FINAL PROJECT REPORT

HYDRAULIC MODEL STUDY ONTONAGON HARBOR WAVE MITIGATION STUDY

Report UMCEE 97-6

By
Elayne M. Crowe
and
Steven J. Wright

THE UNIVERSITY OF MICHIGAN
DEPARTMENT OF CIVIL AND
ENVIRONMENTAL ENGINEERING
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

A physical model of the Ontonagon Harbor was constructed and tested to determine the influence of various proposed wave mitigation structures on wave activity within the harbor. Four basic wave mitigation alternatives were tested. These were:

Alternative 1: Extend the East jetty by adding a wave attenuator on the offshore end.
Alternative 2: Wave attenuators on offshore ends of both East and West jetties along with a wave attenuator on the south end of the east jetty.
Alternative 3: East wave attenuator (Alternative 1) along with a wave attenuator on the south end of the east jetty.
Alternative 4: Steel sheet pile wing walls projecting perpendicular to both jetties near the offshore end of the entrance channel.

The alternatives were tested for four main wave directions, listed below along with US Army Corps of Engineers Wave Information Study statistics (Meadows, 2):

1.) Straight down the channel - 6 % occurrence
2.) 45 degrees to the northeast of the entrance channel axis - 8 % ocurrence
3.) 30 degrees to the northeast of the entrance channel axis - 8 % ocurrence
4.) 30 degrees to the northwest of the entrance channel axis - 28 % ocurrence

It was determined that none of the alternatives tested were particularly effective in attenuating wave energy when the waves entered straight down the channel axis. The major reason for this is that there is little interaction of the waves with the side walls with this wave direction. The only thing that could potentially reduce wave heights in this condition is if the side walls were sufficiently permeable to allow water to flow through them.

For waves arriving from the northeast directions, all alternatives tested were somewhat effective in reducing wave heights. Alternative 1, which was to extend the East jetty to align it with the West jetty was the most effective alternative and generally reduced wave heights by approximately 50 percent compared to the No Alternative response.

For waves arriving from the northwest, which is the most prevalent wave direction, it was expected that extending the East jetty would intercept more incident wave energy and therefore increase wave activity within the harbor. However, testing in which the east jetty was extended with a wave attenuator so that it was aligned with the west jetty indicated no increases in wave heights within the harbor compared to the No Alternative situation. A further offshore extension of the east jetty would result in the interception of more incident wave energy and it is not recommended since waves arrive from the northwest with a much greater frequency than other directions.

In summary, the recommended alternative is to extend the east jetty lakeward until its offshore end is aligned with the west jetty. Furthermore, the construction of the extension with an armor stone cross section (as opposed to steel sheet piling) will serve to dissipate some of the incident wave energy and attenuate waves within the harbor. The addition of a 255 foot long wave attenuator towards the back end of the entrance channel should have some positive effect on wave conditions in the back of the harbor, but the model test results indicated that the effect of this modification was minor.

1.0 INTRODUCTION

The purpose of this report is to summarize the results of a model study completed by the University of Michigan on the Ontonagon Harbor. Following harbor modifications in 1995, several sites in the interior of the harbor apparently experienced increased wave action. The objective of the project was to evaluate potential harbor modifications intended to reduce wave energy within the breakwalls at the Ontonagon Harbor.

2.0 BACKGROUND

The Ontonagon Harbor is located on the southern shore of Lake Superior, approximately 170 miles east of Duluth (Figure 1). The shoreline is oriented northeast-southwest, exposing the site to waves generated over approximately the western two-thirds of the Lake Superior Basin. The harbor is composed of two jetties flanking the outlet of the Ontonagon River, approximately 1400 feet in overall length from the shoreline. The jetties extend onshore of the existing shoreline, each with an overall length of approximately 2500 feet. The jetties are constructed such that the west jetty extends approximately 200 feet further lakeward than the east jetty. The channel is approximately 245 feet wide. Figure 2 shows the layout of the harbor. The harbor was upgraded in 1995 to steel sheet pile (SSP) structures from a dilapidated wooden crib structure.

3.0 EVALUATED ALTERNATIVES

Four main alternatives were evaluated as part of this project:

- **Alternative 1:** East wave attenuator in conjunction with SSP used to rehabilitate the 255 feet of old structure on the south end of the east revetment.
- **Alternative 2:** East and west wave attenuators in conjunction with a wave attenuator used to rehabilitate the 255 feet of old structure on the south end of the east revetment.
- **Alternative 3:** East wave attenuator in conjunction with a wave attenuator used to rehabilitate the 255 feet of old structure on the south end of the east revetment.
- **Alternative 4:** SSP wing walls projecting perpendicular to both jetties near the offshore end of the entrance channel. The location and length of these were as detailed in a drawing provided to define this alternative. Specifically, there were six, 25 foot long wing walls spaced at 100 ft intervals along the west jetty and five, 35 ft long wing walls at the same spacing along the east jetty. The height of these wing walls was two-thirds of the total water depth or fourteen feet.

A series of CAD drawings were provided by the Corps of Engineers from which the basic details of each of these alternatives were obtained. Alternatives 1 and 3 were both tested with two different lengths of approximately 200 feet and 275 feet for the east wave attenuator. The 200 feet corresponds to a condition in which the ends of the east and west jetties are approximately aligned while the 275 foot extension would leave the east jetty further lakeward than the west jetty.

4.0 ANALYSIS PROCEDURE

4.1 Physical Model

A physical model of the harbor was constructed in the University of Michigan Civil and Environmental Engineering Hydraulics laboratory. The physical layout of the harbor was determined from drawings and physical descriptions provided by the U.S. Army Corps of Engineers. The model, including the jetties and the inner portion of the harbor to the M-64 highway bridge, was constructed on a linear scale of 1 to 90 (model to prototype). The selection of model scale ratio was based primarily on the available space and the area required for construction of the model. The model had a water depth of approximately three inches which corresponded to depths within the navigation channel indicated in a harbor survey by the Detroit District, U.S. Army Corps of Engineers dated 5-6 June, 1995. Off the main navigation channel, this survey indicates reduced depths and these were also reproduced in the model. The exact details of the shoreline in the back of the harbor were not available from the harbor survey and were assessed by a review of a videotape taken of the harbor area. On the basis of the videotape, the shoreline was reproduced in the model by placing sand along the model shoreline. The only exception to this is along the west side of the harbor just north of the M-64 bridge where a concrete seawall was apparent and was reproduced in the model as a vertical wall. This shoreline configuration serves to dissipate most of the incident wave energy and this is reflected in the low wave heights measured in the model in that portion of the harbor. After completion of the model tests, it was learned that at least some of the back of the harbor has been constructed that at least some of the back portion of the harbor was composed of the timber crib structure similar to the former entrance channel configuration. Reproducing this condition would have resulted in larger wave heights in the back portion of the harbor and would also have increased the effectiveness of the proposed 255 foot long wave attenuator along the east jetty.

The proposed alternatives for the harbor include the use of rubble-mound sections. Past experience and experimental research have shown that considerable wave energy passes through the interstices of this type of structure and is dissipated internally within the rock structure. In small-scale models, rubble-mound structures reflect relatively more and absorb or dissipate less wave energy than geometrically similar prototypes. Consequently, some adjustment in small-scale model rubble-mound structures is needed to ensure satisfactory reproduction of wave transmission characteristics. Previous findings (1) for breakwater studies has shown that a close approximation of the correct wave energy transmission characteristics can be obtained by increasing the size of the rock used in the 1:90 scale model to approximately two times that required for geometric similarity. Accordingly, the rock sizes for the various alternatives for the harbor were computed linearly by scale, then multiplied by two to arrive at the actual size used in the model.

4.2 Wave Periods

Wave information for the harbor was provided in the Draft Harbor Reflection Study for Ontonagon, Michigan (2). Based on the report (Tables II and III), the wave periods for the harbor range from approximately 3 to 8 seconds, with average periods between 3.7 and 4.8 seconds. Initially various wave periods in these ranges were evaluated in the harbor to determine the period to use for the analysis of the alternatives. The waves were generated in the model using a plunger type wave machine that could be adjusted to various frequencies. With the wave generator in a fixed location, wave periods were more or less continuously varied over the range of 3 to 8 seconds. Variations in the period did not appear to have a significant effect on the relative wave heights in the harbor. However, it was determined that the incident wave angle did have a significant effect of wave behavior. Based on this analysis, it was determined that testing would be completed for various incident wave angles at one wave period. As an average representation, a prototype period of 4.5 seconds was selected for the detailed analysis. This corresponds to a model period of 0.47 seconds (scaled 1 to 9.49 [$90^{0.5}$]).

4.3 Incident Wave Angle

In evaluating the alternatives, incident waves were measured from different angles with respect to the axis of the jetties. The wave orthogonal directions used in the testing included:

- Parallel to the axis of the harbor jetties (0 degrees)
- At angles of 30 and 45 degrees to the northeast of the harbor axis
- At an angle of 30 degrees to the northwest of the harbor axis

During a preliminary investigation, the incident wave angle was varied more continuously over the range discussed above to ensure that there were not any particular directions that resulted in above average wave activity within the harbor. Generally, it was observed that wave activity towards the back of the harbor declined as the wave direction deviated from parallel to the harbor jetties. However, near the harbor entrance, the wave heights along walls may be increased due to the wave reflections at higher angles of incidence. Although these effects appeared to vary more or less continuously with wave direction, the wave height at a specific location within the entrance channel could be altered significantly due to the nature of the reflection process. The wave directions discussed above were selected to be consistent with the proposal in the original scope of work. The one exception is that waves incident at 45 degrees to the northwest of the channel axis were not studied because these exhibited lower wave heights. The positions that wave heights were recorded were generally selected according to the desire to measure the maximum wave height within a general area of the harbor.

4.4 Wave Heights

Seven sites in the harbor were selected for observation during the study. These points include one location (Point 1) used to measure the incident wave, three locations along the channel (Points 2, 3, and 4), and three locations of concern in the interior portion of the harbor (Points 5, 6, and 7). Point 5 represents the location in the model where the greatest wave activity and largest waves were observed (in the model) for the interior of the harbor. It was also subject to the greatest variability and results for that location show considerably more scatter than at all other measurement locations. Points 6 and 7 were identified as interior harbor areas of concern by the U.S. Army Corps of Engineers. Figure 2 shows the approximate locations of the selected test sites. Point gauges were installed at these locations for measurement of the wave heights.

An incident wave height (measured at Point 1) equivalent to approximately 5 feet in the prototype was used for testing the model. Wave activity in the harbor is reported by normalizing the interior wave amplitudes to incident wave height so that the results presented can be generalized beyond this specific incident wave height. A ratio allows for direct computation of the wave height in the harbor at a given incident wave height that varies generally with wave period as discussed in Meadows (2).

5.0 ERROR ANALYSIS

The model results are subject to some uncertainty. The following is a list of potential error for the project:

- The wave height measurements have a overall uncertainty of about 5-10 percent for higher wave heights. This uncertainty is a combination of the measurement precision as well as variations in actual wave heights in the model. Expressed as a percentage, the measurement uncertainty increases with lower measured wave heights. Repetitive measurements were made to reduce the magnitude of this uncertainty.
- Slight variations in water depth over the course of the project can have an effect on the results, but this is more of a problem in investigations in harbors with significant resonant interactions.
- Due to wave interactions with the boundaries of the wave tank, there are long period beats in the wave height that require persistent observation to ensure that a consistent method of defining the measured wave height is maintained.
- In some cases, the waves produced by the wave generator may not have been fully developed at Point 1 (the measured incident wave).

The overall measurement uncertainty was greater with larger wave heights, but in terms of a percentage of the wave height, the uncertainty reduces with wave height. An estimated measurement uncertainty is included in the presentation of results in Figures 3-9. Each of the larger wave heights indicated has an estimated 95 percent confidence interval (under the assumption of random measurement error) indicated; this estimate was obtained from a series of replicate measurements (combing the results from all locations in order to obtain a larger statistical sample) from which the standard deviation of the measured wave heights was computed. It should also be recognized that only the positive uncertainty is indicated in the figures and that a negative measurement uncertainty of the same magnitude is also present. Since the uncertainty estimates were based on the cumulated measurements for all points, the error bars for Point 5 probably do not represent the true measurement uncertainty at that location. For the lowest wave heights, the error bar indicates the estimated magnitude of the measurement precision (0.001 ft) which is based on an interpretation of the apparatus used to measure the wave heights. This may under-estimate the actual measurement uncertainty, but it should be of that order.

6.0 TESTING AND RESULTS

Each of the alternatives was evaluated to determine its effectiveness in reducing wave energy within the harbor. The harbor was initially tested with the existing harbor configuration to serve as a base for comparison.

6.1 Evaluation of Existing Harbor Configuration

The existing harbor configuration was tested with a wave period of 4.5 seconds at incident wave angles of 0 degrees, 30 and 45 degrees to the northeast, and 30 degrees to the northwest. The goal of this testing was to establish a base to use as a comparison with results from testing the alternatives.

In addition, this analysis provided information on the general trend of the waves in the harbor. For all incident waves, the general trend appeared to be very similar. The location of the greatest wave activity (as measured by amplitude) was in the channel of the harbor (Points 2, 3, and 4). The wave activity decreased along the channel and the smaller wave activity was measured at the interior of the harbor (Points 5, 6, and 7).

