COASTAL ENGINEERING AND THE DEVELOPMENT OF BOSTON HARBOR

by

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Abstract

The limitations imposed on the development of Boston Harbor by coastal phenomena are important considerations in the planning process. Wave erosion can require rip-rap or seawalls around landfills, and restricts the creation and modification of beaches. Storm waves, in conjunction with high astronomical and storm tides, fix the minimum elevation of landfills, causeways and bridges. The navigation and docking of small craft limit allowable tidal currents, thus limiting landfill configurations, and require areas sheltered from wave action. Waves also can interfere with water-based construction activity.

Introduction

Boston Harbor, with its numerous islands, channels and bays, presents many opportunities for development. Such development may include landfills, causeways, bridges, channel realignments, marinas, and other modifications to the natural configuration of the harbor.

Engineers, architects and planners investigating possible developments of this harbor space must consider from the beginning the limitations imposed on projects in the harbor by the natural phenomena associated with the marine environment. This environment influences the development of the Boston Harbor space in several ways:

1. Waves cause erosion of the shoreline, requiring coastal protection. Generally, this protection consists of a cover layer of rock rip-rap along the shoreline, or, at points of severe wave attack, sea walls, as at the northeast end of Long Island.
2. Waves also affect beaches, causing both a seasonal onshore-offshore movement of sand and a longshore drift. (See the section on the construction of beaches.)
3. Marinas and other docking or anchorage facilities need to be designed to provide adequate protection for moored boats and floats.

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4. Extreme storm waves, especially in conjunction with "storm tides", a combination of high astronomical tides and wind-induced tides, can overtop seawalls and embankments, causing flooding of land areas behind.
5. Tidal currents in excess of 3 knots in channels can be a hazard to navigation. Since tidal currents are affected by the shoreline and bottom configuration, this places constraints on landfill arrangements and channel closures.
6. Wave action can interfere with water-based construction activities. Barges, dredges, and floating cranes cannot function safely or effectively in waves higher than about 2-6 ft., depending on the size of the equipment and the wave period.

The above limitations are imposed essentially by three natural phenomena: waves, tides and currents. The nature and effects of each are considered in detail below.

I. Waves

Waves in the harbor arise from three sources: ocean-generated storm waves, ship waves, and waves generated locally by winds in the harbor.

Ocean wave data[1] for Nausett Beach, Cape Cod, have been obtained from the U.S. Army Corps of Engineers. By eliminating waves from the SSE and south, adjustments for the sheltering effect Cape Cod has on Boston can be made. The adjusted data, shown in Figures 1 and 2, describe approximately the ocean waves well outside the harbor, in depths greater than 100 feet or so. The data are presented as the approximate number of hours per year the waves were in each height and period range. The values reported, except ship waves, give the significant wave height, often written $H_{1/3}$. This is defined as the average of the highest 1/3 of the waves in a record, and is related to the maximum, etc., by the following:

$$H_{1/10} = 1.27\,H_{1/3}$$

$$H_{max} = 1.67\,H_{1/3}$$

Wave heights estimated visually usually correspond to the significant height.

[1] These data were obtained from past weather records and used as the basis for wave forecasts. Assuming the weather statistics do not change, the wave statistics produced can be applied to future years.

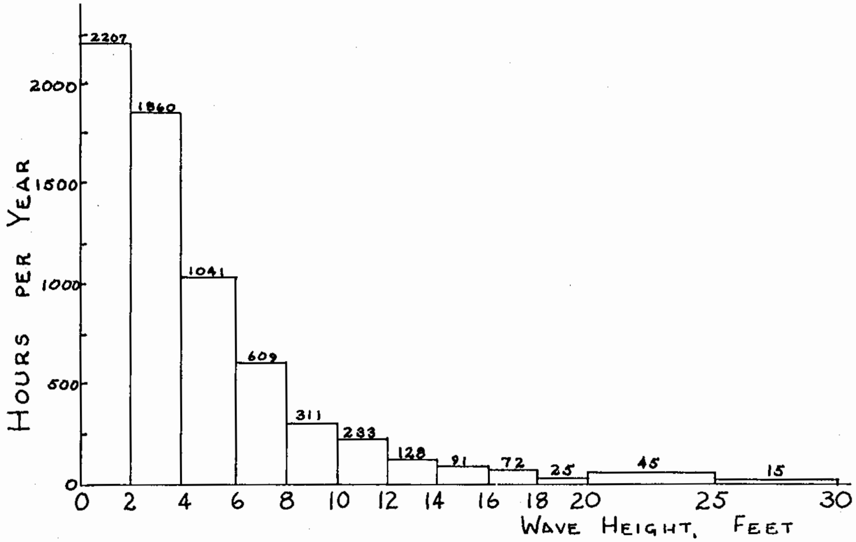

Fig. 1 Wave Heights off Boston Harbor.

