Floating Breakwaters for Small Craft Facilities

Floating breakwaters represent a viable alternative for wave protection. The selection of the type of floating breakwater, and its design, depend heavily on site conditions and ultimate application.

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WHILE THE CONCEPT of floating breakwaters (FBWs) is not new, their use is not very widespread. However, the demand for increased berthing space primarily for recreational small craft has stirred interest in the use of FBWs for wave protection. More exposed locations are being considered for marinas and small craft facilities, posing significant problems in providing suitable wave protection. Current environmental regulatory policies and issues have made FBWs a more attractive option to the conventional rubble mound or fixed barrier type of breakwaters because they have minimal impact on water circulation and the marine or lacustrine habitat. Since FBWs are transportable, they can be removed or relocated if necessary. This mobility also means that FBWs are adaptable to prefabrication and off-site construction. A FBW is often less expensive to construct than a conventional breakwater, especially in deep water. However, a direct cost comparison is difficult to make, since an FBW does not offer the same degree of wave protection as a rubble mound breakwater, for example, and maintenance costs are typically greater.

Floating breakwaters reduce incident wave heights (their lengths and periods remain unchanged) by converting wave energy via reflection, absorption and dissipation through turbulence created by inducing breaking and by friction. FBWs do not stop all wave action, but rather reduce wave heights to acceptable levels under certain specified conditions. FBWs become impractical for small craft applications when the incident wave period exceeds approximately four seconds. With the exception of severe storms, such short period waves usually occur in relatively shallow protected bays or lakes, where the *fetch* (the uninterrupted distance over which waves can develop) does not exceed two to three miles and perhaps up to five miles under certain circumstances. FBWs are essentially wave transparent to longer period ocean swells and seiche motions. In addition, the applicability of an FBW depends on:

- the degree of exposure,
- variation in water depth and intervening

islands over the fetch,

- tide range and currents,
- ice conditions,
- the annual/seasonal wave climate,
- frequency and severity of storms, and
- the degree of protection required.

Usually wave heights of less than one foot should be maintained within marinas. For fishing and larger commercial vessels, greater transmitted wave heights may be allowable.

Several sources, including the proceedings of two specialty conferences on FBWs, describe the current knowledge on FBWs.[1,2,3,4] However, much of the considerable body of literature on FBWs is highly theoretical or describes only a particular installation. Very little information is oriented toward the general FBW design problem and, in specific, on the design and application of FBWs to wave protection for small craft (*i.e.,* yachts and commercial vessels generally under 50 to 60 feet length). Engineering investigations for design should properly include site-specific wave measurements and/or numerical models to determine the wave climate as well as physical and/or numerical modeling to verify FBW wave transmission characteristics and mooring loads. However, the designer is most often forced to proceed without the benefit of such information due to the high costs involved in securing that data.

One alternative type of FBW, floating tire breakwaters, have received a great deal of attention, especially during the 1970s. This attention was presumably due to their low cost and ease of construction, and that they provided a way to dispose of a plentiful and durable waste material. Floating tire breakwaters consist of bundles of scrap tires bound together in various arrangements. Design guidelines exist for floating tire breakwaters,[5,6] and there is a considerable body of literature on their practical application.[7] However, they have a relatively low effectiveness, are prone to break-ups, and are considered unsightly by many.

Wave Climate & Design Criteria

The feasibility of employing an FBW at a given site must be established after a preliminary assessment of the local wave climate has been made and the relative merits of alternative wave protection, or even no protection, have been compared. Such a comparison should include the relative total cost and cost/benefit; *e.g.,* the cost per marina slip, construction costs, maintenance and life cycle costs, regulatory and licensing status in light of relative environmental impacts, and the degree of protection that will be required and afforded by a given breakwater type. The various design parameters for each alternative form a feedback loop in the evaluation process. Figure 1 summarizes some of the key aspects in the FBW design process.

The single most important step in the design process is the evaluation of the local wave climate. In general, wind-generated waves and, at some locations, vessel wakes will be controlling factors in the FBW's design requirements. For this evaluation, records of actual wave measurements are desirable. However, the wave climate is most often "hindcast" from wind records used with nautical charts to determine the water depths along the fetch, F_e, the distance over which the wind blows uninterrupted from a given direction. Preliminary estimates of wave heights, H, and periods, T, can then be made for a given wind speed and duration using methods provided by the U.S. Army Corps of Engineers' *Shore Protection Manual,* Vincent and Lockhart, and Grosskopf and Vincent.[8,9,10] If sufficient data is available, then annual and monthly (or seasonal) histograms of wave height can be prepared. Also, a long-term probability distribution of the maximum expected wave conditions should be prepared that is based on the frequency and duration of storm conditions for winds from a given direction.