The wave activity generally appeared to be the worst with an incident angle of 0 degrees. As the incident angle increased, the wave heights at each point decreased relative to the wave heights measured for the incident angle of 0 degrees. This was noted as a general trend, however, there are cases where measured wave heights did not follow this pattern. This was most likely associated with the complex interaction of wave reflections with the jetty walls. For example, if waves were incident upon the model from the northeast, a region of high wave activity would be found along the interior of the west jetty where the waves were directly incident. These waves would reflect onto the east jetty further down the entrance channel and these in turn were reflected back to the west jetty even further into the harbor. The exact locations where these local regions of high reflected waves vary with the direction of the incident waves and somewhat confound the interpretation of the experimental results.

Figure 3 presents a comparison of the wave heights measured at locations 2 through 7 for each of the incident wave angles. The wave heights have been normalized with a common incident wave height (using the wave height at Point 1 with an incident angle of 0 degrees).

6.2 Evaluation of Alternatives

Each of the alternatives listed in Section 3.0 was tested with a wave period of 4.5 seconds and varying incident wave angles. Following an initial evaluation of the model, it was determined that an incident wave angle of 0 degrees results in the highest wave heights regardless of the alternative. Therefore, the complete range of incident angles was not used for every alternative. For Alternative 3, testing was completed for wave angles of 0 degrees, 30 and 45 degrees to the northeast, and 30 degrees to the northwest. It was determined to be sufficient to take measurements for the remaining alternatives at incident wave angles of 0 degrees and 45 degrees to the northeast. Data were collected at the same seven locations as tested for the existing harbor configuration.

The measured wave heights taken for alternatives are presented in Table 1. Again, the wave heights have been normalized with a common incident wave height (using Point 1 measured for the existing harbor configurations with an incident angle of 0 degrees).

The results show the same general trend in wave heights for the alternatives. As before, the location of the greatest wave activity (as measured by amplitude) is in the channel (Points 2, 3, and 4). The wave heights reduce proceeding down the channel, and are smallest at the interior points (Point 5, 6, and 7). This is the same general trend that appeared in the testing of the harbor with the existing configurations (no alternatives).

As previously indicated, the worst wave conditions occur with an incident wave angle of 0 degrees. At this orientation, the wave heights in the interior of the harbor (Points 5, 6, and 7) are two to three times as great as the wave heights measured at the remaining incident wave angles.

In general, the alternatives tend to aid in the reduction of wave heights at points in the harbor (compared to the wave heights measured with no alternative). However, there is not a significant reduction in wave energy for the worst wave condition. The main reason for this is that the worst wave condition (regardless of alternative) occurs when the waves enter parallel to the jetties (at 0 degrees). At this orientation, the waves proceed directly down the channel and into the interior of the harbor with the least amount of interactions with structures along the walls of the channel. None of the alternatives provide significant relief for this situation. Even Alternative 4, which involves wing walls which project into the channel do not appear to significantly alter the wave climate further into the harbor. Figure 4 shows the reduction in wave height for each of the alternatives for the incident wave angle of 0 degrees. As seen in the figure, there was little variation in the wave heights in the channel (Points 2, 3, and 4) for any of the alternatives (the results for the Alternative 1-S wave height at Point 2 is anomalous with all the other data and should not be interpreted to be a real effect). Although the model indicated little influence on wave attenuation when the wave direction is aligned with the channel axis, it should be remembered that waves will only infrequently arrive from this direction. Wave statistics for Ontonagon (see Table II, Meadows (2)) indicate waves are aligned to within ten degrees of the channel axis only about five percent of the time.

As the incident angle increases, the general trend for all alternatives is a reduction in wave height in the onshore section of the channel (Point 4) and the interior portion of the harbor (Points 5, 6, and 7). With the increase in incident wave angle, more reflections and wave activity occur in the offshore portion of the channel. This results in dissipation of wave energy and reduced wave heights in the interior of the harbor. Figure 5 shows the reduction in wave heights for the alternatives for an incident wave angle of 45 degrees to the northeast. This figure shows the reduction in wave heights at Points 3 and 4 for this incident angle compared to an incident angle of 0 degrees. For this orientation, the alternatives further reduce the wave height at Points 2, 3, and 4. Reductions in the wave height also occurred for some of the alternatives at Point 5, and for all of the alternatives at Point 7. Point 6 wave heights were apparently not reduced by any of the alternatives, at least to within the measurement uncertainty.

Alternative 1 and Alternative 3 are very similar. The difference in the alternatives is the use of different material for the rehabilitation of the 255 feet of old structure on the south end of the east revetment. Both of the alternatives were evaluated with two different lengths for the east attenuator (approximately 200 feet and 275 feet). Figures 8 and 9 show the comparison of the measured wave heights for incident angles of 0 degrees and 45 degrees to the northeast of the harbor opening, respectively. A comparison of these alternatives suggests a slight advantage to the longer attenuator. The longer attenuator results in reductions of wave heights at the measured points in the harbor. However, for the worst wave condition at an incident angle of 0 degrees, the reduction is small. The main reason is that the attenuator does not provide significant reduction of wave energy at this incident angle. In addition the longer wave attenuator results in a condition where the east jetty extends beyond the west jetty and this would deflect more wave energy into the harbor whenever waves are from the west or northwest. Since these wave conditions are more prevalent according to Meadows (2), this would not be a desirable condition.

The difference in the material for rehabilitation of the 255 feet of old structure on the south end of the revetment did not have a significant effect on the wave energy in the channel. Figure 4 indicates an improvement in wave conditions at locations within the harbor beyond the wave attenuator, but this is not indicated for the waves incident at 45 degrees which are indicated in Figure 5. The exact reason for the differences between Alternatives 1 and 3 in Figure 5 are not clear but intuitively, the addition of the wave attenuator (Alternative 3) must result in some improvement in wave conditions further back in the harbor due to its dissipation of wave energy but apparently the effect is relatively small as there is little difference in the Alternative 1 and 3 results.

7.0 CONCLUSIONS

The results of the model testing indicates the following general conclusions from the above discussion of results:

• With the existing harbor, the worst conditions for wave activity are associated with a situation where the incident wave orthogonals as aligned parallel to the axis of the channel entrance. Under this condition, waves propagate to the back of the harbor without significant reflection and wave conditions in the back of the harbor are worse compared to other incident wave directions. However, this condition only occurs infrequently, less than five percent of the time according to published waves statistics.

• Near the offshore end of the entrance channel, waves that are incident at some angle to the channel axis reflect off the SSP walls and may result in locally increased wave heights compared to the parallel incident wave condition. However, the result of this reflection process is to progressively reduce the wave height towards the back of the harbor and wave heights are generally reduced significantly compared to the parallel incident wave condition.

• None of the alternatives tested showed a significant effect in reducing wave heights within the harbor for waves aligned with the axis of the entrance channel. With the exception of one location (Point 5), the differences between the various alternatives appear to be within measurement uncertainty. One would generally expect all of the alternatives tested to have some positive influence in reducing wave heights, but the effect is apparently small since materials along the walls of the entrance channels do not significantly interact with waves propagating in this direction.

• All of the alternatives tested showed some promise in reducing wave activity in the event that incident waves were not aligned with the axis of the entrance channel. In particular, the extension of the east jetty was effective in reducing wave amplitudes for waves arriving from the northeast. The main reason for this effect appears to be a reduction in effective width of the channel entrance (projected width perpendicular to the incident wave) as the east jetty is extended lakeward to match up with the west jetty. Examination of the effect of increasing the extension of the east jetty from 200 feet to 275 feet indicates that some additional improvement is achieved. Extending the east jetty by 275 ft would however, place it further lakeward than the west jetty and therefore deflect more wave energy arriving from the west and northwest into the harbor, generally increasing wave heights within the harbor. Since this range of wave directions has the highest frequency of occurrence according to Meadows (2), this situation should be avoided. The 1-S and 3-S alternatives result in an extension of the east jetty to approximately align with the west jetty and would avoid some of this interception of additional wave energy. According to Figure 7, this configuration results in no perceptible change in wave conditions within the harbor for waves arriving from the west northwest. Finally, rehabilitating the 255 ft towards the south end of the east jetty with an armor stone wave attenuator does not appear to have a significant effect on wave attenuation, but intuition indicates that this alternative must provide some wave reduction in the back of the harbor.

- Given the above conclusions, it appears that the most reasonable alternative would be to extend the east jetty until its offshore end is aligned with the west jetty. The proposed construction of armor stone would be preferable to steel sheet piling due to the ability of armor stone to dissipate more wave energy. This alternative will not have a significant impact on wave conditions when the incident waves are aligned with the axis of the channel entrance, for which the worst wave conditions in the back of the harbor may be expected to occur. However, it will result in lower wave conditions for waves incident from the northeast and perhaps only a slight and probably negligible increase in wave activity for waves from the northwest.

8.0 REFERENCES

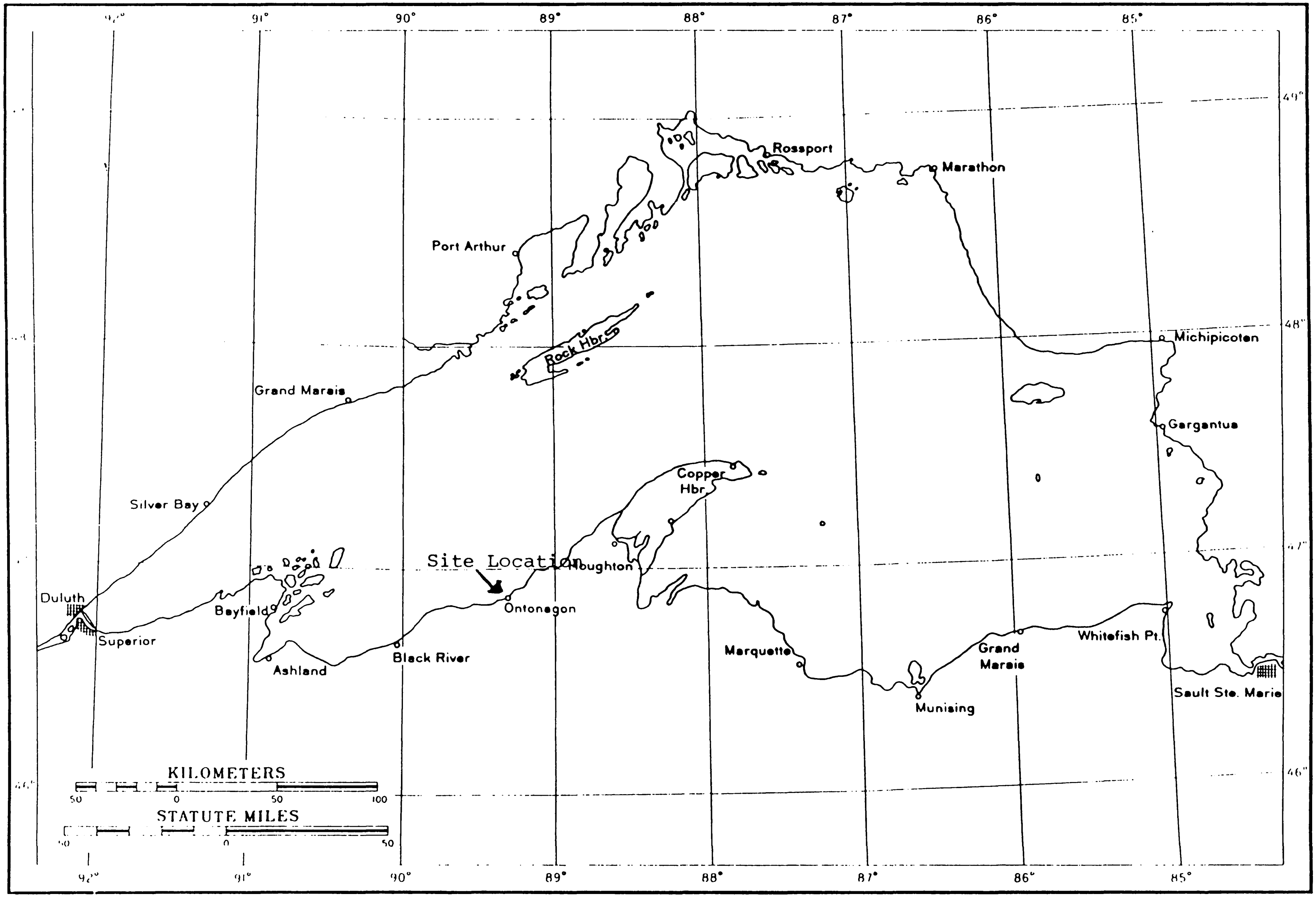
1. "Prevention of Shoaling at Port Orford, Oregon," C.E. Chatham, Journal of the Hydraulics Division, ASCE, Vol. 107, HY11, 1981, pp. 1303-1316.

2. "Harbor Reflection Study for Ontonagon Michigan," L. Meadows, Report to US Army Engineers Detroit District, Riverine and Coastal Section, 6 June 1996.

