Coastal Engineering Technical Note

SMALL-BOAT HARBOR DESIGN EXPERIENCE (LESSONS LEARNED) THROUGH PHYSICAL MODELING AND SUBSEQUENT PROTOTYPE PERFORMANCE

PURPOSE:

To summarize lessons learned relative to hydraulic design of small-boat harbors. Lessons learned were based on physical hydraulic modeling results and subsequent prototype performance of harbors that had been model tested.

INTRODUCTION:

Physical coastal hydraulic models have played a very large and important role as a design tool and source of insight for solving coastal engineering problems in the United States since the 1940's. The evolution of modeling techniques, procedures, and equipment now allows simulation of very realistic wave and current phenomena that have become better understood through modeling experience and basic and applied research. The scale model is commonly used to aid in planning harbor development, and in design and layout of breakwaters, jetties, groins, absorbers, etc. to obtain optimum harbor protection and verify suitable prototype performance. Harbor modifications generally are required to provide acceptable wave protection, alleviate undesirable current conditions, reduce shoaling, and/or decrease amplification of long period wave energy in a harbor.

An inventory of modeled small-boat harbor projects has been compiled (Bottin 1992). Since the early 1940's, 59 coastal model studies of 55 small-boat harbor sites in the United States and/or its territories have been conducted at the U.S. Army Engineer Waterways Experiment Station (WES). These model studies have been conducted for 8 sites in Hawaii, American Samoa, Guam, and Alaska; 19 locations on the U.S. Pacific Coast; one project in Puerto Rico; one in the Bahamas, 9 sites on the U.S. Atlantic Coast, and 17 locations on the U.S. shorelines of the Great Lakes. Site locations are shown in Figure 1.

Modifications made to the original project designs as a result of model investigations have been identified in study reviews. Originally proposed designs for most of the projects proved to be ineffective in achieving the desired level of protection, and subsequent modifications developed in the models were required to render the designs functionally acceptable. These reviews and analysis have resulted in a summary of lessons learned through physical modeling with respect to small-boat harbor design (Bottin 1991, 1992). Of the 55 harbor sites modeled, 25 have been constructed in the prototype, and these projects have been reviewed to determine if they were constructed as recommended and have performed adequately as predicted by the model studies. The data obtained indicate how the projects have performed and