Because the effectiveness of an FBW is determined primarily by the length of the wave to be attenuated, it is the wave period, T, that is of prime importance, more so than the height. Wave length is related to the wave period in deep water by $L = 5.12T^2$. Deep water is commonly defined as a water depth, d, that is greater than half of the wave length ($d > L/2$). This equation for wave length can

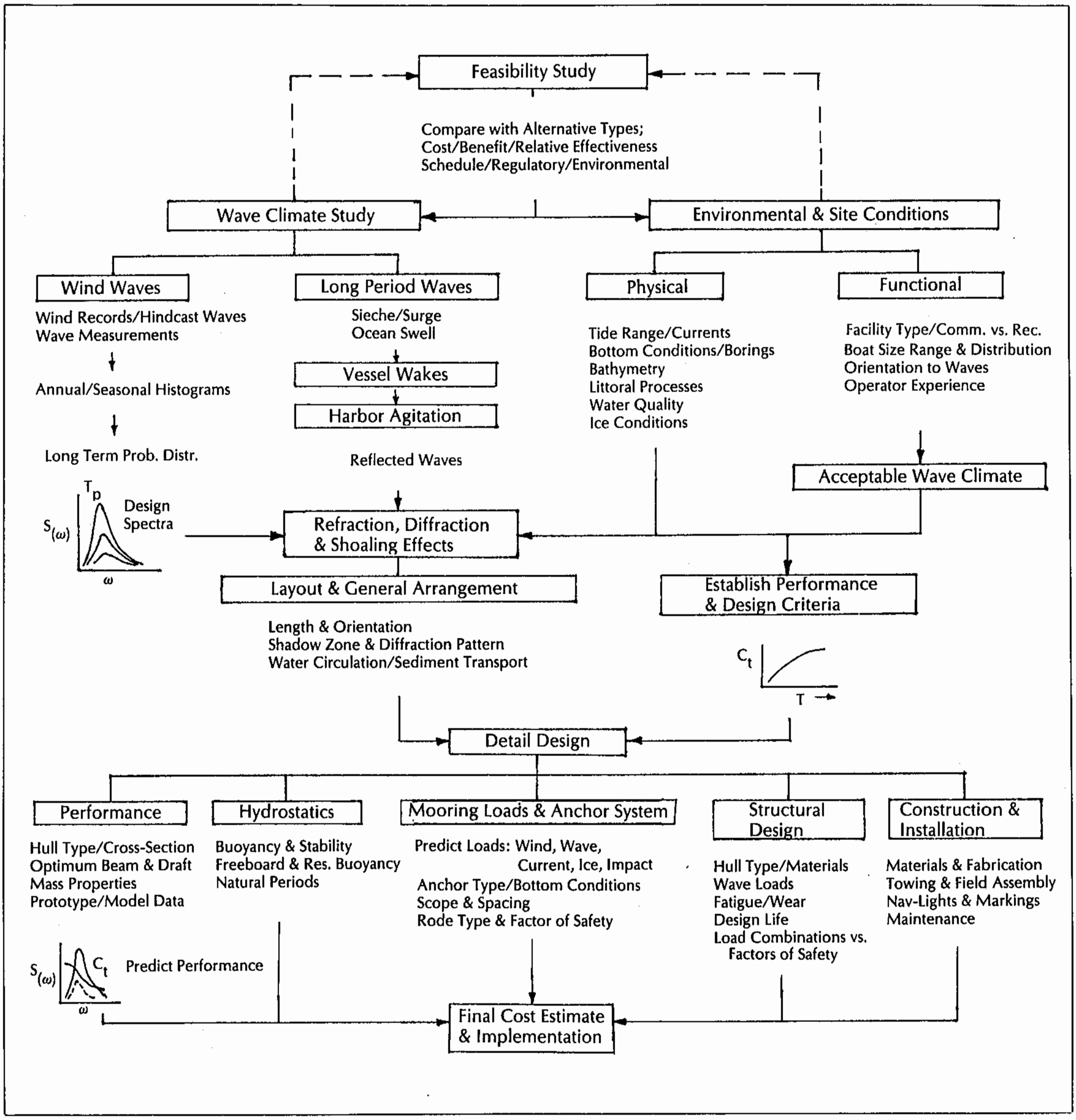

FIGURE 1. Floating breakwater design procedure summary flow chart.

be assumed to be valid for most applications since the deepwater relationships of the first order sinusoidal wave theory may be applied within transitional water depths as shallow as $d > L/5$ with a less than 10 percent error.