Table 1. Measured Wave Heights

		Orientation					
		0 Degrees		30 Degrees NE	45 Degree NE	30 Degrees NW	
Location 2	No Alternative	0.852		1.321	0.950	0.934	
	Alternative 1-S	0.478			0.516		
	Alternative 1-L	0.409			0.358		
	Alternative 2	0.723			0.748		
	Alternative 3-S	0.816		0.742	0.717	1.006	
	Alternative 3-L	0.887			0.472		
	Alternative 4	0.836			0.472		
Location 3	No Alternative	0.748		0.717	0.503	0.519	
	Alternative 1-S	0.591			0.289		
	Alternative 1-L	0.535			0.038		
	Alternative 2	0.566			0.365		
	Alternative 3-S	0.618		0.401	0.358	0.500	
	Alternative 3-L	0.731			0.308		
	Alternative 4	0.604			0.264		
Location 4	No Alternative	0.481		0.726	0.245	0.311	
	Alternative 1-S	0.439			0.069		
	Alternative 1-L	0.358			0.019		
	Alternative 2	0.478	(1)		0.085		
	Alternative 3-S	0.566	(1)	0.201	0.075	0.406	(1)
	Alternative 3-L	0.358			0.132		
	Alternative 4	0.538			0.104		
Location 5	No Alternative	0.562		0.236	0.195	0.264	
	Alternative 1-S	0.387			0.019		
	Alternative 1-L	0.368			0.000		
	Alternative 2	0.189			0.189		
	Alternative 3-S	0.151		0.156	0.057	0.321	
	Alternative 3-L	0.396			0.057		
	Alternative 4	0.406			0.123		
Location 6	No Alternative	0.143		0.082	0.104	0.179	
	Alternative 1-S	0.217			0.088		
	Alternative 1-L	0.208			0.009		
	Alternative 2	0.220			0.179		
	Alternative 3-S	0.236		0.094	0.160	0.160	
	Alternative 3-L	0.340			0.132		
	Alternative 4	0.274			0.160		
Location 7	No Alternative	0.124		0.142	0.160	0.104	
	Alternative 1-S	0.085			0.000		
	Alternative 1-L	0.075			0.000		
	Alternative 2	0.104			0.057		
	Alternative 3-S	0.094		0.038	0.057	0.104	
	Alternative 3-L	0.132			0.038		
	Alternative 4	0.019			0.038		

(1) Due to wave attenuator on south end of east jetty, wave height varied across the channel at this location. Presented the highest measured value in summary table/graphs.



Rossport
Marathon
Port Arthur
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Grand Marais
Gargantua
Copper Hbr.
Silver Bay
Site Location
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Superior
Whitefish Pt.
Ashland
Black River
Marquette
Grand Marais
Sault Ste. Marie
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50 0 50
92° 91° 90° 89° 88° 87° 86° 85°
49° 48° 47° 46°

Figure 1

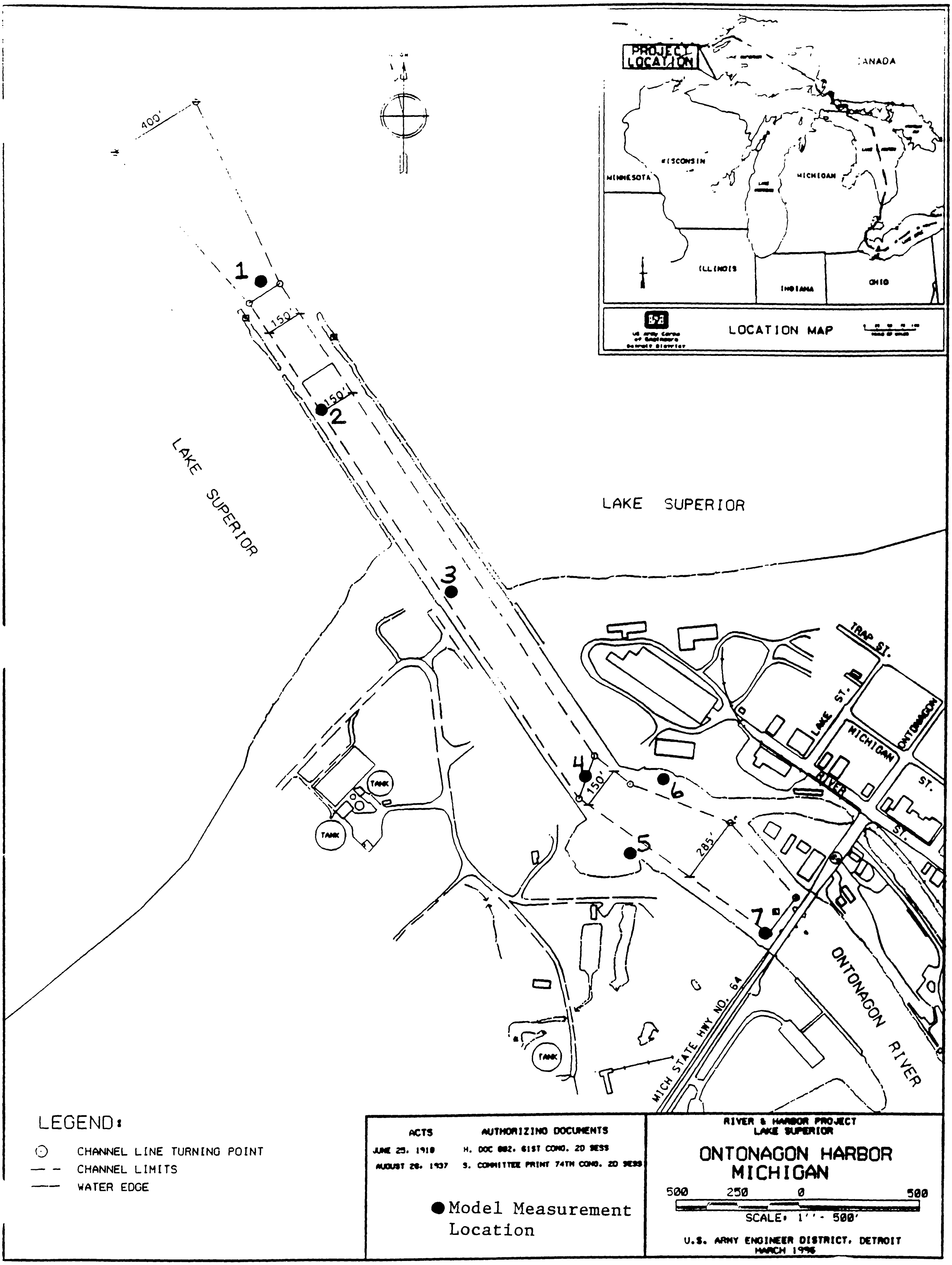

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Figure 2

Figure 3
Comparison of Wave Heights Measured at Points 2 through 7 for Existing Harbor Configuration for All Incident Wave Angles

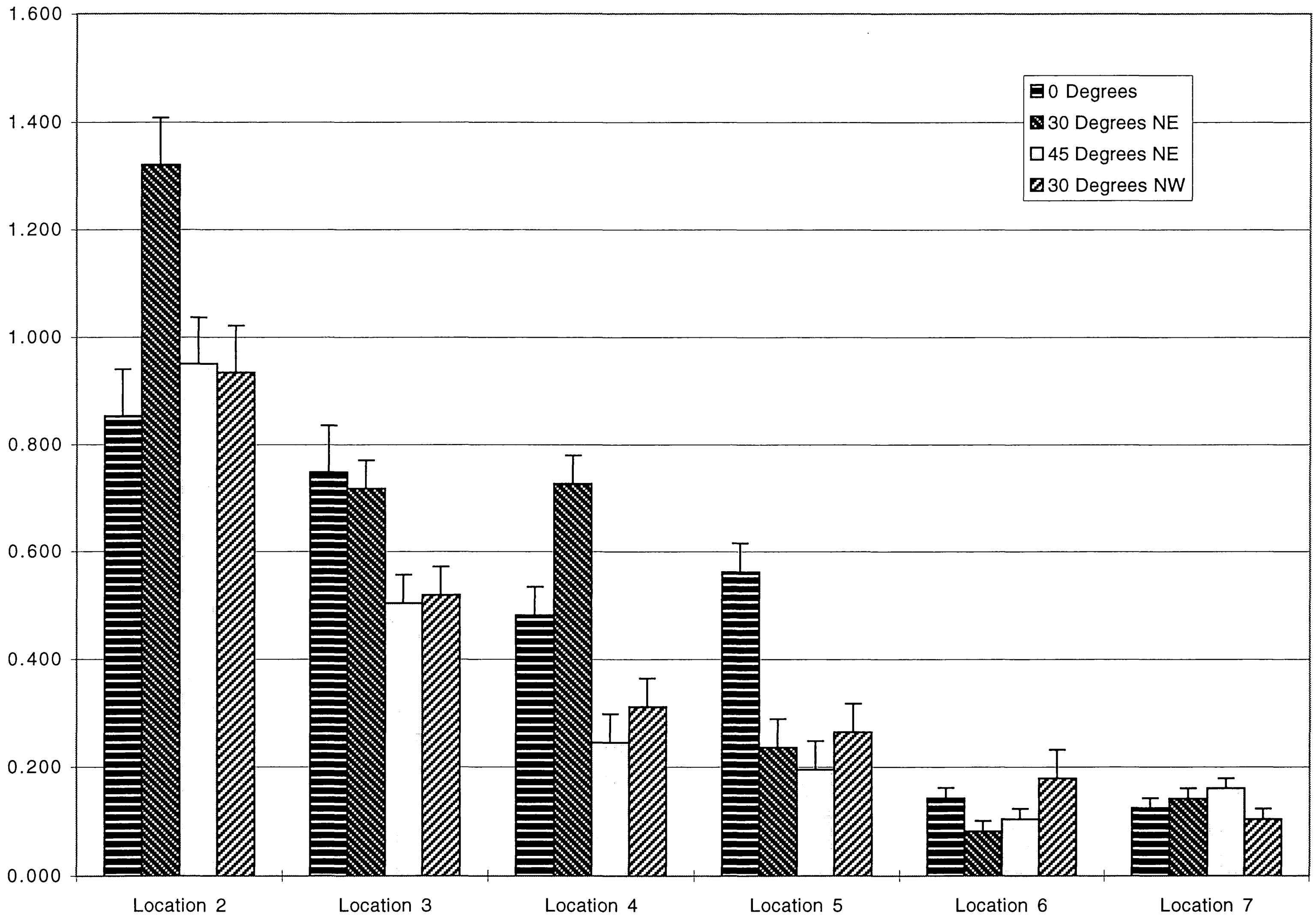


Figure 4
Comparison of Normalized Wave Heights at Points 2 through 7 for Alternatives 1 through 4 at an Incident Angle of 0 Degrees

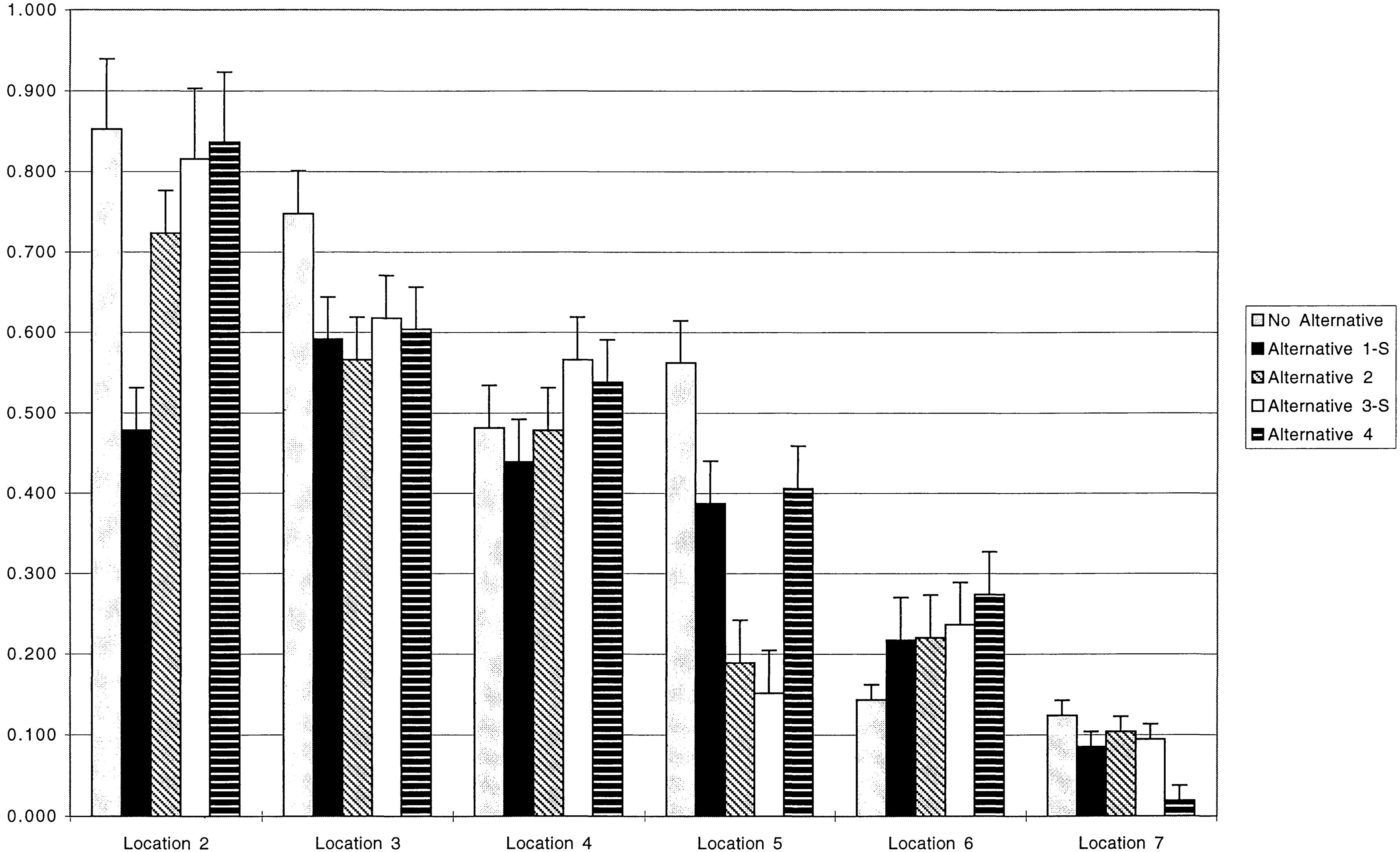


Figure 5
Comparison of Normalized Wave Heights at Points 2 through 7 for Alternatives 1 through 4 at an Incident Angle of 45 Degrees to the Northeast of Harbor Opening