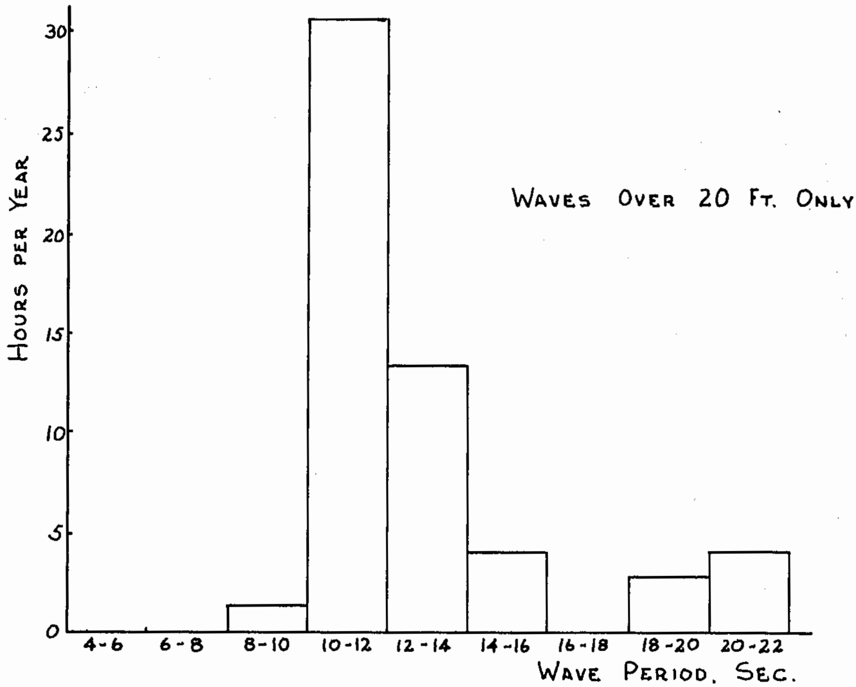

Fig. 2 Wave periods off Boston Harbor.

The speed of a wave in shallow water decreases with decreasing water depth. Thus ocean waves approaching the harbor are refracted by the irregular bottom configuration, with the incident wave energy being focused on islands, shoals and headlands – particularly Outer Brewster (and, to a lesser extent, the other Brewster Islands), Shaf Rocks, and Green Island. A good deal of wave energy is transmitted into the harbor, however, through the major channels – President Roads and Nantasket Roads. In his historical book on the "Islands of Boston Harbor", E. R. Snow mentions "Breakers 40 feet high. . .sweeping right across the mile-wide area between Deer and Long Islands. . ." during a major storm. Once inside the harbor, this wave energy is spread out, and the heights reduced significantly. It is not possible, at present, to predict with any reasonable decree of accuracy the quantitative effect of ocean waves inside the harbor. Further investigation is definitely required. From the navigation chart for Boston Harbor (U.S.C. & G.S. Chart No. 246), however, one can identify several areas inside the harbor likely to be subject to waves at least 60-70% as high as those outside the harbor. For a storm producing waves 30 feet high in the ocean, which Figure 1 indicates may occur once or twice each year, Figure 3 shows the areas that may be subject to waves 20-30 feet high ($H_{1/3}$). More accurate predictions, and predictions of ocean wave heights farther in the harbor and their frequency of occurrence, will require further study.

Locally-generated wave heights can be estimated for various locations, based on the wind speed and fetch (distance over which the wind blows, upwind from the point of interest). These estimates are given in Table I for Spectacle, Thompson and Long Islands, and apply just offshore of the windward side of the island, as indicated by the wind direction shown. The wind speeds were arbitrarily chosen to represent a stiff breeze of frequent occurrence, a storm occurring perhaps yearly, and an occasional hurricane, respectively.

Ships' waves, for vessels of all types traveling at speeds less than 8 knots, are generally less than a foot high, and generally less than two feet for speeds up to 12-14 knots.