However, the sea surface is composed of ill-defined waves of various heights and periods. One way to make some degree of order out of such "chaos" is to characterize the sea state in terms of the wave energy present. Since the energy per unit of sea surface is proportional to the square of the individual wave heights, a sea spectrum can be described whereby the total spectral energy, $S_{(\omega)}$, can be represented as a function of the wave frequency, $f = 1/T$; or, for mathematical convenience, the circular frequency, $\omega = (2\pi)/T$. Figure 2 presents a family of spectra based on the Bretschneider spectral format.[11] Michel presents a simplified explanation of sea spectra and spectral techniques.[12] A spectral peak period, T_p, where most of the wave energy is concentrated can then be defined for a given sea state. The spectral

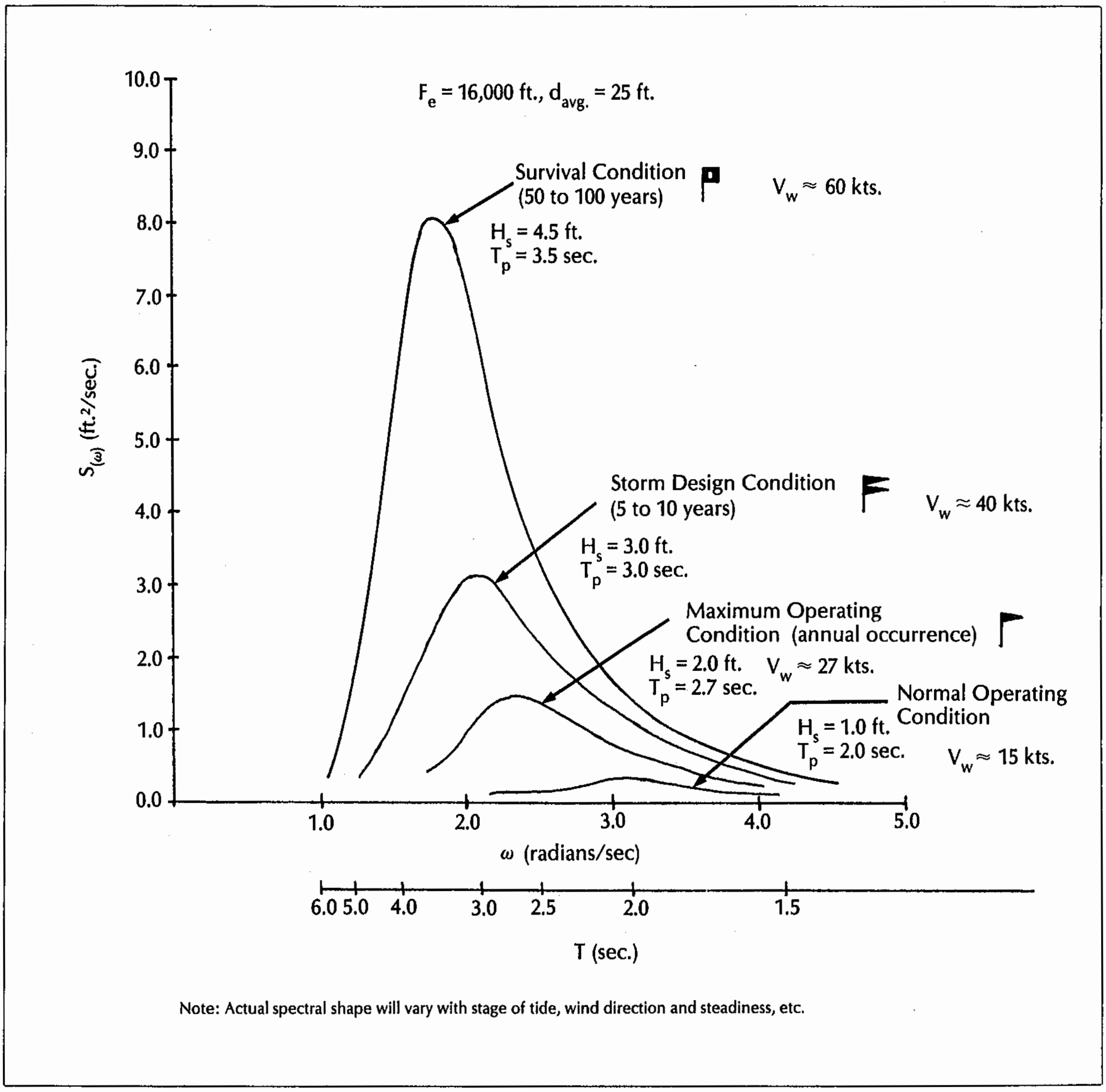

FIGURE 2. Floating breakwater design conditions — family of wave spectra for varying sea states.

peak period is also used to determine the effectiveness of a particular FBW. The family of spectra shown in Figure 2 has been developed for a specific site and assigned statistical return periods. It illustrates the shift towards the low frequency (longer period) end of the spectrum as wind speed and duration increase.