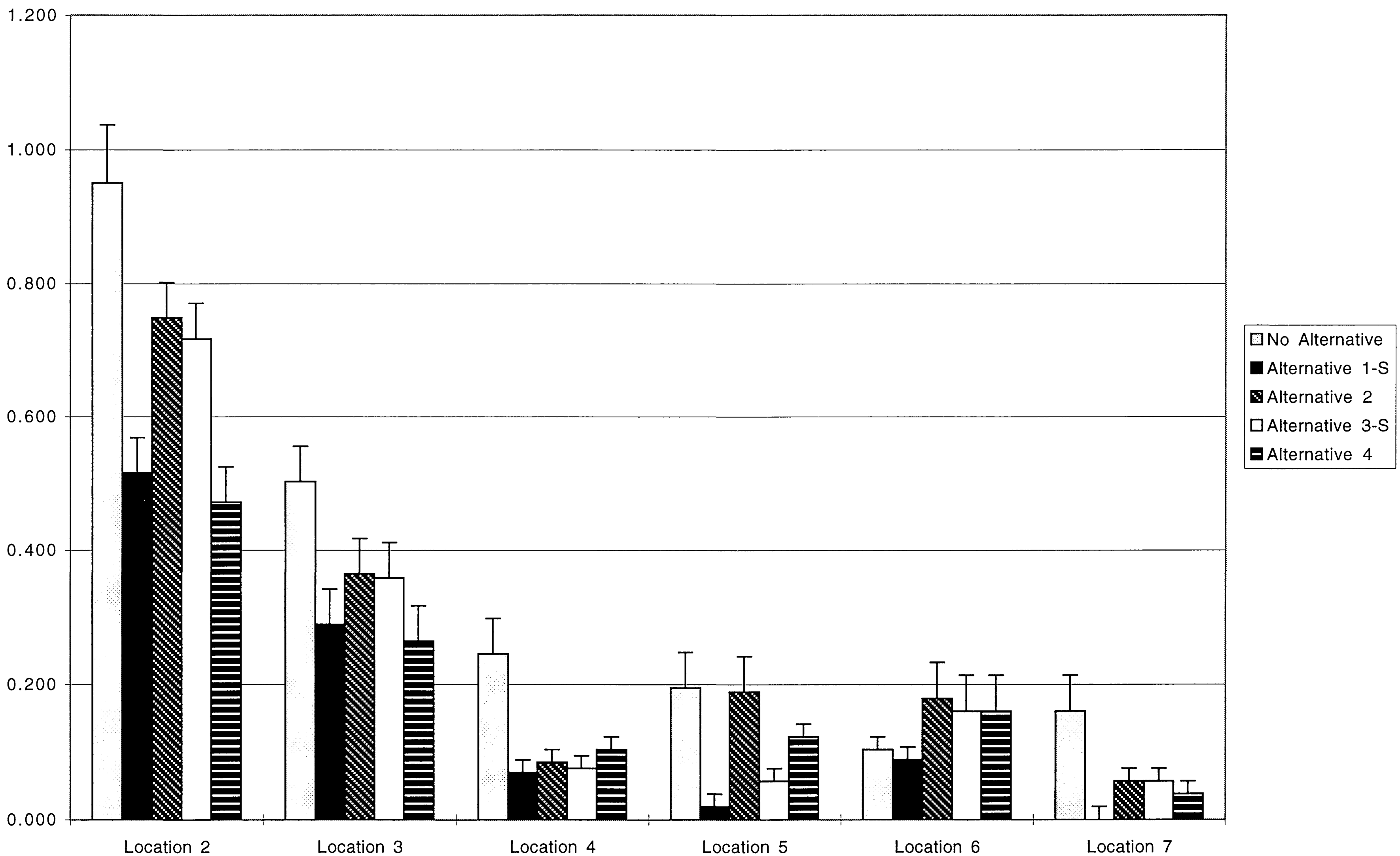


Figure 6
Comparison of Normalized Wave Heights at Points 2 through 7 for Alternative 3 at an Incident Angle of 30 Degrees to the Northeast of Harbor Opening

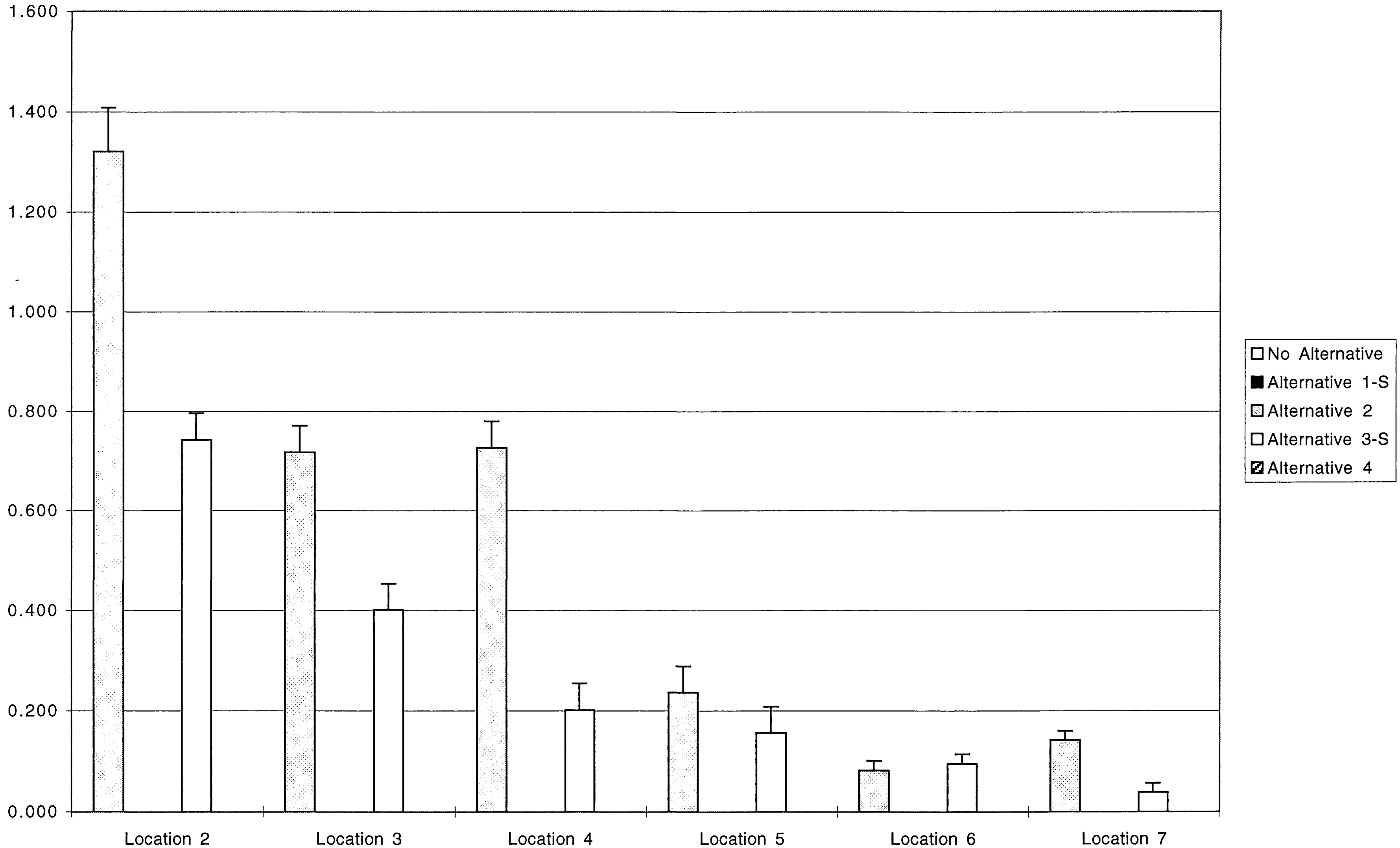


Figure 7
Comparison of Normalized Wave Heights at Points 2 through 7 for Alternative 33 at an Incident Angle of 30 Degrees to the Northwest of Harbor Opening

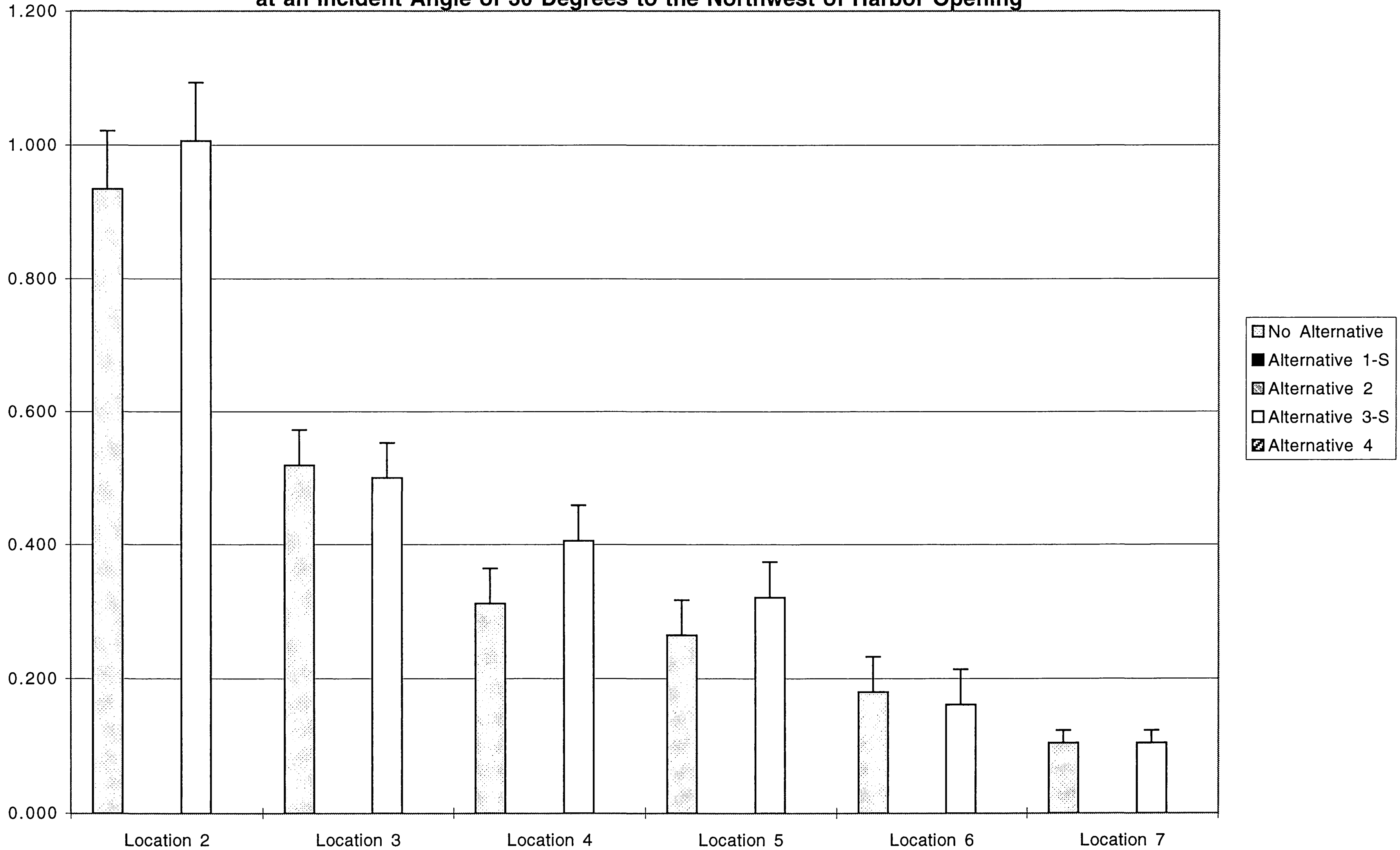


Figure 8
Comparison of Long and Short East Attenuator for Alternatives 1 and 3 at an Incident Angle of 0 Degrees