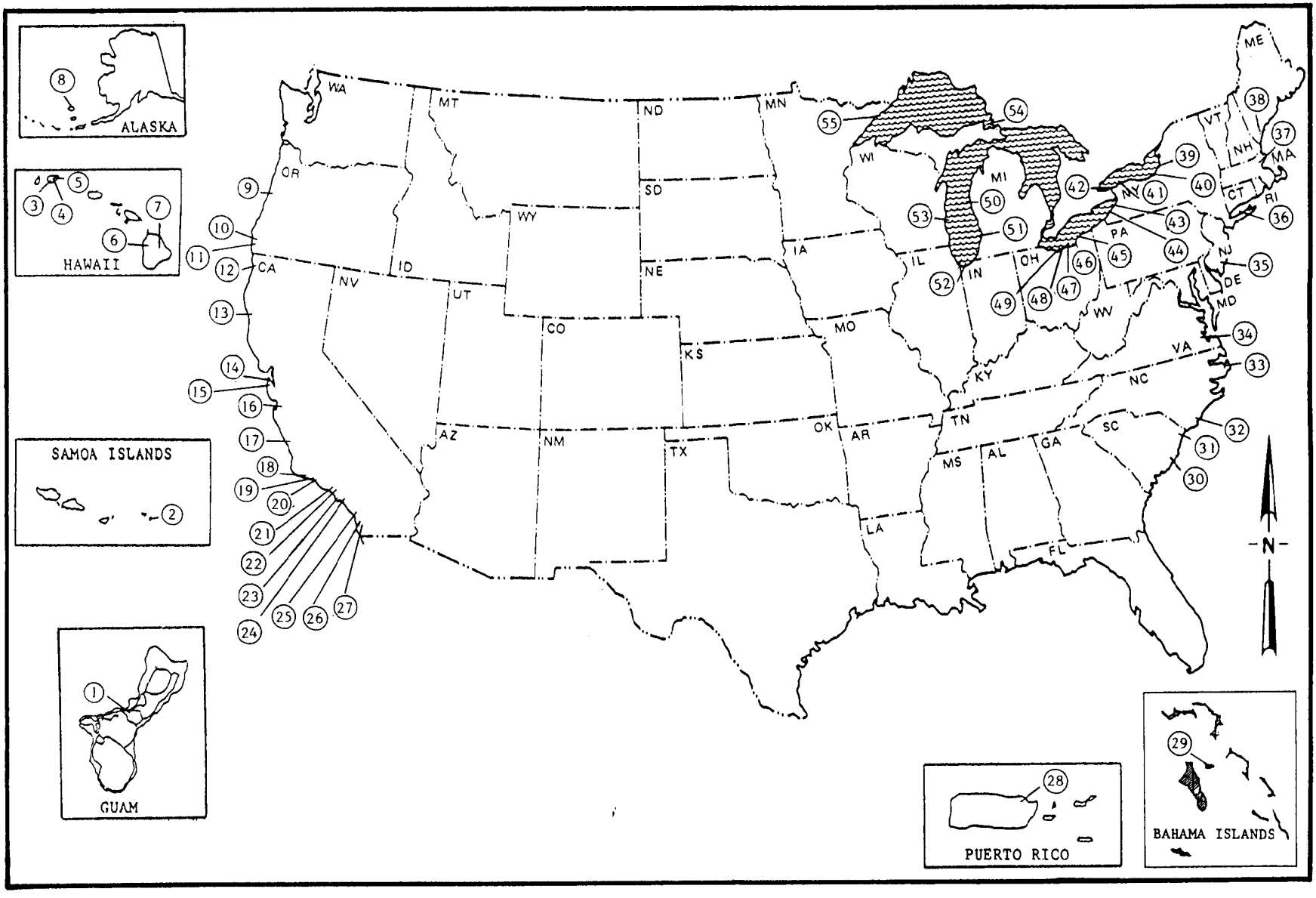

Figure 1. Locations of sites where physical model investigations have been conducted

include problems encountered since construction.

SUMMARY OF MODEL REVIEW:

Of the 59 model investigations conducted at WES, 17 were conducted for new harbor sites where unimproved conditions existed, and 42 were conducted at existing harbor sites where structures were present. Some of these sites included expansion of the existing harbors, however, most studies were conducted to develop remedial plans of improvement where problems occurred.

Test results for the originally proposed designs of the 59 model studies indicated that 46 proposed designs were ineffective in achieving the desired results, and therefore, subsequent design modifications, as determined by the model tests, were required to make the designs functionally acceptable. Of the 13 originally proposed designs that met the established criteria, 10 projects were overdesigned. Model tests for these 10 harbor sites indicated the originally proposed structure lengths could be reduced, crest elevations lowered, etc., and still provide the level of protection required. Thus, as a result of the model findings, the design was changed and construction costs were significantly reduced. Of the 59 hydraulic model investigations conducted, only three of the originally proposed designs provided adequate protection and were not overdesigned. For these projects, model tests verified improvements provided adequate harbor protection, and that reductions in structure length, etc., in an effort to reduce costs, could not be made.

SUMMARY OF PROTOTYPE PERFORMANCE:

Twenty-five small-boat harbors have been constructed in the prototype subsequent to being model tested at WES. All these harbors have been reviewed to determine, first, if they were constructed as recommended in the model investigations and, secondly, to determine if they have performed adequately and as predicted by the model studies. Project performance data were obtained from reliable sources, but were not detailed and in-depth in most cases. Data obtained give an indication of how the projects have functioned and include any problems encountered since construction.

Of the 25 small-boat harbors that have been constructed, nine were constructed exactly as recommended in the model investigation. An additional 10 projects were constructed with slight modifications. In some cases, these projects consisted of structures that were curved instead of having a dog-leg, slightly longer structures than recommended, and/or a reorientation that would provide the same structure overlap and thus should provide equal protection. These 19 projects appear to be providing the same harbor protection that was predicted by the recommended plans developed by the model studies. The other six projects were constructed with the same basic configurations, as recommended in the models, but they had shorter structures, wider entrances, deeper depths, and/or may have omitted an element (or structure) of the design. Variations from the recommended design of these six projects could reduce their functional efficiency.

An assessment of the performance of the prototype harbors reveals that most perform as predicted by the model studies. Three of the projects receive complaints of excessive wave action in the mooring area and/or at a boat ramp. A review of the model investigations, however, indicated that the established wave height acceptance criterion in the harbors was 2.0 ft at these locations for storm wave conditions. For the more current model studies, an acceptance criterion of 1.0 ft or less is generally established. Model tests for the three studies in question show wave heights of 1.0 to 1.6 ft in the harbor during everyday wave conditions. Model studies predicted the wave conditions correctly; it is just that the selected wave height criterion for the studies was too high. The other projects studied have performed very well during storm wave conditions.