Within relatively protected bays, lakes and harbors, durations on the order of half an hour are typically required for the steady-state condition known as a fully-developed sea to exist. Waves incident upon the FBW may be modified by refraction, shoaling and diffraction effects, but the total wave climate over time at the site is otherwise completely defined by the family of spectra. In practice, the exact spectral shape will vary somewhat from the idealized format shown. However, the peak period and its height distribution can be correlated with a given wind speed associated with a particular statistical return period. The significant wave height, H_s, is defined as the average of the highest one-third in a particular sample. The maximum wave height that may be obtained approaches

2 * H_s, and the highest 10 percent ($H_{1/10}$) are approximately 1.3 * H_s. A general description of wave statistics and other aspects of the marine environment are provided in an earlier work.[13] Wave steepness, H/L, may have an important effect on FBW performance. In protected, relatively shallow water, wave steepnesses are typically within the range of $1/9 \leq H/L \leq 1/17$. Waves theoretically break when they reach a maximum steepness of 1/7 and when they enter water of depth $d \leq 1.3 * H$.

The wind wave climate may also be affected by the tide range and the presence of currents. Sites exposed to long period waves, such as ocean swells and harmonic oscillations known as seiche or harbor surging, will be likely to be found unsuitable, since FBWs are essentially wave transparent at longer wave lengths. Furthermore, an FBW may develop its own harmonic motions within the usual range of ocean swell periods. Enclosed basins, especially those with relatively steep and smooth sides may be subject to further wave agitation due to reflected waves from the basin sides. The placement of a breakwater can actually increase wave agitation under certain circumstances, such as in the case of "trapped" boat wakes, which should be considered in the original planning and siting of an installation.

Waves caused by vessels are dependent on vessel speed, draft and water depth, and their heights tend to diminish rapidly with distance from the sailing line. For yachts and harbor craft travelling at less than 10 knots, wave lengths will typically be less than 40 feet, and heights will be less than approximately 2.5 feet at 100 feet or more from the sailing line.[14,15]

Once the wave climate has been defined and other environmental and site conditions determined as outlined in Figure 1, a level of acceptable wave heights within the mooring area must be determined so that FBW minimum performance criteria can be established. Since acceptable wave heights are a subjective judgment, such criteria will vary with the nature of the facility; *i.e.,* commercial *vs.* recreational, size and type of the average boat size, distribution of boat sizes, operator experience and vessel orientation to incident waves. For yachts, the consensus seems to be that wave heights should be kept below 8 inches to 1 foot most of the time and, perhaps, 1 to 1.5 feet for commercial type vessels. LeMéhauté has reviewed wave height and harbor agitation criteria for a wide range of marine facilities.[16] A study performed for the Canadian Fisheries and Ocean Department, Small Craft Harbors Branch, has developed provisional criteria for a "good" wave climate within small craft harbors that takes into account wave period, vessel orientation to waves and the frequency for exceeding a given wave height.[17] Since it is impractical to maintain a desirable minimum level of disturbance within the mooring area at all times, certain design thresholds can be defined whereby wave heights are maintained within the prescribed limits under specified conditions. Each spectral curve in Figure 2 illustrates a threshold limit for the site in question where the design conditions have been defined as follows:

Normal and Maximum Operating Condition. The FBW is effective in reducing incident wave heights, H_i, by approximately 75 and 50 percent, respectively, corresponding to sustained wind speeds of up to approximately 30 knots.

Storm Design Condition. The FBW wave attenuation is reduced to approximately 50 to 25 percent, but the structure remains fully intact corresponding to sustained wind speeds from 30 to 45 knots.

Survival Condition. Wave attenuation is less than 20± percent, and minor structural damage may occur although the hull and moorings remain intact. This condition corresponds to a 50- to 100-year storm event during which vessels should be removed from the site if possible.

Figure 3 illustrates the required FBW performance characteristics under the conditions cited above for a proposed FBW design. The transmission coefficient, C_t, is defined as the ratio of the transmitted wave height to the incident wave height, or $C_t = H_t/H_i$.