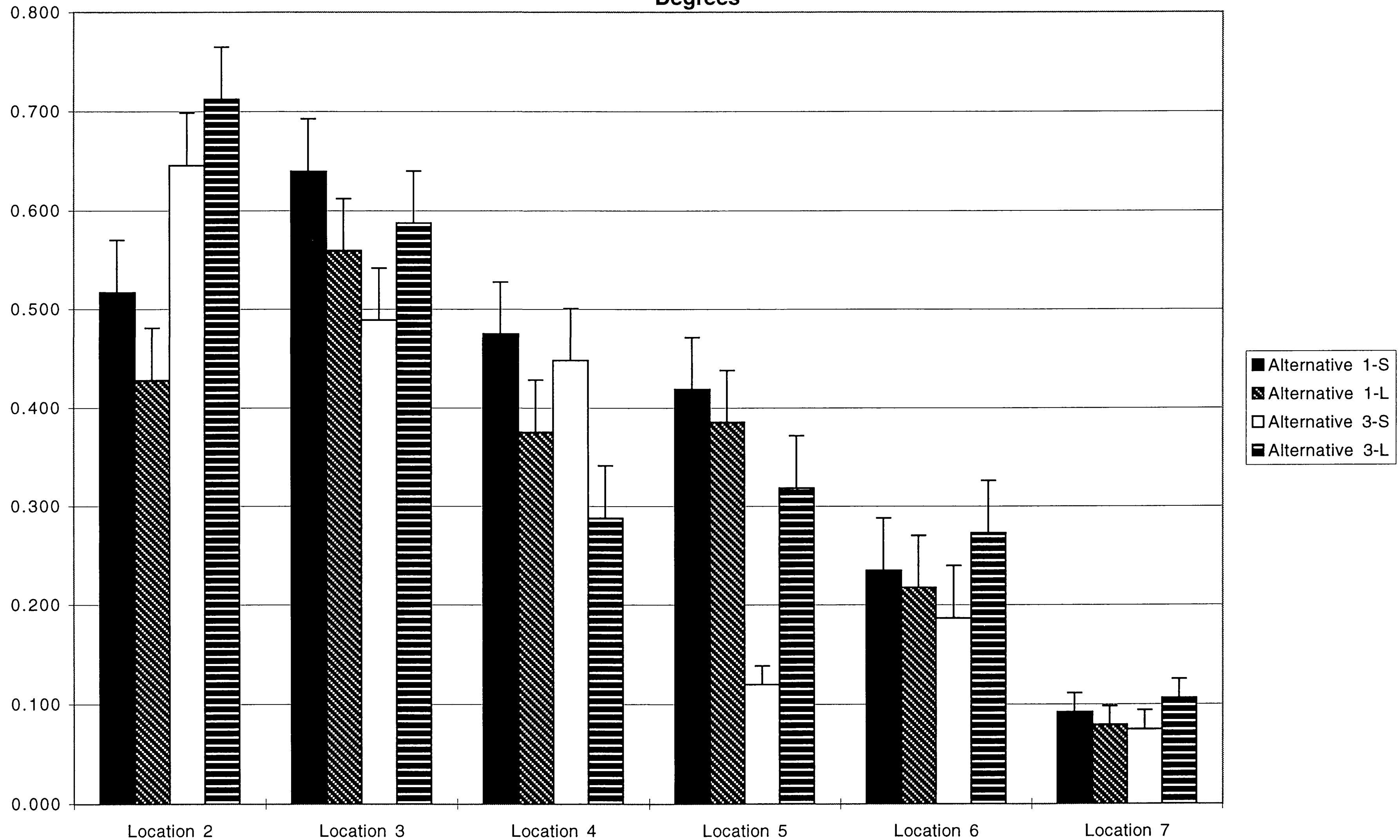
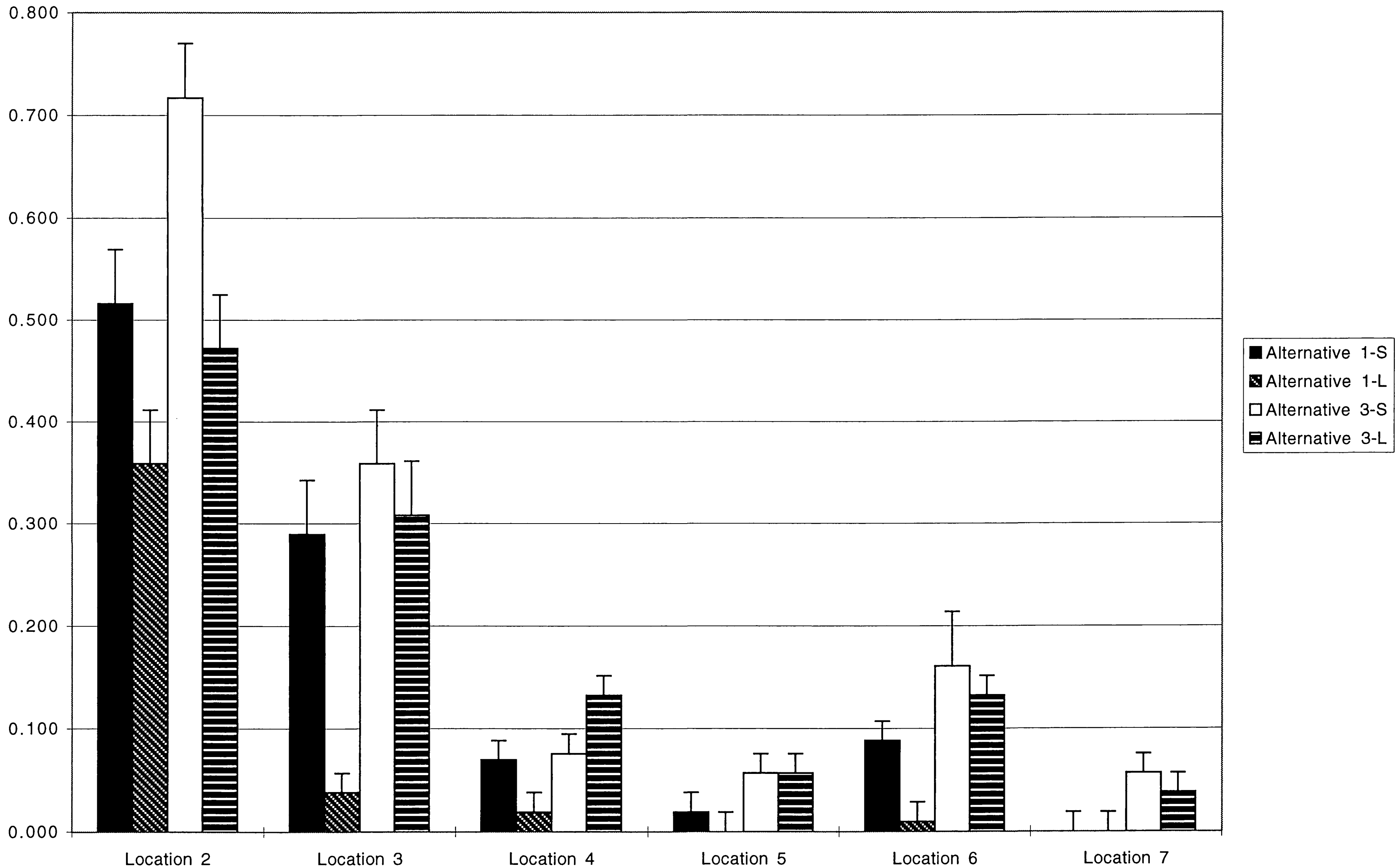


Figure 9
Comparison of Long and Short East Attenuator for Alternatives 1 and 3 at an Incident Angle of 45 Degrees to Northeast of Harbor Opening



Addendum to

FINAL PROJECT REPORT

HYDRAULIC MODEL STUDY ONTONAGON HARBOR WAVE MITIGATION STUDY

Report UMCEE 97-6

By

Steven J. Wright

THE UNIVERSITY OF MICHIGAN
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
ANN ARBOR, MICHIGAN

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For

U.S. Army Corps of Engineers
Detroit District

LIST OF FIGURES

This Addendum presents the results of additional testing of the Ontonagon Harbor model constructed at the University of Michigan. This supplemental testing was performed during June, 1997. The purpose of the additional testing was primarily to investigate issues that were raised during a discussion of the results of the initial study. The original model and testing methodology described in the original report was also used in this additional testing; the original report can be referred to for specific details. One major difference in the testing was that while the wave height measurements were made in the same general vicinities as in the original model testing, they were not made at coincident locations. Specifically, the original measurements determined the wave heights in the entrance channel near the center of the channel while the results presented herein were made along the western jetty at roughly the same locations along the channel. Wave heights in the back of the harbor were measured near the same general locations as in the original testing, but were not in precisely the same locations. Consequently, it will not be possible to directly compare results presented herein to those in the original report.

Various conclusions were drawn and recommendations were made in the original report. After reviewing the results of this more recent testing, the original recommendations for mitigation of wave activity within the harbor are still considered to be valid. The original recommended alternative consisted of a rubble mound extension of the east jetty to bring the end into alignment with the west jetty and to rehabilitate a 255 foot long section of the east jetty with an armor stone wave attenuator. The current investigation indicated little if any effect of the length (within the limits of variation considered in the orginal study) of the east attenuator on waves from the northwest. The main reason for this appears to be that the waves entering the harbor from this direction are diffracted around the offshore end of the west jetty and do not appear to significantly interact with the east jetty. The original model results also indicated that the 255 foot wave attenuator would have minimal effect on the waves in the back of the harbor. The current investigation examined this issue under conditions where the back of the model harbor was modified to provide less damping of the waves. Under these circumstances, the 255 foot wave attenuator is indicated to have more influence on wave heights, but even then, the effect is relatively minor. However, these more recent results indicate that the wave attenuator would be effective in damping wave motion under at least some conditions.

MODEL TESTING - CONDITIONS AND PROCEDURES

The original report can be referred to for a more detailed description of the model as well as the testing conditions and methodology. The same general approach was used in this supplemental testing. A prototype wave period of 4.5 seconds and an incident wave height of approximately 5 feet were reproduced at the model scale. However, all test results are presented scaled as a ratio of the observed wave height at a given measurement location to the incident wave height. The condition tested in the model consisted of a simulation of existing conditions as well as four alternatives proposed by the Corps of Engineers. These four wave mitigation alternatives were:

- **Alternative 1:** East wave attenuator in conjunction with SSP used to rehabilitate the 255 feet of old structure on the south end of the east revetment.
- **Alternative 2:** East and west wave attenuators in conjunction with a wave attenuator used to rehabilitate the 255 feet of old structure on the south end of the east revetment.
- **Alternative 3:** East wave attenuator in conjunction with a wave attenuator used to rehabilitate the 255 feet of old structure on the south end of the east revetment.
- **Alternative 4:** SSP wing walls projecting perpendicular to both jetties near the offshore end of the entrance channel. The location and length of these were as detailed in a drawing provided to define this alternative. Specifically, there were six, 25 foot long wing walls spaced at 100 ft intervals along the west jetty and five, 35 ft long wing walls at the same spacing along the east jetty. The height of these wing walls was two-thirds of the total water depth or fourteen feet.

Wave heights were measured at seven specific locations in all tests; Figure 2 from the original report is included to define these measurement locations. Location 1 was considered to be the incident wave and all other wave heights were normalized by the height of this wave. Wave heights at locations 2 through 4 were measured along the west jetty. When these were observed to be somewhat inconsistent with the results in the orginal study for duplicate conditions, the person performing the original experiments was contacted and it was subsequently learned that the orginal measurements were made near the center of the entrance channel in locations 2 through 4. However, this was well into the supplemental testing program and it was not felt to be feasible to recreate the original measurement locations in any case so the new measurement locations were used for all results reported in this Addendum. A check with wave heights measured near the center of the channel indicated them to be much more consistent with the original results than the ones reported herein. For this reason, the results in this Addendum cannot be compared directly to the original testing results.

Each wave measurement was repeated five times and the standard deviation of the five measurements was used to indicate the uncertainty in the measurement. Each graph presents a positive error bar equal to two standard deviations (approximating the 95th percentile confidence interval) in a manner consistent with the original presentation.

TESTING AND RESULTS

Initial testing did not concentrate heavily on waves from the northwest since earlier analyses had indicated that waves from the northeast may be more critical. One objective in the supplemental testing was to examine more closely waves arriving from the northwest since waves from the west and northwest occur with a higher incidence according to US Army Corps of Engineers wave statistics. In the supplemental testing, a comprehensive set of measurements was made for waves arriving inclined 30 degrees and 45 degrees counterclockwise from the axis of the entrance channel (alignment of 340° DTN). Figure 10 presents the results of normalized wave heights for the No Alternative (existing harbor configuration) for incident waves aligned with the channel axis as well as waves at 30 and 45 degrees to the northwest. These results were initially unexpected in that the existing harbor configuration has the west jetty extended nearly 200 feet lakeward of the east jetty and there is no effective harbor opening for waves arriving at 45 degrees to the northwest of the channel entrance. Observations in the model indicated that the source of wave energy within the harbor was due to diffraction around the west jetty such that the diffracted waves turned towards alignment with the entrance channel axis and generally resembled waves that were incident with a direct alignment to the channel axis. A visual inspection indicated that the overall wave activity within the model harbor was only a little less with the 45 degree NW waves compared to the perfectly aligned waves. The 30 degree NW wave patterns was more complicated due to a partial reflection off the east jetty. With the exception of measurement location 2, Figure 10 indicates that the normalized wave heights are fairly similar at all locations and there is no pattern in the results in which one direction has consistently higher waves at all locations. In general, the 45 degree NW waves are smaller at the back of the harbor (Locations 5 through 7) than the other two directions and this is consistent with the observations of overall wave activity.