Tracer tests were conducted in the models of several projects to qualitatively assess sediment deposition and scour patterns. All these prototype projects have been evaluated with regard to shoaling, and it appears they are performing as defined by the model test results. Shoaling patterns in entrances or mooring areas have not occurred since construction.

Structures have been constructed in the prototype for three tidal inlet sites that were model tested. The entrance channels are stable at two of the prototype sites, but at the other site, the channel appears to be meandering between the jetties. This site is subject to extreme freshwater discharges, however, and the jetty spacing had to accommodate flood flows. When freshwater discharges are low, the channel meanders between the jetties. Also, the model was a fixed-bed study, which makes it extremely difficult to predict a stable channel configuration. In summary, with the exception of the one tidal inlet study, the projects constructed in the prototype, that did not vary radically from the recommended designs formulated in the model studies, are performing as predicted by the model investigations.

LESSONS LEARNED:

The interaction of storm wave phenomena at harbor sites (propagation of wave energy into harbors, diffraction of energy through harbor entrances, reflection of energy from structure and facilities, energy reaching the harbor through wave overtopping and/or transmission of structures, wave generated currents, and/or storm surge currents, etc.) is very complicated. When river and/or tidal currents are present, the complexity of the dynamic hydraulic system increases. Also, shoals formed in the entrances may cause breaking waves or may redirect wave energy, through wave refraction, to other areas in the harbor (areas that generally may not experience problems). Through the use of physical modeling, many lessons have been learned, however, refining the design of any project still remains very difficult.

The first step for the successful design of a harbor project is to obtain up-to-date, realistic, accurate design wave and water level conditions. The designer should know the expected storm wave characteristics (period, height, direction, spectral shape, etc.) at the site. He/she should know tidal conditions (tidal heights, velocities, prism, etc.), river discharges, ice problems, predominant direction and volumes of sediment movement, long period

wave conditions, and seiche activity, if applicable. The design of a project is very dependent upon high quality definition of hydrodynamic design conditions. The designer should also establish performance criteria that will satisfy the needs of the local harbor users. Prototype data from various harbors indicate that the design performance criteria were met at several sites, but continual complaints by harbor users have been received since project construction.

Studies have shown that it is generally desirable to prevent wave energy from entering a harbor as opposed to attempting to dissipate energy once inside the harbor. Wave energy entering a harbor can be minimized by overlapping breakwaters at the entrance, reducing the entrance opening if acceptable, constructing breakwaters that are not easily overtopped by waves and using impermeable breakwater cores to reduce wave transmission. Offshore structures, constructed seaward of the entrance, also may be used advantageously, Care must be taken, however, if the harbor is located at a river mouth. Flow restrictions in the entrance opening may contribute to flooding upstream, or ice jamming in colder climates.

Physical limitations and/or construction costs may prohibit the construction of structures which will minimize wave energy entering a harbor. Studies reveal that it is very difficult to reduce wave energy once it enters the harbor; however, measures can be taken to absorb this contained energy. Rubble wave absorbers and/or spending beaches may be constructed at critical locations (where wave energy is high) in the harbor and effectively dissipate energy and, thus, reduce undesirable wave effects. Also, in other areas where standing waves exist, spending beaches, rubble absorbers and revetments, and/or concrete absorber units (i.e. such as igloos) may be effective in the reduction of wave energy.
Harbor entrance channels should not be aligned parallel to predominant incident wave crests. If this is done, small-craft must enter broadside to incoming waves which is very hazardous. In areas where these conditions currently exist, breakwater arms or extensions may be constructed seaward and parallel to the entrance channel. This will provide calmer conditions in which vessels can be better controlled prior to entering the harbor.

Vertical wall breakwaters and vertical harbor structures are highly reflective and should be avoided in areas where these reflections would have a negative impact. Waves reflected off entrance structures result in very confused and hazardous navigation conditions. Vertical walls inside harbors, where relatively high wave energy is present, cause hazardous anchorage and mooring conditions and can result in frequent damage to facilities and small boats. Reflections from vertical structures also have induced erosion of adjacent beaches and/or shoreline.

