permeable construction using wave percolation to absorb energy, or impermeable, receiving the full force of the wave.

Structures tested for this study included a rubble mound, a vertical crib, and combinations of both structures. The rubble mound is composed of layers of material. A permeable plastic fabric sheet is first placed on the lake bed. Fluids are able to pass through with relative ease while a sand layer laid on top of the sheet is contained. Large stones are fitted into the sand and surmounted by rows of very heavy armor stone. These must be located with considerable care to minimize dislodging by wave action. Behind the armor stone is a sheet steel wall serving as a divider for different sized materials and as a spray shield. Model tests showed it to be ineffective as a spray deflector because any spray fallout had occurred as a result of impact on the armor stone and wave run-up well in advance of the shield system.



The full crib employed for this study consisted of parallel runs of piles embedded in the lake bottom and extending to a height equal to the shoulder of the supported roadway. The crib is basically an energy absorbing device but total dissipation does not occur and some wave reflection is apparent.



Model Testing

To simulate wave and spray conditions in this area, model studies were conducted at the St. Anthony Falls Hydraulic Laboratory, University of Minnesota, under the direction of Professor C. E. Bowers.[3] The laboratory testing facility is a channel 9 feet wide, 6 feet deep and 250 feet long. It is equipped with a wave generator capable of duplicating waves up to 2 feet high and 20 feet long. To simulate storm conditions a wind generator was placed over the top of the channel and run to simulate winds of 50 mph.

Models of the structures to be tested were constructed in the channel bed at a 1:25 scale ratio. Tests of structures in deep water were conducted with a bottom profile similar to the profile at Station 478+70 with a toe depth of 19 feet.

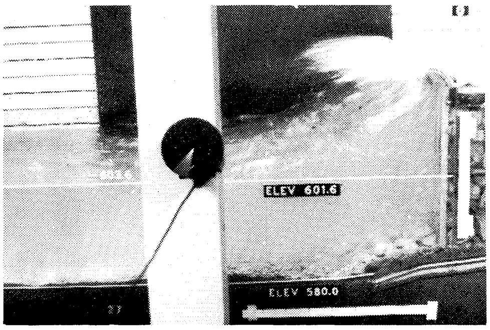
A crib model was constructed with two rows of 16" square concrete piles. Walers were installed with ties connecting them. Stones of several sizes were tried as fill for the crib. Wave action extending back through the large stones in the crib and spraying over the top caused the rock fill material to move out through the voids between the 3-foot stones.

To prevent this loss, it was necessary to add a filter layer which allowed for passage of water through the structure but which acted as a barrier against rock displacement.

Other problems arose with the vertical crib design. While its permeable face dissipated much of the wave force, there was still a considerable amount of spray.

Several versions of the spray deflector were tried on the crib model. These were attached to the waler immediately behind the front row of pilings. Aluminum trays were placed behind the wall to compare water accumulation with different spray screens. The most effective deflector was a curved steel screen describing a 73-degree arc on a 5.25 foot radius. When set at a constant elevation along the top of the wall, this screen also provides the most aesthetically pleasing view of the wall.

To obtain information on velocities inside the wave, adjacent to the face of the structure and along the lake bottom, plastic particles with a specific gravity of about 1 were added to the flow. This 1/10-second time exposure indicates these relative velocities and shows the effectiveness of the wave screen.



A rubble mound was built with a surface slope of 2 horizontal to 1 vertical, using two layers of 8-ton stone over a filter layer of 1600 lb. stones and other filter materials. A considerable amount of up-rush and spray could be seen. The spray often carried over the rocks, disturbing the land behind the structure. Some movement of armor rocks and other rocks was also caused.

A comparison of spray properties shows that to achieve an equivalent spray rate of 1 inch per hour at the same location for the rubble mound and crib structures, the rubble mound would have to be 60 feet lakeward of the crib. This comparison was made under the worst 12-second wave spray condition.

A modified crib was built consisting of a crib type structure from lake bottom to water level (elevation 601.6). From there a rubble mound was extended upward at a 15:1 slope to elevation 620. However, even with a curved spray screen similar to the one used on the crib structure, spray was considerably worse than in the straight crib design.

To test the structures in shallow water, they were rebuilt in a model duplication of Station 484+00, one of the shallow water sites where storms were most severe. Large waves breaking about 100 feet from the breakwater plunged into the toe and created up-rush velocities on the protective structures.

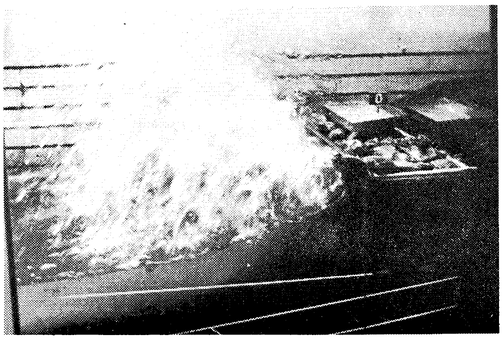
This area thus became more critical than the deep profile.