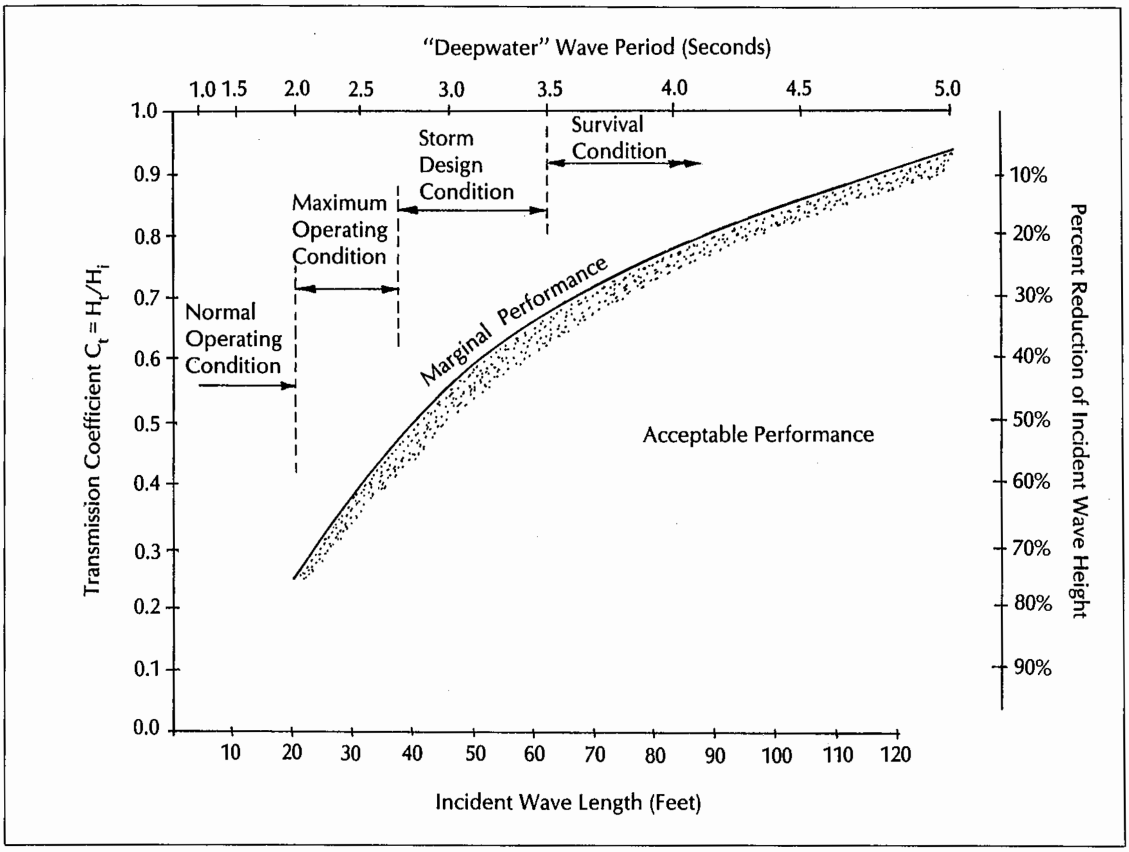

FIGURE 3. Minimum required wave attenuation performance for design conditions.

Design Considerations

The analytical treatment of the general problem (*e.g.*, wave transmission, motions and mooring forces) of a restrained floating body is a complex task. A practical solution is even more complicated by the need to properly evaluate the hydrodynamic added mass and damping coefficients that are non-linear functions of the relative water particle accelerations and velocities, respectively. Adee and Martin, and Yamamoto, *et al.*, furnish the theoretical background for evaluating motions and forces on moored floating objects.[18,19]

Figure 4 provides a definition sketch that illustrates the dimensions for a typical rectangular prism type of FBW. In addition to the incident and transmitted waves, the figure defines a reflected wave, with a height, H_r, that propagates seaward and that may form a standing wave pattern in front of the FBW. For the case of perfect reflection without other energy losses, H_i, H_t and H_r are related by $H_i^2 = H_r^2 + H_t^2$. A FBW commonly possesses three degrees of rotational freedom — termed roll, pitch and yaw — and three degrees of translational freedom — termed heave, surge and sway. Of these motions, heave (the vertical rise and fall), roll (rotation about the longitudinal axis) and sway (translation in the direction of wave advance) are critical to FBW performance. In particular, sway motion has the greatest effect on wave transmission and is restrained by the horizontal force component of the mooring line. Gravity is a restoring force for heave and roll. Therefore, both heave and roll exhibit free natural periods that are affected only slightly by mooring restraint.