Model tests have shown that absorbers installed along the slips of various harbors are essentially ineffective in reducing long period wave energy. In harbors where the mode of oscillation of a basin is equal to the frequency of incident long period wave energy, the harbor basin will respond and standing waves may result which, in turn, could result in damage to vessels and facilities. Changing the geometric configuration of the basin where economically feasible could remedy the condition, but new configurations may

respond to other naturally occurring wave frequencies. These problems are very difficult to alleviate, however, model testing has indicated that the amount of long period wave energy entering a harbor can be slightly reduced by offshore structures that overlap the entrance. To be effective, the offshore structure needs to be relatively impermeable.

Harbor facilities and/or boat ramps should not be constructed directly behind an entrance opening. Wave energy propagating through entrance structures may cause undesirable conditions. In areas where physical limitations exist, harbor facilities may be protected by interior breakwater structures or revetted moles. Prototype performances of various harbor sites have shown these improvements to be very effective, however, when inner structures or moles are constructed, future expansion is sometimes limited. Inner breakwaters and revetted moles also have been used effectively to protect harbor facilities in the lee of existing structures where wave overtopping and/or excessive wave transmission exist.

Harbor entrances should not be oriented toward the direction from which sediment is moving alongshore. If this is done, in most cases, protective structures will serve as a trap and sediment may deposit in the entrance channel. It is desirable to build structures that will contribute to natural sand bypassing around the harbor entrance. Tests have shown that structure and entrance openings constructed toward the downcoast side of the predominant direction in which sediment is moving alongshore contributes to natural bypassing. An outer curved breakwater which overlaps a short shore-connected structure tends to allow sediment to move around and downcoast. The shorter downcoast structure prevents sediment reversals moving along the shoreline from entering the entrance. Prototype performances of several harbor sites have indicated that qualitative methods of determining sediment movement used in model investigations have been reliable. Improvement plans were developed that would prevent shoaling in the harbor entrances and/or mooring areas. These plans, after being constructed in the prototype, have proven very effective.

At some existing harbors, sediment moving alongshore is intercepted by a structure and moves seaward along its axis and subsequently deposits in the entrance channel. Model tests and prototype performance have indicated that spurs installed on the updrift sides of the structures tend to deflect sediment away from the entrance. At some sites, spurs also have proven to be beneficial in deflecting undesirable cross-currents away from harbor entrances.

Model tests and prototype performance data have shown that segmented breakwaters are effective in providing wave protection while having minimal effects on tidal circulation. They proved more effective than baffled breakwaters in model tests. Consideration may be given to using segmented structures in lieu of floating or baffled breakwaters, where both wave protection and harbor flushing is required. Segmented rubble absorbers inside a harbor, as opposed to a continuous absorber, also have proven to be effective. This design alternative may result in significant cost savings through reduction in stone quantities.

Waves breaking across reefs generally result in very strong currents alongshore. These cross-currents may be hazardous to small craft entering a harbor entrance through the reef. Model test results and prototype performance data have shown that breakwaters may be used to deflect these currents offshore away from the entrance, and thus, alleviate or minimize hazardous cross currents in the entrance. Circulation channels also have proven to be very effective in providing harbor flushing for harbors situated in reef areas.

In tidal inlets, an even distribution of flow (without excessively high or undesirably low velocities) is required. Past model test results have indicated that inlet stabilization jetties should be about the same length. They also should be parallel or dikes should be installed to divert or concentrate the flow of tidal currents through the desired channel alignment and thus prevent channel meandering. The spacing between the jetties is important to help ensure a stable inlet. Where weir sections and deposition basins are used to trap sediment moving alongshore, it is important that the location of the weir be properly selected and that the weir be installed low enough to allow sediment to move over the structure and into the deposition basin but high enough to prevent excess wave agitation.

ADDITIONAL INFORMATION:

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REFERENCES:

Bottin, Robert R., Jr. 1992. "Physical Modeling of Small-Boat Harbors: Design Experience, Lessons Learned, and Modeling Guidelines," Technical Report in press, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bottin, Robert R., Jr. 1991. "Design Experience Gained Through Physical Modeling of Small-Boat Harbors," World Marina '91, Proceedings of the First International Conference, pp. 292-301, American Society of Civil Engineers, New York, NY.

PHYSICAL MODELING GUIDELINES:

Guidelines that designers of small-boat harbors can use to determine when and what type physical model investigation can be used to enhance and optimize his/her project design will be presented in a subsequent Coastal Engineering Technical Note (CETN).