Preliminary tests indicated that shallow waves breaking on a rubble mound had much greater force than was initially thought. Extreme erosion at the toe allowed some of the toe protection material to tumble into the scour hole. The rubble mound was therefore not tested in the shallow profile.

Several versions of the modified rubble mound with crib structure were tested on the model. The rubble mound section had a slope of 2 horizontal to 1 vertical and was protected by two layers of 4-ton armor stone. Initial wave tests indicated that practically all waves broke within 120 feet of the shoreline as opposed to the deeper profile where large waves broke as far as 500 feet from the structure. Smaller waves with a breaker height of 13 to 15 feet plunged directly on the structure face causing serious rock movement. The surge and up-rush of the larger waves entirely swamped the crib --with large amounts of water splashing onto the roadway. Having determined the modified rubble mound was not a satisfactory design for this location, the crib structure was tried in shallow water.

This crib was similar to the deep water model, with 16" x 16" concrete pilings spaced 38 inches on center and a back row of pilings 6 feet on center and 20 feet behind the front of the structure. The space between was filled with 3 and 4-foot stone, followed by a layer of smaller stone as a wave action barrier and then topped by another row of 3 to 4-foot stone. A 15-foot curtain wall was again used with a 4-foot filter layer and quarry run material. The toe protection consisted of a double layer of 1600 lb. stone on top of a layer of plastic filter material. This extended out 30 feet from the face of the piles and was excavated to 6 feet below the lake bottom. A curved wave screen was placed at the top of the piling.

While the waves broke within 150 feet of the breakwater, and produced high up-rush velocities, the permeable structure dissipated most of this energy. Waves 13 feet high broke against the face of the breakwater and threw spray 50 feet above it--but this was deflected by the curved screen. There was some rocking of the 8-ton armor stone but no serious movement occurred. A 19.5-foot, 125-year wave threw spray 100 feet into the air and 150 feet lakeward but produced less movement of stone than the 16-foot wave. The crib structure had proven the best design for this shallow-water location. A brief test was run of an impermeable face on the crib structure. The splash and spray caused by wave impact increased greatly. The crib with an impermeable face was the largest spray producer of the models tested.



Cost of construction was estimated for three alternative shore protection systems:

Alternative A - The rubble mound located 60 feet lakeward of the wall line for the concrete crib: $9,160,000.

Alternative B - Concrete crib with layered fill placements behind the back piles: $5,900,000.

Alternative C - Concrete crib with perforated, corrugated metal retainer along the back piles: $5,650,000.

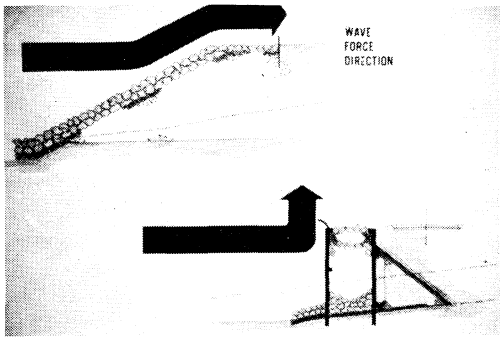
The rubble mound was not considered economically feasible. The two crib alternatives varied in cost by less than 4.5%--and while Alternative C had the cost advantage, the study recommended Alternative B because of the advantage of the permeable layer behind the back piles in arresting rock movement.

Ice Studies

The Duluth area is subjected to icing conditions almost six months of the year. Because of the importance of ice acting on structures for these extended periods, an additional study was performed combining laboratory testing and field observations.[5] Design criteria with respect to icing conditions included:

1. A minimum of spray in normal and extreme icing conditions.
2. Wall stability under all icing conditions.
3. Retardation of ice climbing and ice damage.
4. An aesthetically pleasing structure.
5. An easily and economically maintained structure.

Icing of shore and harbor structures occurs above the waterline when temperatures drop below freezing. Sloping walls are iced easily by up-rush, spray and splash even with modest wave action. This is because waves break directly on the structure. Vertical permeable walls will become iced to a lesser degree because up-rush and splash do not reach the same heights as on a sloping wall. Production of splash and spray is smaller because waves seldom break on vertical walls. There is also significant difference in the hydrodynamics of sloping and vertical walls. Waves breaking along a sloping wall give momentum to splash and spray along a path parallel to the slope. In a vertical wall, the wave uprise is almost totally vertical. The influence of icing is therefore more severe behind sloping rubble mound walls than behind vertical crib walls.



Ice cover on a permeable wall would contribute to instability if passages between stones were plugged with ice. Wave reflection also increases in an ice-clogged vertical wall, but the high velocity of storm waves makes clogging improbable. Clogging increases hydrostatic forces in either wall but the major component of a wave force is horizontal. On a sloping wall this must be absorbed by the armor rock on the face of the wall. A vertical wall is constructed so these forces are dissipated or transferred through the pilings to the earth below.

Further laboratory studies were conducted by Dr. Per Bruun as Chairman of the Department of Port and Ocean Engineering of the Technical University of Norway. Experiments at the Harbor Institute confirmed that ice floes caused failures in the armor rock and face of sloping permeable walls.