Shore Protection

Ship waves are only of significance in interior, well-protected channels, where their height may be exceeded only by rare storms. For protecting new fill areas from erosion, a design wave height of two feet should be used. Banks built on a slope of two horizontal to one vertical or flatter can be protected by a layer of heavy rock perhaps two feet thick, and extending from 2-3 ft. below MLW to the level of the fill, or at least to 15 ft. above MLW.

Since a storm passing Boston generates both ocean waves and waves inside the harbor, waves from both sources need to be considered simultaneously. While the ocean waves have periods in the range 10-14 sec. (Figure 2), locally-generated storm waves have periods in the 3-5 sec. range. It is not

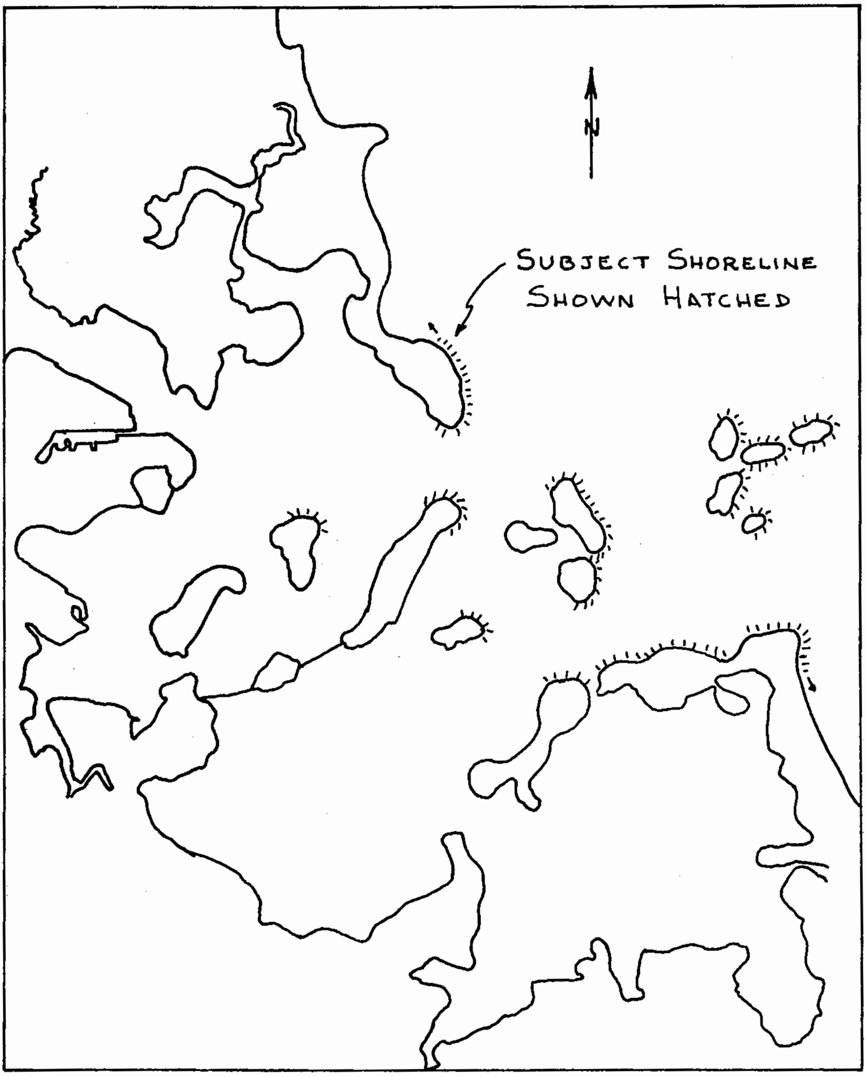

Fig. 3 Areas Subject to Severe Wave Action - Boston Harbor

Table I – Locally Gen. Waves

Location	Wind Dir.	Fetch Naut. Mi.	Wind Spd. Knots	$H_{1/3}$ Ft.	$T_{1/3}$ Sec.
Spectacle Is.	N	1.3	20	< 2	2.3
			50	3.7	3.5
			90	6.8	4.6
	NE	1.4	20	< 2	2.3
			50	3.7	3.5
			90	6.8	4.6
	E	0.8	20	< 2	2.2
			50	3.2	3.2
			90	6.2	4.0
Thompson Is.	NE	1.8	20	< 2	2.5
			50	4.2	3.7
			90	9.0	5.1
	NW	0.8	20	< 2	2.2
			50	3.2	3.2
			90	6.2	4.0
Long Is.	NW	1.8	20	< 2	2.5
			50	4.2	3.7
			90	9.0	5.1
	SE	1.6	20	< 2	2.5
			50	4.0	3.7
			90	8.0	4.8