The results of testing the various alternatives are presented in Figure 11 for waves from 30 degrees NW and in Figure 12 for waves from 45 degrees NW. Directly comparing the two figures, it generally appears that the wave activity from 45 degrees NW is reduced compared to 30 degrees NW (with the exception of Location 2) and this is consisent with the No Alternative observations. Also, there appears to be very little difference among the four alternatives in Figure 11, as the differences are generally within the estimated uncertainties. A similar conclusion is derived from Figure 12 although there is more variation in performance from one measurement location to another. Since the predominant mechanism for wave entry into the harbor is diffraction around the west jetty and the diffraction process tends to align the waves with the channel axis, these conditions are fairly similar to the case where the incident waves are aligned with the channel axis. Previously it was found that the various wave mitigation alternatives had little impact in attenuating incident waves for waves aligned with the harbor axis, and the same result is generally indicated in Figures 11 and 12. Therefore, it appears that any of the proposed wave mitigation alternatives would have only little effectiveness in reducing waves arriving from the northwest of the channel axis.

Additional testing was performed to examine the issue of the length of the east jetty since the original study recommended that the length be reduced to prevent capture of more wave energy from the northwest. Figures 13 and 14 present the results of this testing comparing the effect of the length of the east jetty for Alternatives 1 and 3. The S alternative involves the east jetty extended only to alignment with the existing west jetty while the L alternative was the length proposed in the orginal drawings supplied by the Corps of Engineers. Two things are apparent from an examination of Figures 13 and 14. First of all, there is little difference between Alternatives 1 and 3 and so the 255 foot wave attenuator towards the back of the east jetty again appears to have little effect in attenuating waves, as concluded in the original study. Secondly, the length of the east jetty appears to have only minor effect on the waves arriving from the northwest. The only place where there appears to be an obvious effect is at Location 2 for the 30 degree NW waves. In this configuration, the longer east jetty would result in more direct reflection of waves off the esat jetty and this is indicated by higher waves at Location 2. However, the differences are relatively minor further back in the harbor and therefore it appears that the length of the east jetty should not have a significant impact on waves from the northwest.

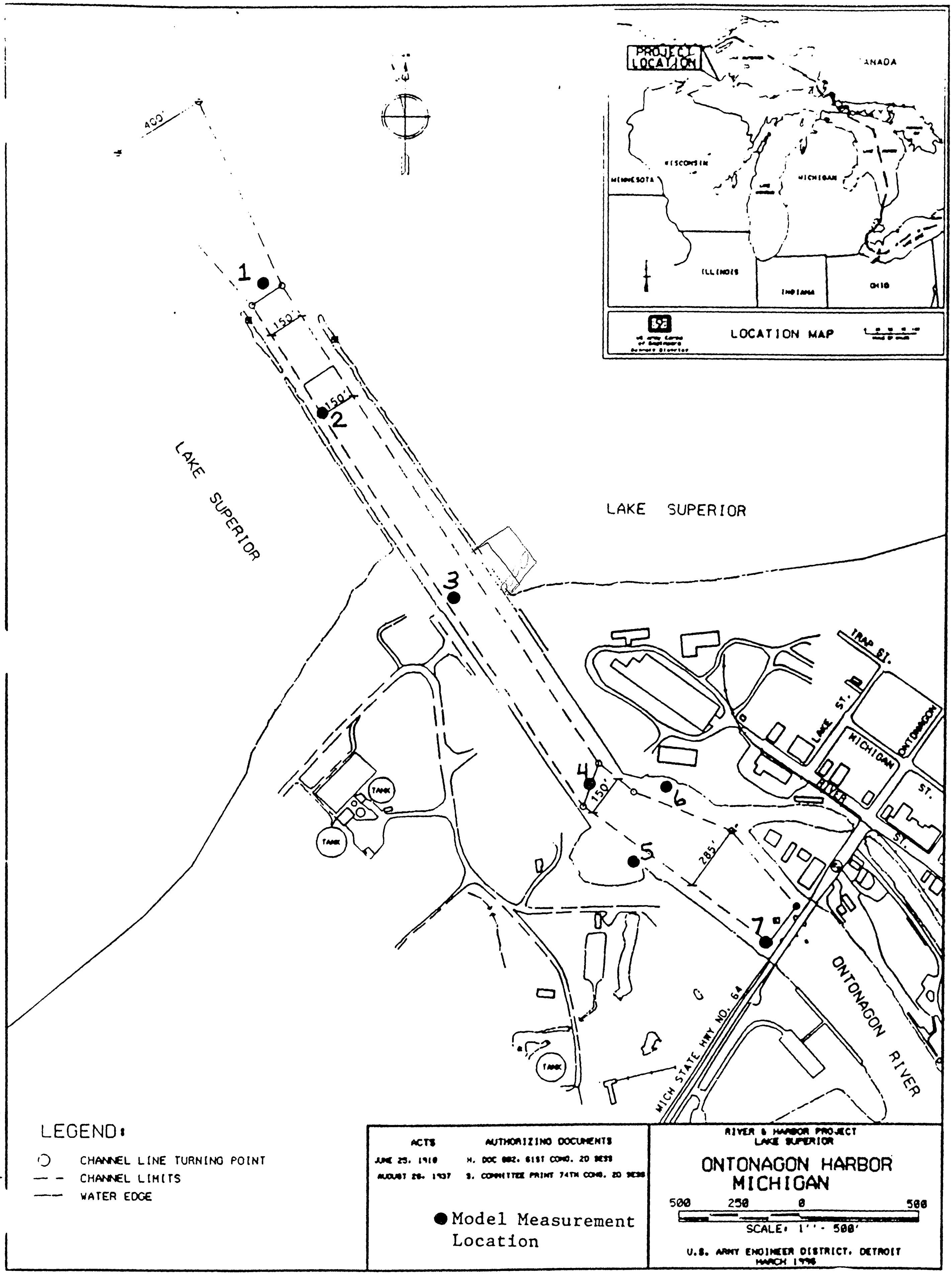
Two additional sets of experiments were performed that altered the wave reflection characteristics in the back of the harbor. As discussed in the orginal report, much of the back of the model harbor was modeled under the assumption of natural beaches, whereas subsequent discussion indicated that the timber crib structures were also present in the back of the harbor in some locations. The model was modified by replacing the sand fill in the back of the harbor by concrete block walls, thereby increasing the reflection coefficients of the back harbor walls. Testing was performed for waves arriving aligned with the channel axis and 30 degrees to the northeast and the results are presented in Figures 15 and 16, respectively. Compared in these two figures is the No Alternative condition and Alternatives 1 and 3 for both the original model harbor configuration as well as the higher wave reflection conditions in the altered model. The label "sand" indicates the original configuration while "no sand" indicates the altered configuration in these figures. Although there are some deviations, the removal of the wave adsorbing beaches in the back of the harbor generally resulted in higher waves throughout most of the model. Comparisons at Location 6 are probably not appropriate since the model was altered considerably in that region.

One major purpose for performing these tests was the expectation that the 255 foot wave attenuator may indicate increased effectiveness in an environment of increased wave reflection. This is fairly clearly indicated at nearly all measurement locations in Figure 15 but hardly any effect can be discerned in Figure 16. This may be explained on the basis that waves aligned with the channel axis tend to propagate directly down the entrance channel and move past the wave attenuator without significant interaction with it. However waves reflected from the back of the harbor tend to propagate in a variety of directions and therefore more cross channel waves propagating back through the entrance channel would be expected with the increased wave reflection. This in turn apparently increases the energy dissipation in the wave attenuator. On the other hand, the 30 degree NE waves already have a cross channel component as they enter into the harbor and some effectiveness of the wave attenuator occurs even without the greater wave reflection in the back of the harbor. Figure 16 indicates however that this effect is small and both figures indicate only a limited improvement in wave conditions with the addition of the wave attenuator. Nevertheless, there is an indication that it would be of some effectiveness and this was not demonstrated in the original study.

CONCLUSIONS

- Waves arriving from the northwest are diffracted around the west jetty and tend to propagate directly down the entrance channel and tend to behave similar to incident waves aligned with the channel axis. Testing indicated only limited effectiveness of any of the proposed alternatives in reducing wave activity within the harbor for waves arriving from the northwest.
- The length of the east jetty doesn't appear to have a significant impact on wave attenuation for waves arriving from the northwest. However, the shorter jetty reduced the wave activity near the channel entrance
- The wave attenuator proposed for rehabilitation of a 255 foot section of the east jetty will probably exhibit a nominal improvement on wave conditions within the harbor.

Given these results, the recommendations made in the original study are still considered to be valid. Namely, the extension of the east jetty to alignment with the west jetty by installation of a wave adsorbing armor stone structure is recommended along with the iinstallation of the wave attenuator proposed for rehabilitation of a 255 foot section of the east jetty.


PROJECT LOCATION
CANADA
WISCONSIN
MINNESOTA
MICHIGAN
ILLINOIS
INDIANA
OHIO
LOCATION MAP
LAKE SUPERIOR
LAKE SUPERIOR
400'
150'
150'
150'
285'
1
2
3
4
5
6
7
TRAP ST.
LAKE ST.
MICHIGAN
ONTONAGON
ST.
RIVER
ST.
TANK
TANK
TANK
MICH STATE HWY NO. 64
ONTONAGON RIVER
LEGEND:
CHANNEL LINE TURNING POINT
CHANNEL LIMITS
WATER EDGE
ACTS
AUTHORIZING DOCUMENTS
JUNE 25, 1910
H. DOC 802, 61ST CONG. 2D SESS
AUGUST 26, 1937
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Model Measurement Location
RIVER & HARBOR PROJECT
LAKE SUPERIOR
ONTONAGON HARBOR
MICHIGAN
500 250 0 500
SCALE: 1'' = 500'
U.S. ARMY ENGINEER DISTRICT, DETROIT
MARCH 1996

Figure 2

Fig. 10
Comparison of wave heights Measured at Points 2 through 7 for Existing Harbor Configuration at Various Incident Wave Angles

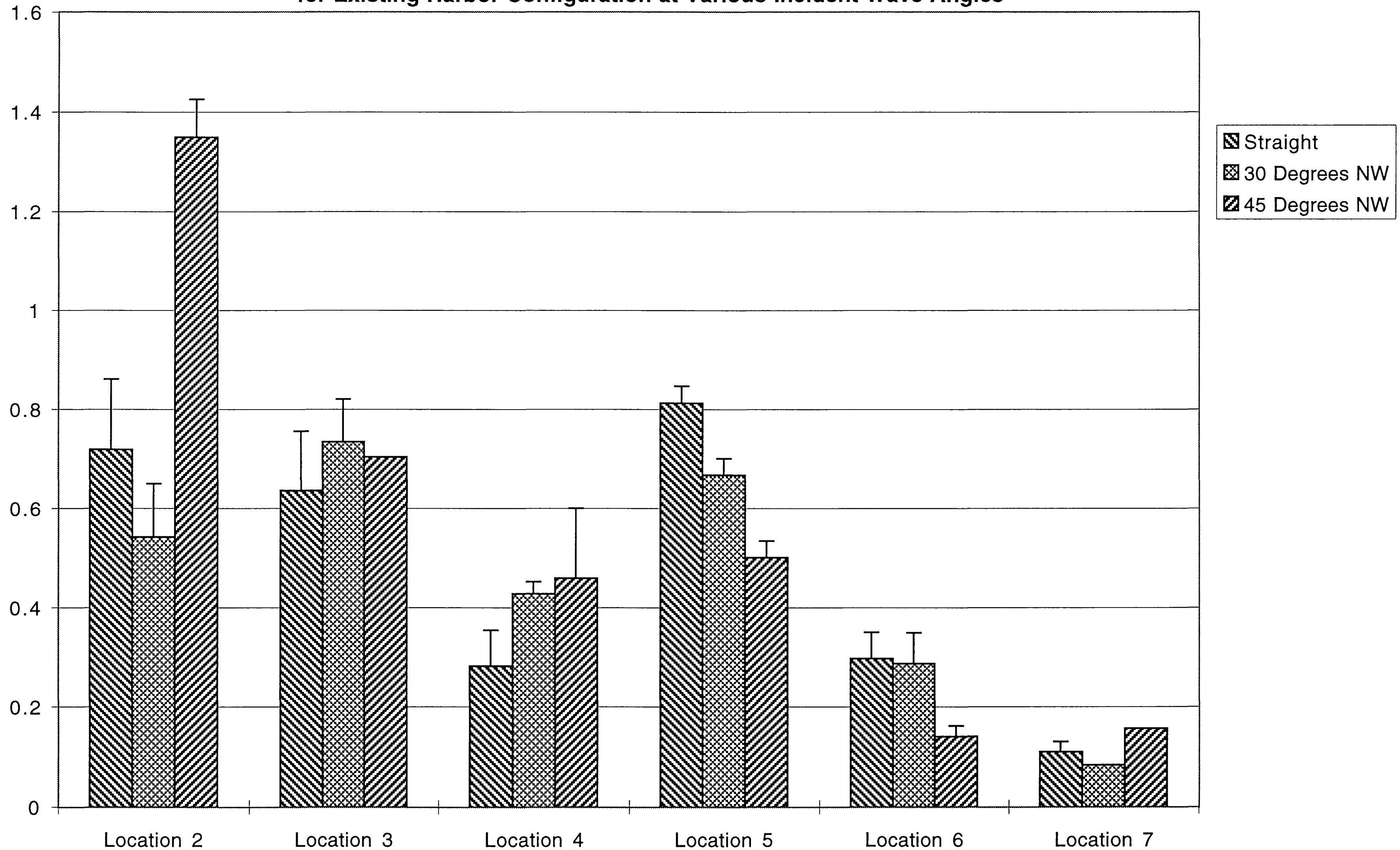


Fig. 11
Comparison of Normalized Wave Heights at Points 2 through 7 for Alternatives 1 through 4 at an Incident Angle of 30 Degrees NW