Some basic physics can also be applied to the icing situation. When water freezes it expands, resulting in remarkable pressure build-up. A temperature change of 2° centigrade per hour, beginning at minus 20° centigrade (or 4° Fahrenheit), can cause a lateral ice pressure of 16 kg/cm^2 (or 5 pounds per square inch). These pressures can result in extreme forces against all structures.

In one instance, a lighthouse designed to withstand ice forces of 100-150 metric tons per meter was sheared off at the base by icing effects.

High pressures against objects may also occur as a result of energy transfer from air or water to ice. This occurs when winds and currents moving with ice fields impart forces to the ice capable of causing considerable ice build-ups on shores and shore structures. Ice floes pushed toward coastal structures may or may not be washed ashore. When a vertical wall is encountered, the possibility of ice deposition is almost non-existent. Tests showed that ice floes in wave-agitated waters seldom collided with a vertical wall. Due to gravitational and inertial forces, the ice tended to slide down the backside of a wave before touching the wall. Sloping walls are a different situation. While ice usually does not accumulate on a one-on-one slope (45°), it is readily deposited on a two-on-one incline. The rougher the surface material, the easier for ice to remain and climb further.

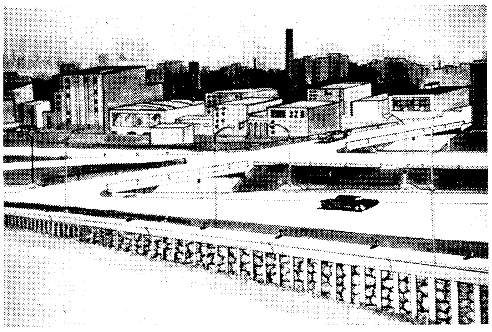
Model testing was carried out at a University of Norway facility similar to the St. Anthony Falls Laboratory. In spray tests with the ice present, a one-to-two rubble mound and a modified rubble mound produced almost equal amounts of spray for 13-foot waves. The vertical crib model produced little spray. Spray production also decreased with decreasing water depth. Model tests agreed with field observations that icing rarely occurs on vertical cribs but is a regular hazard of sloping walls. Several tests showed that icing increased up-rush and spray. Both the build-up of hydrostatic pressure and ice impact against armor stone tend to damage the rubble mound section of a breakwater.

The appearance of the structure is another consideration. The clean lines of a vertical crib structure are compatible with the engineered ribbon of the freeway. A low wall tends to collect trash on its slope and needs frequent maintenance.

The opportunity also exists at Duluth to create a walkway or promenade along the crib wall, adding a recreational dimension.

Maintenance can become a major factor in the cost of a seawall if it is incorrectly suited to its location. A rubble mound wall is especially difficult and costly to repair in deep water. Hydraulic tests showed that toe stones would be moved lakeward by scour. Much machinery and skilled labor would be necessary to replace stones washed from the face of the sloping wall. These efforts would necessarily follow the major storm season. The most frequent failure of the vertical cribs in this situation was loss of fill material from inside the crib. The top of the crib, however, would provide a rough roadway, giving a dump truck and crew easy access to failure points. Maintenance would be infrequent and relatively trouble-free.

At the completion of all studies, the permeable rock-filled vertical crib appeared to be the structure best suited to shore protection in the "Duluth pocket." The crib model withstood tests of the most severe storms indicated by Dr. Bruun's hindcasting studies. It performed well in deep and shallow water maintaining its stability and bottom equilibrium throughout the tests. The curved wave screen performed more effectively when mounted on the crib than on any other model. There will be little ice effect on this type of vertical wall. Its construction costs compare favorably with other breakwater models, it produces a strong and clean structure in character with the Duluth shoreline and it is effective as a seawall protecting a major link in the U. S. Interstate Highway System.



The frontiers of development are now pressing into environmentally sensitive Arctic locations. Responsible engineering efforts in these areas must recognize the delicacy of these severe regions with finely balanced environments.

We think the proposal for the protection of Interstate 35 recognizes this situation. If constructed as proposed, the road and seawall will have a minimum effect on the physical environment in Duluth and will re-establish the equilibrium of the lake bottom soon after completion.

We hope this analysis and recommendation of Howard, Needles, Tammen & Bergendoff and their associated consultants has been of interest and that our experiments in this unique situation may be of value in future applications under similar conditions.

References:

[1]This report has not, as of this writing, been formally accepted by the Federal Highway Administration, Department of Transportation.

[2]Location Report for Interstate Routes in Duluth, Howard, Needles, Tammen & Bergendoff for Minnesota Department of Highways, (1958).

[3]Shore Protection Study, Interstate Route 35 in Duluth, Howard, Needles, Tammen & Bergendoff, (1967).

[4]Shore Protection Model Study for Interstate Route 35 in Duluth, Institute of Technology, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, (October, 1967).

[5]Shore Protection Study: Supplement Report No. 1, Howard, Needles, Tammen & Bergendoff, (March, 1969).