understood how these interact. In the area around Thompson Island, the locally-generated waves run up to 4 ft. in the largest "annual" storm; probably the ocean waves are approximately the same height. For a 6-ft. design wave, at a tide level of +12 ft., erosion protection for new fill areas can be provided for a slope of 2:1 or flatter by a 2 to 3 foot layer of rock extending from 6 ft. below MLW to 18 ft. above, at a cost of perhaps $35-50 per foot of shoreline for a 2:1 slope, $70-100 for a 4:1 slope, if the rock can be trucked to the site and dumped; the cost doubles if the rock has to be barged to the site. More exposed locations may require a raised embankment to prevent flooding, while more sheltered locations would require less rock. The figures given above are, therefore, only general costs for protecting fill areas.

Marinas and Other Docking Facilities

Small-craft shelter requirements vary, depending on the type of mooring (rigid, as wharfs and finger piers, or an anchorage) and the use. Pleasure craft at a rigid mooring will likely sustain damage from waves over 1-2 ft. high, depending on the size of the craft, the wave steepness (long swells or chop – chop is worse), and the skill of the boat owner in tying the boat. Boats at a properly designed mooring with room to swing can ride out nearly any sea that they could handle underway. The large amount of space required for moorings, however, limits the use of anchorages in many parts of Boston Harbor. Marinas in virtually all parts of the harbor need to be partly enclosed by fill or by a breakwater to provide proper protection.

A breakwater built to 18 ft. above MLW, in water 10 ft. deep at MLW, with 1.5:1 side slopes, will cost approximately $1000-1500 per linear foot. In general, permanent docking along pile-supported causeways is not recommended. However, the western and southwestern sides of filled causeways will, in most cases, be adequately protected. Fair-weather docking at most sites will require no protection, except that such facilities on the outer islands should be on the west or southwest sides of the islands, in coves where possible.

Beaches

A beach is not just an inert heap of sand that happens to be at the water's edge. The action of the waves on the sand keeps the beach in a continual state of flux. Basically, there are two main modes of transport: onshore and offshore, and longshore drift. The onshore-offshore movement on natural beaches generally occurs in an annual cycle. Steep waves from the winter storms tend to move material from the beach to deeper water where it forms offshore bars, while the gentler summer swells tend to move it back on shore. The exact mechanisms involved are not well understood, but the fact that this happens is well documented[1] Many a wide summer beach disappears almost entirely in the winter to reappear the next summer.

More serious is the longshore movement of sand, called "littoral drift". This is caused by waves breaking at an angle to the beach, and moving the sand in the direction of the longshore component of the wave advance. The quantities transported can be considerable – at one California beach, the rate is estimated at 300,000 cu.yd./year southward. This is nearly a ton of sand per minute.

Man-made structures disrupt the longshore flow of sand. A single jetty, or groin, built out from the beach will trap sand on the upcoast side, while erosion is increased on the downcoast side. If many of these groins are spaced along the shore, they allow the beach to re-align itself more perpendicular to the direction of approach of the prevailing waves, thereby lessening the transport rate. A groin, however, never created a single grain of sand; you have to have a supply to begin with, and there are virtually no sources in Boston Harbor. However, littoral transport of the past has left its mark on many of the harbor islands: rocks and cliffs on the exposed sides, tapering off to gravel, sand, or mud on the sheltered sides.

The rate of movement of sand, both onshore-offshore and longshore – depends on the intensity of wave action. In protected locations, it may be possible to construct beaches and maintain them at relatively low cost. The presence of mud and other fine sediments in many of the more protected portions of the harbor, however, suggests that a nice sand beach may become contaminated with mud fairly rapidly. In more exposed locations, the waves which move the sand about also tend to keep it clean.

For example, on Long Island the present configuration of the shoreline and adjacent areas suggest that sand would move to the southwest, since most waves come from the east and northeast; on the southeastern side of the island, it would probably end up in the deep channel, while on the northeastern side, Moon Head would possibly trap some. It might be possible to reduce the transport rates sufficiently by constructing groins along the shore, but more detailed studies would be required to determine the costs involved, both for initial construction and for maintenance. The Corps of Engineers accepts responsibility for maintaining natural public beaches; whether they would do so for constructed beaches is open to question.