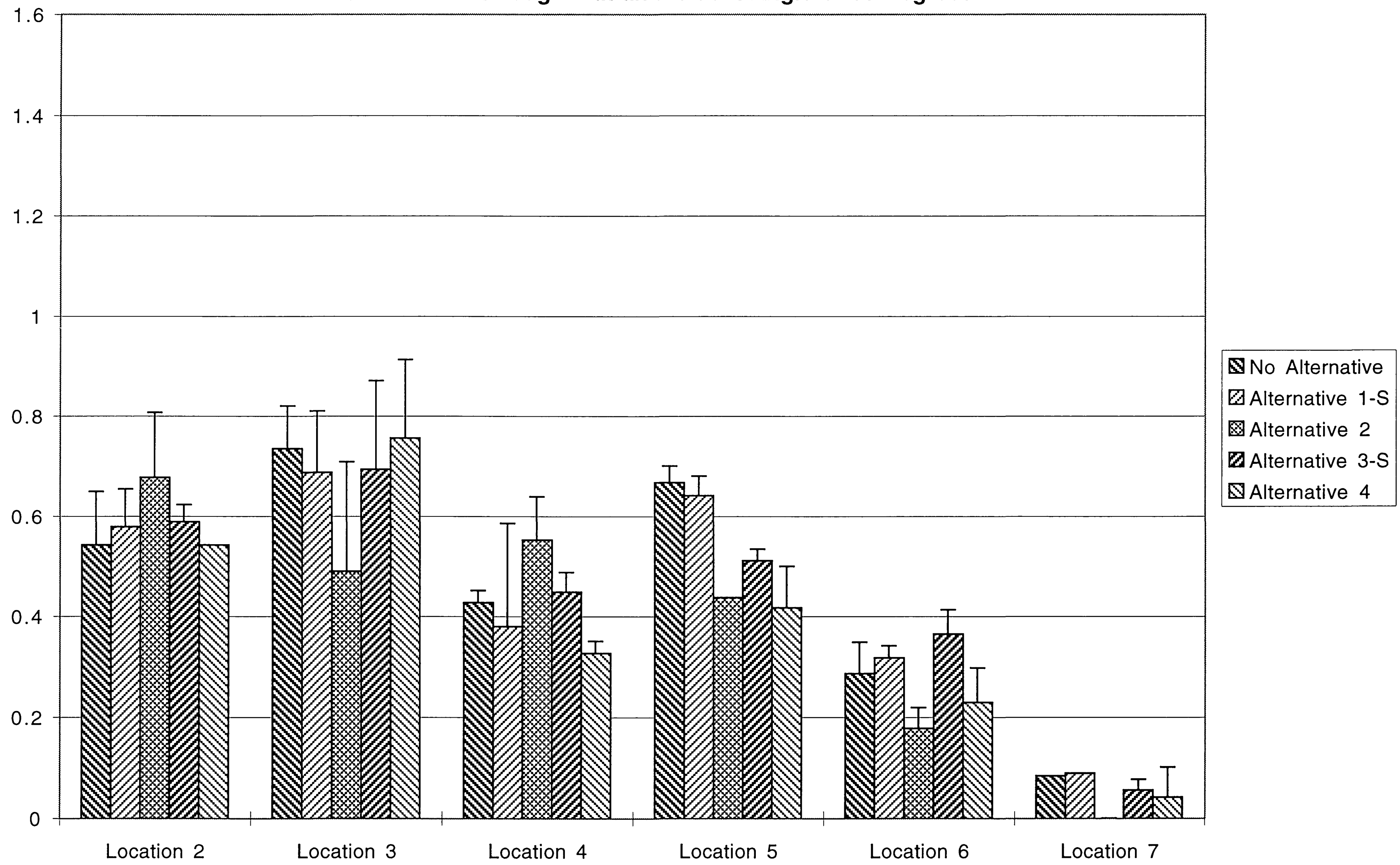


Fig. 12
Comparison of Normalized Wave Heights at Points 2 through 7 for Alternatives 1 through 3 at an Incident Angle of 45 Degrees NW

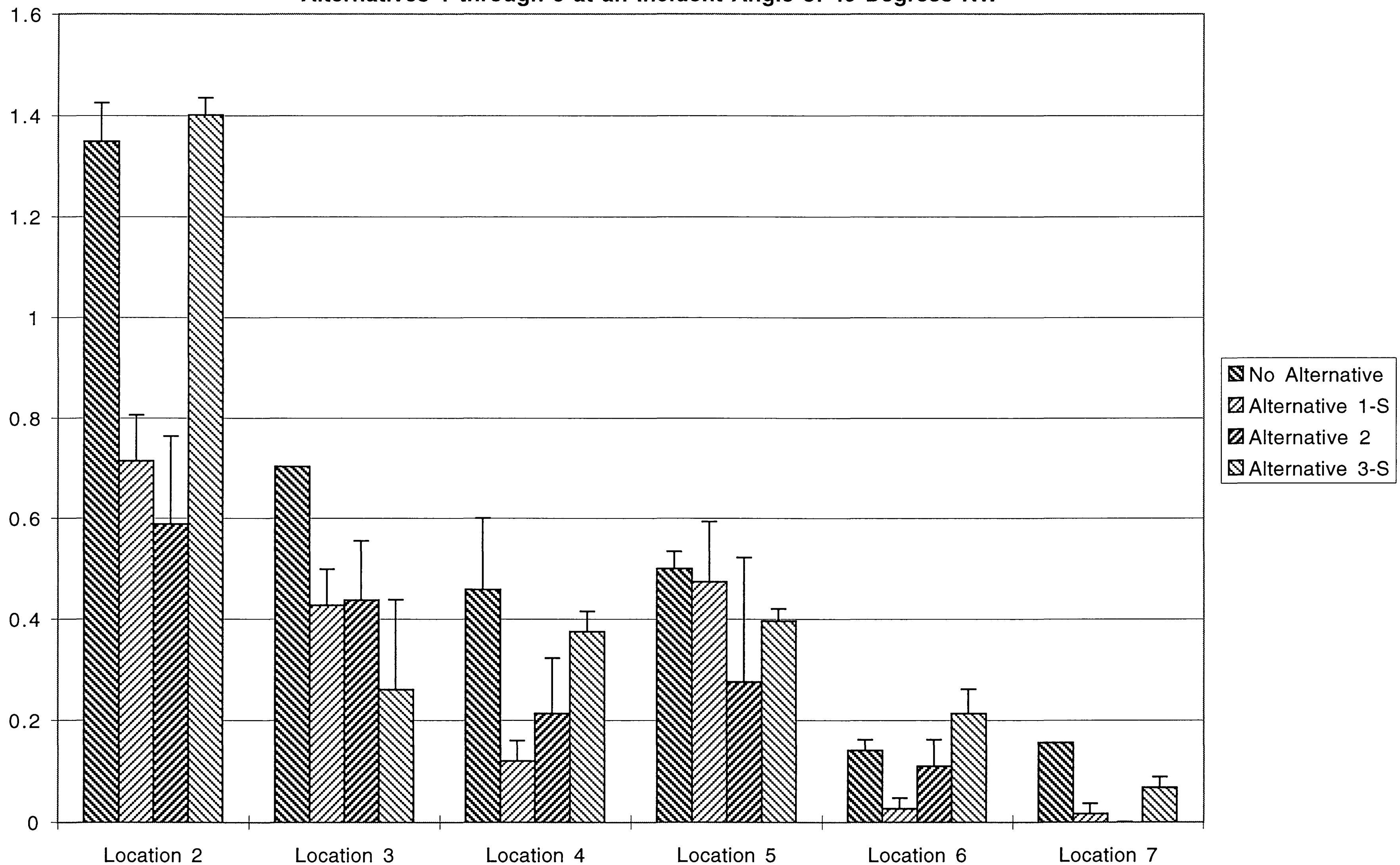


Fig. 13

Comparison of Long and Short east attenuator for Alternatives 1 and 3 at an Incident Angle of 30 degrees NW

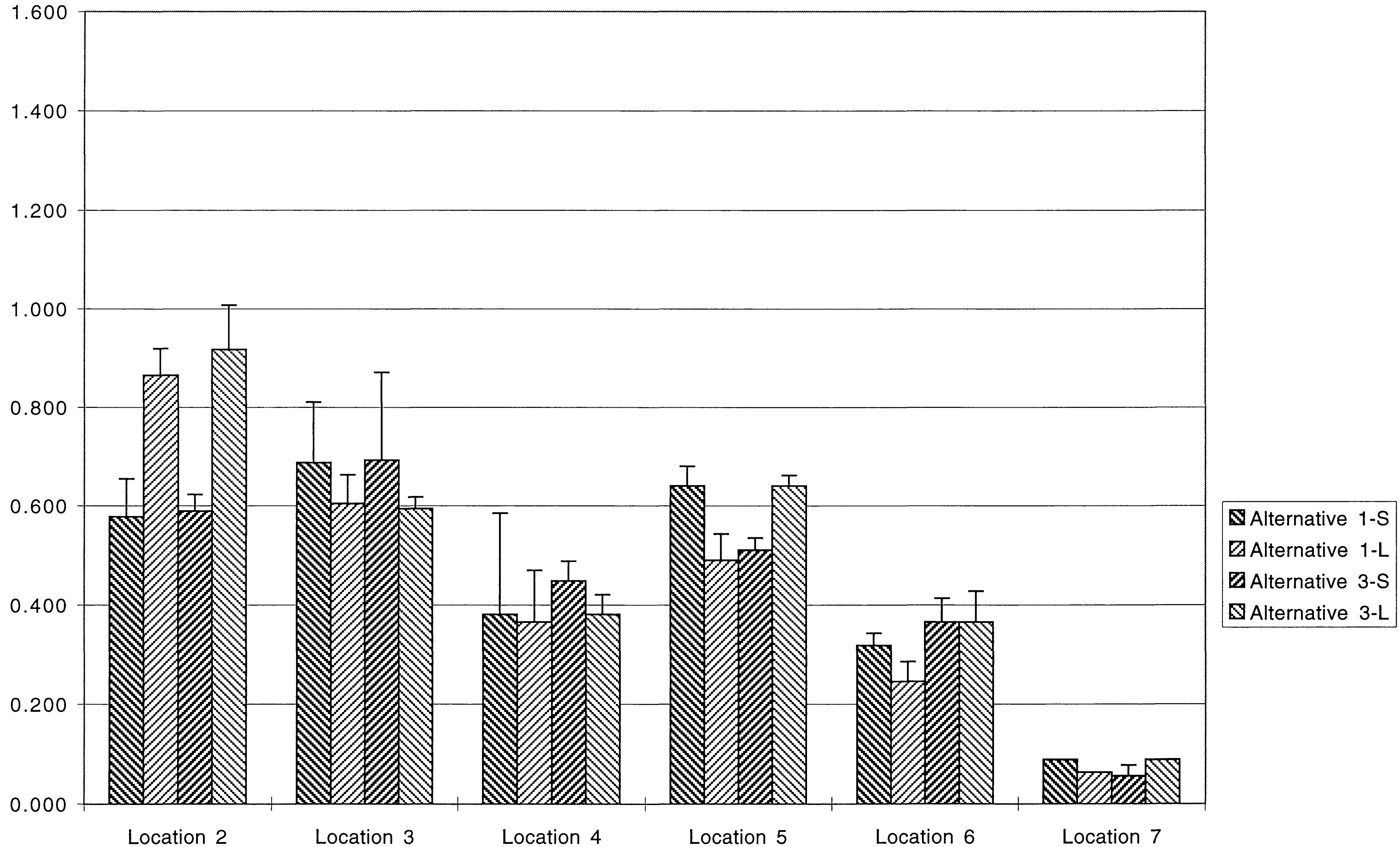


Fig. 14
Comparison of Long and Short east attenuator for Alternatives 1 and 3
at an Incident Angle of 45 degrees NW