Under most conditions, the more rigidly fixed and steady the FBW remains under wave excitation, the greater the wave attenuation will be and the higher the mooring loads will be. FBWs may be moored rigidly to piles or

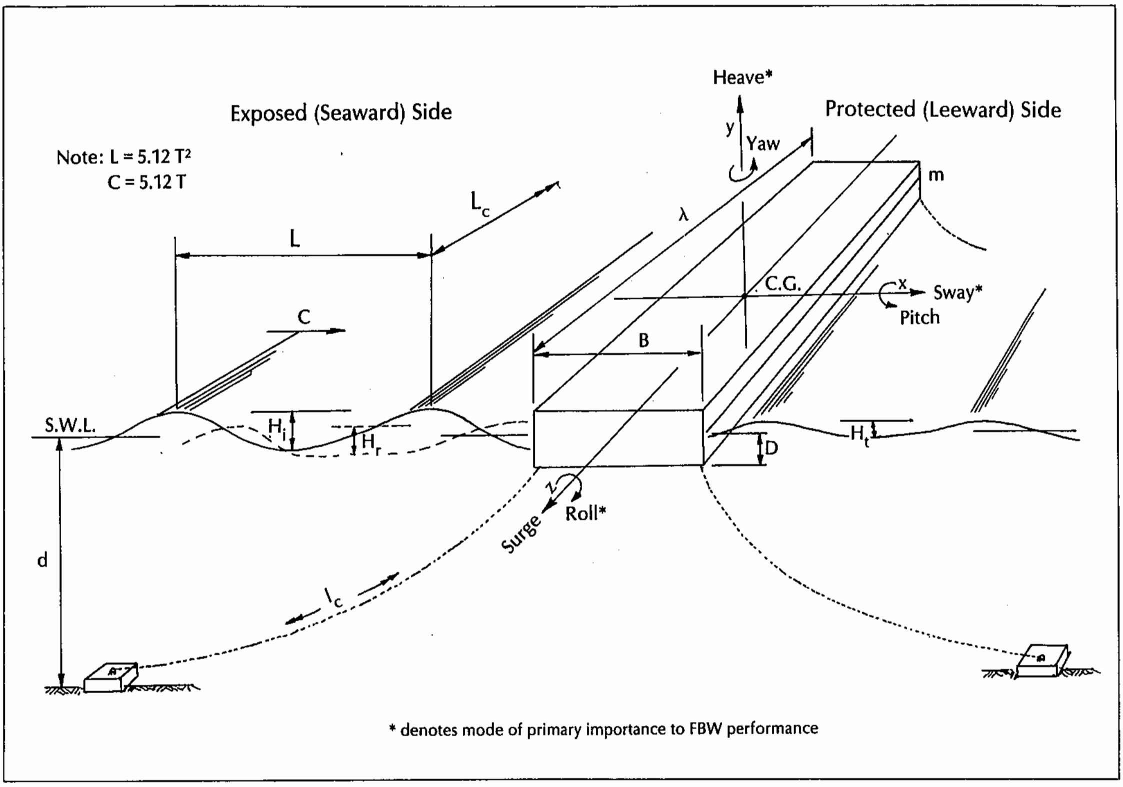

FIGURE 4. A floating breakwater definition sketch.

dolphin clusters, or spread-moored with chain, cable or rope mooring lines to fixed bottom anchors. Pile anchor systems require suitable bottom conditions and are subject to high mooring loads, slamming and wear, and therefore are employed less often than spread moorings.

The selection of the hull type, or cross-sectional shape, for an FBW is important from a cost and construction perspective. Three basic hull types are:

- the solid rectangular prism, as represented by a barge
- the catamaran hull consisting of two parallel rows of pontoons or floats interconnected by a cross-structure (the caisson type is considered to be a special case of catamaran since its two pontoons are cross-connected by a cross-float that forms rectangular cells in plan view)
- the raft type of FBW consisting of independent hulls or pontoons moored lengthwise to the direction of the wave attack and loosely interconnected with cables or chains and having a gap width between hull units approximately equal to the hull width

The first two types are predominantly vertical wall sided reflecting FBWs that reduce incident wave energy primarily by reflecting them back seaward. The raft FBW dissipates wave energy by inducing wave breaking and creating turbulence. It reflects a only small amount of incident wave energy back seaward.