For a very rough initial cost estimate for beach construction, using sand with a median diameter of 1 mm and a beach slope of 1:5, with a beach 60 yd. wide (with approximately half the beach below the high tide mark), and 1 yd. thick, at $2.50/yd. for sand, gives approximately $200. per linear yard of beach.

[1] A readable and competently written book on the subject is "Waves and Beaches" by Willard Bascom, available in paperback.

II. Tides and Storm Tides

The principal datum planes and selected tide levels are related to the Boston Low Water Datum as shown in Table II. These data indicate a 1-ft. rise in sea level by the year 2020; this should be taken into account in the design of fill elevations.

The waves and storm tides basically determine the elevation to which fill must be made. Considering the highest tide of record, 15 ft. above MLW, and allowing for a 1-ft. rise in sea level and 2 feet for drainage assurance, gives a ground elevation of +18 ft. above MLW, or approximately 13 ft. above the MSL datum of the U.S.G.S. topographic maps.

Table II – Datum Planes and Tide Levels

Highest tide of record (1951)	15.0 ft.
Mean high water (1941-59)	9.8 ft.
Mean tide level (1941-59)	5.05 ft.
Projected mean tide level, year 2020	6.0 ft.
Mean sea level (U.S.G.S. Datum)	4.87 ft.
Boston low water datum	0.00 ft.
Boston City Base	–0.78 ft.
Lowest tide of record	–3.48 ft.

Along exposed portions of the shore, a higher embankment should be provided to protect against wave overtopping and flooding. More detailed information on wave statistics, proposed shoreline configurations, and suggested land uses (i.e., susceptibility to damage) is needed before estimates can be given; however, if a cost of $50. per linear foot of shoreline is used for protection for all fill areas, the variations should average out.

Structural causeways should be built to clear the highest waves expected, at the highest tide level, both to prevent damage and to assure use of the causeway during storms. For most locations, a clear elevation of 22-24 ft. above MLW to the underside of the span should suffice; for areas such as between Castle and Spectacle Islands, or Spectacle and Long Islands, however, this should be increased to 28-30 ft. Filled causeways similarly should not flood excessively during severe storms, unless alternate emergency access is available. With alternate routes, roadway elevations of 16-18 ft. above MLW are acceptable; without, 20-24 ft. should be used. Both figures should be increased by 5 ft in exposed locations such as those mentioned above. Filled causeways require the same protection from erosion as other fill areas.

III. Harbor Currents

Harbor currents under present conditions are given in the U.S.C. & G.S. publication "Tidal Current Charts – Boston Harbor". An examination of these charts, in conjunction with the navigation charts, gives a good indication of the principal flows in the harbor.

The three constraints posed by tidal currents are as follows:

a. Closing off channels carrying significant volumes of water will tend to increase velocities in other channels providing water to the same basins. These increased velocities can be calculated from the current charts and navigation charts by assuming that the same volume of water still enters and leaves the basin with the tides. Currents in excess of 3 knots (5 ft./sec.) are considered hazardous to small craft.

b. In constructing enclosed basins for marinas, the surface area of the basin and the tide range indicate the required entrance cross-section, both to prevent erosion of the inlet and to keep tidal velocities less than 3 knots.

Approximate values are given in the table below.

Basin Surface Area, Acres	Entrance Cross-Section Below Mid-Tide Level, ft.^{2}
3	60
10	200
30	500
100	1,400
300	4,000
1,000	10,000

The flow velocities here range from 1.5 to 3 ft./sec. in the inlet.

c. Tidal flows must be adequate to prevent the concentration of pollutants, and to nourish shellfish.

Since it is anticipated that most transportation links between islands would be pile-supported causeways, which do not impede tidal currents, no significant changes in tidal flows are foreseen. Three possible fill causeway links – Squantum-Thompson Island, Thompson-Spectacle Island, and Moon Head-Long Island – would not close off channels transporting significant volumes of water. Thus closing any two of these gaps would not be likely to have any serious consequences. One of the three should be left open to assure flushing of the enclosed shallow zone.

Conclusion

The above data and estimates are intended to indicate some of the engineering restrictions on harbor development that should be considered in the early planning stages. They are, of necessity, very general. As the planning process proceeds to the consideration of specific, detailed projects, competent engineering would be required to define the specific requirements and associated costs for each proposal.