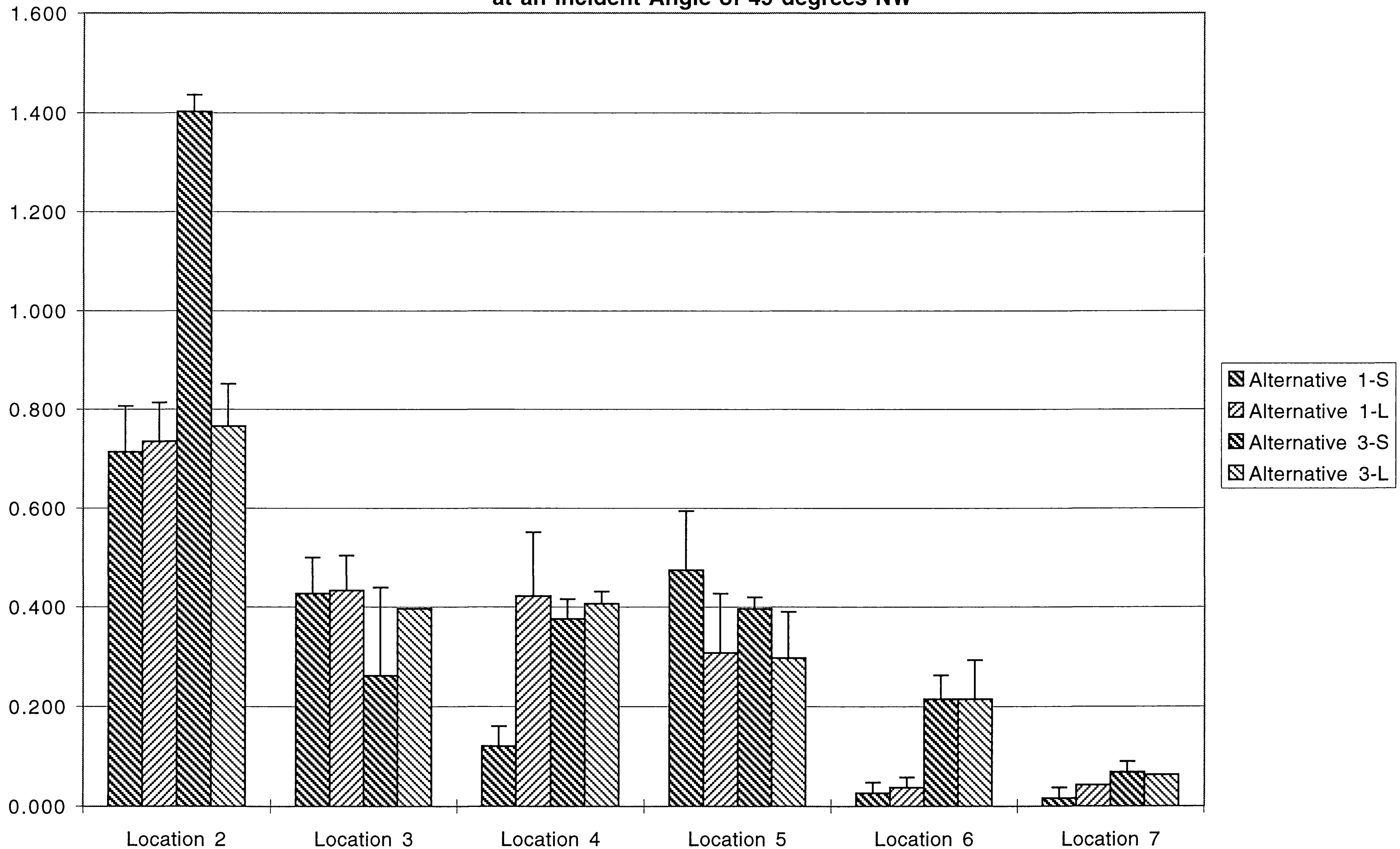


Fig 15.
Comparison of Normalized Wave Heights for Alternatives 1 and 3 after Altering Wave Reflection Characteristics in Back of Harbor, 0 Degree Incident Waves

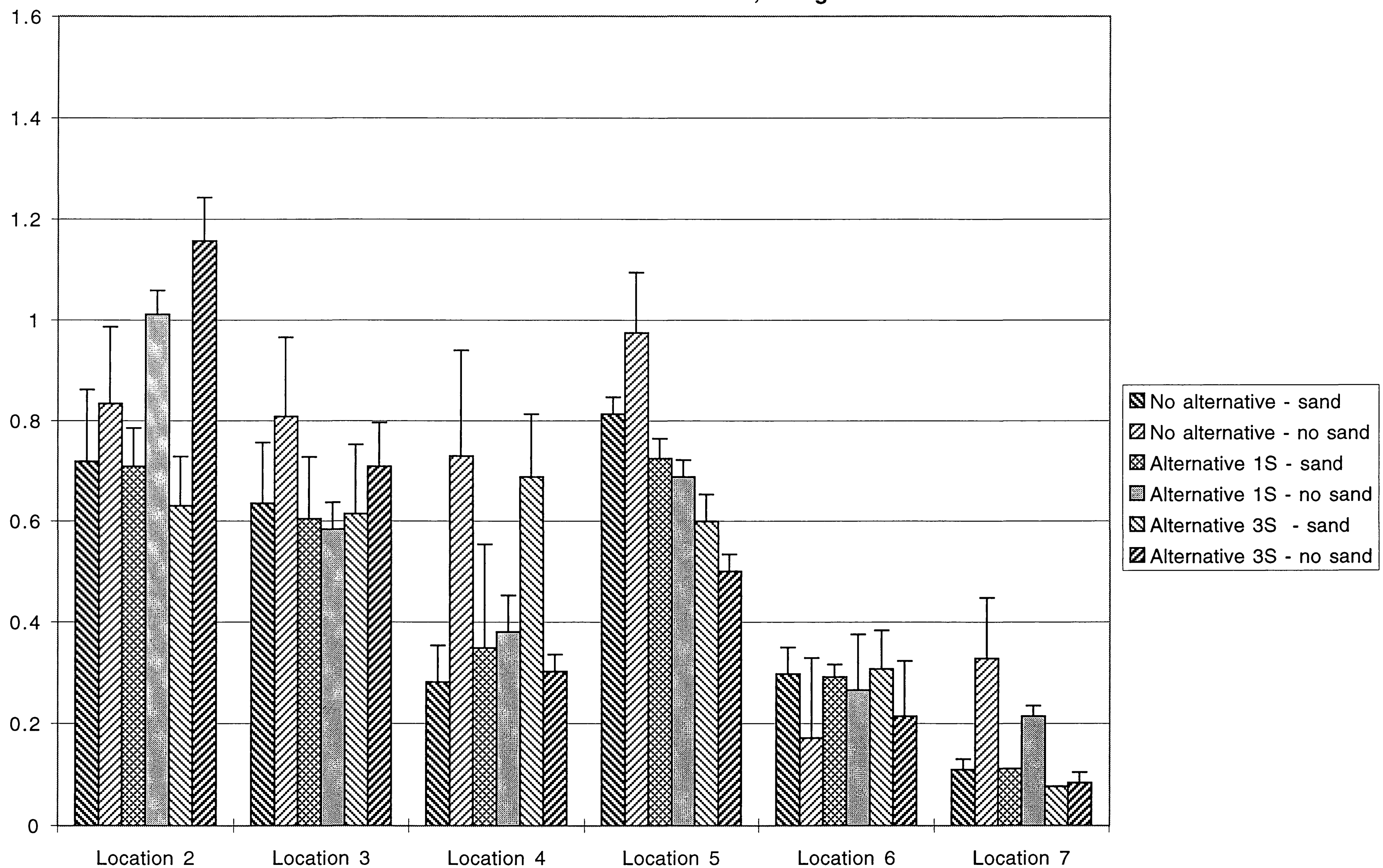
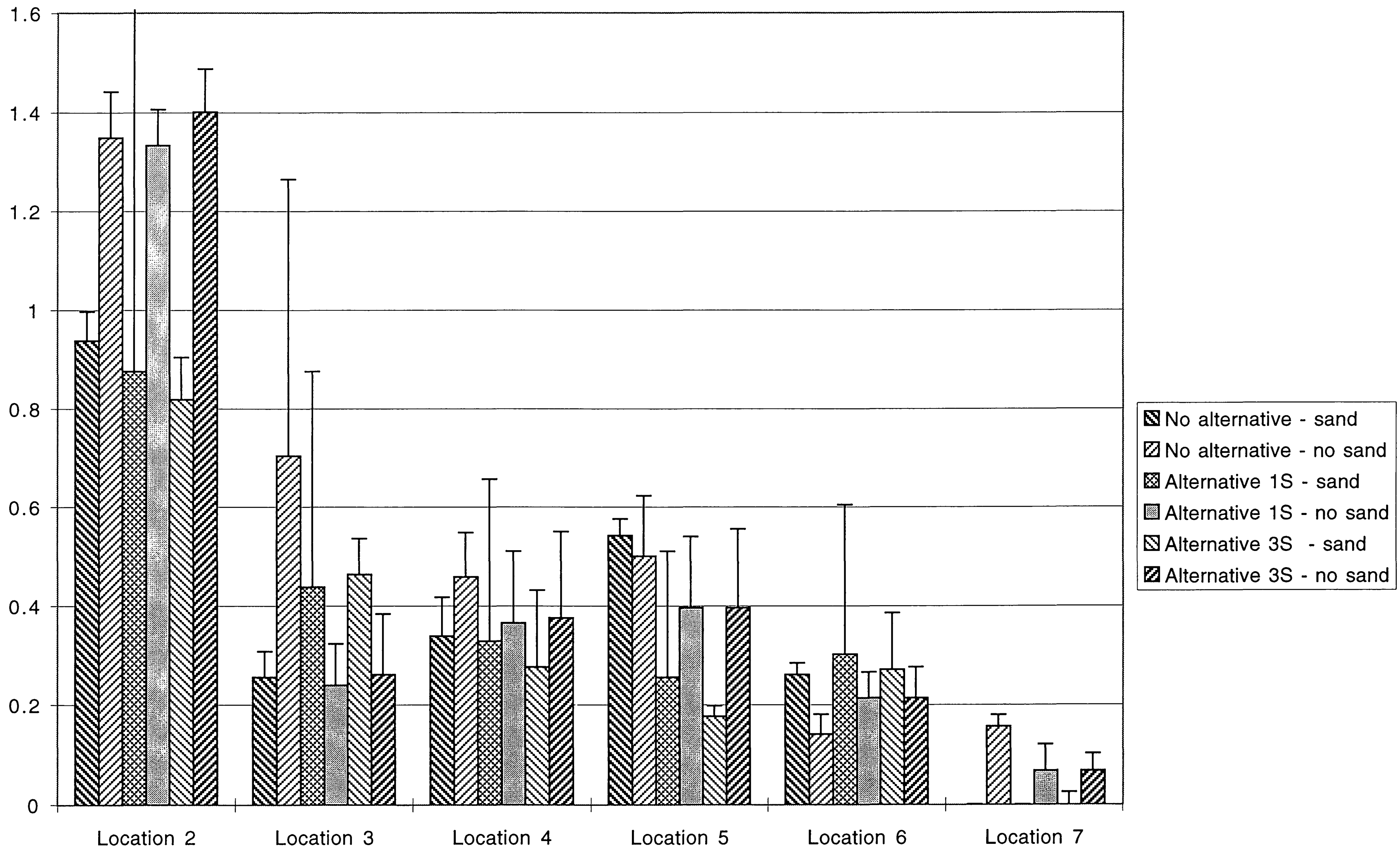


Fig. 16
Comparison of Normalized Heights for Alternatives 1 and 3 after Altering Wave Reflection Characteristics in Back of Harbor, 30 Degree NE Incident Waves



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AIIM SCANNER TEST CHART # 2

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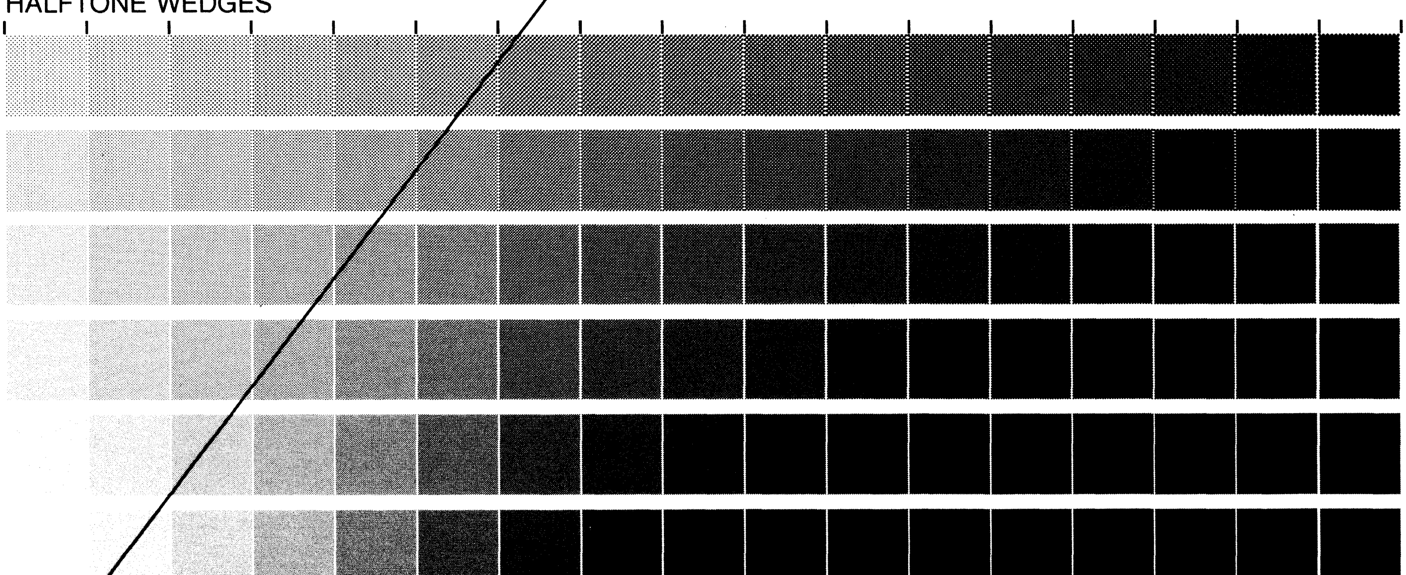

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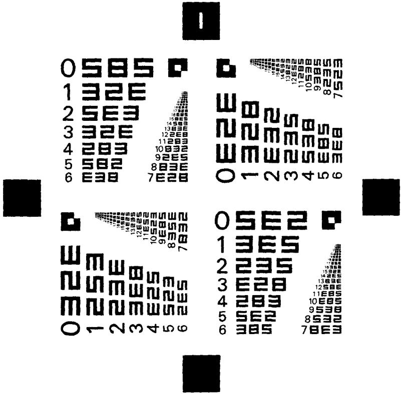

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