FBW Performance

Predicting FBW wave attenuation performance under prescribed conditions is the central focus of design. Due to the many interacting factors, model test and prototype data cannot necessarily be scaled or extrapolated to a specific case with a high degree of reliability. Limited prototype data exists for catamarans[20] and for prism[21] hulls. Model tests have been carried out on a wide variety of hull types,

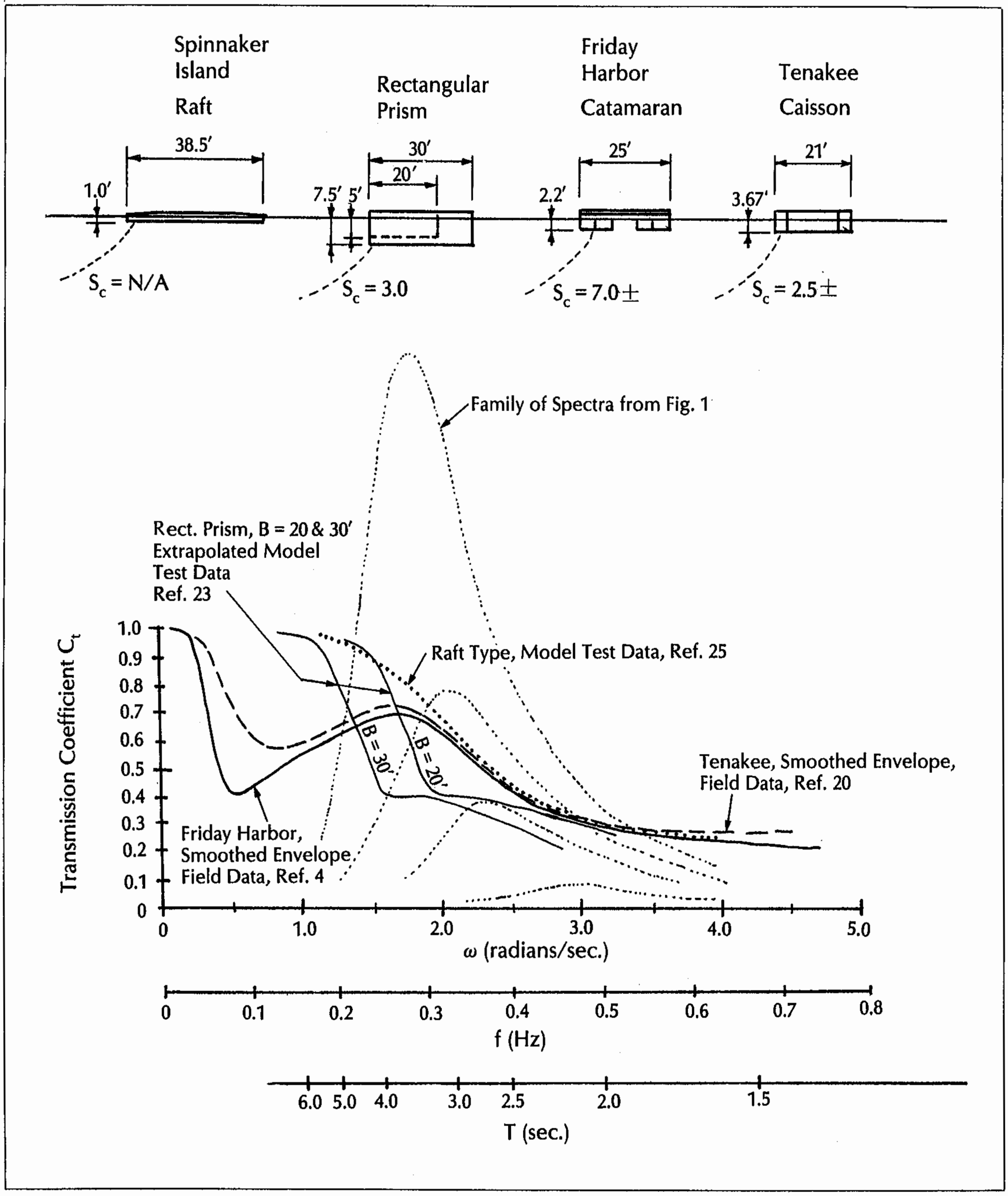

FIGURE 5. Comparison of wave transmission coefficient data for selected floating breakwaters.

but most commonly on prismatic cross-sections.[22,23,24]

Figure 5 presents a comparison of the transmission coefficient from selected model and prototype data. Direct comparisons cannot be made between hull types due to differences in mass, mass moment of inertia, materials of construction, anchor system characteristics, *etc.* C_t is plotted as a function of circular frequency, ω, with the family of design spectra from Figure 2 as background for comparison purposes. The relation of the spectral peak to the value of C_t at that frequency largely determines the effectiveness

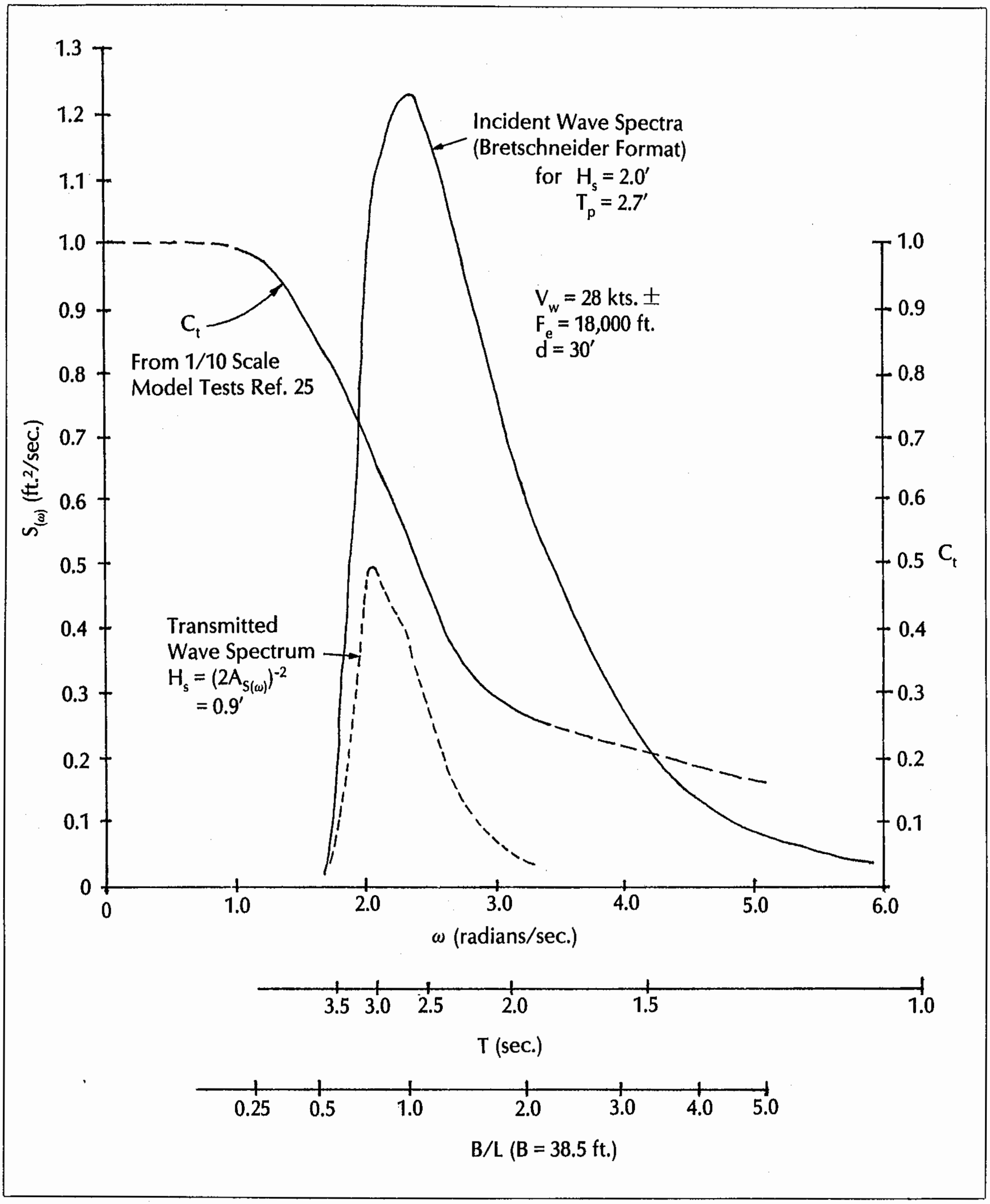

FIGURE 6. Incident and transmitted wave spectra for a raft type floating breakwater.

of the FBW.

An example of the spectral analysis technique is illustrated in Figure 6 for a raft FBW. The transmitted wave spectrum is produced by multiplying each ordinate of the incident wave spectra by the square of C_t. The root mean square of the wave height is obtained by taking the square root of the area under the curve, $A_{S(\omega)}$, and the significant wave height is determined by $H_s = (2A_{S(\omega)})^{-2}$. For the sea condition for the example shown in Figure 6, the raft has reduced the incident significant

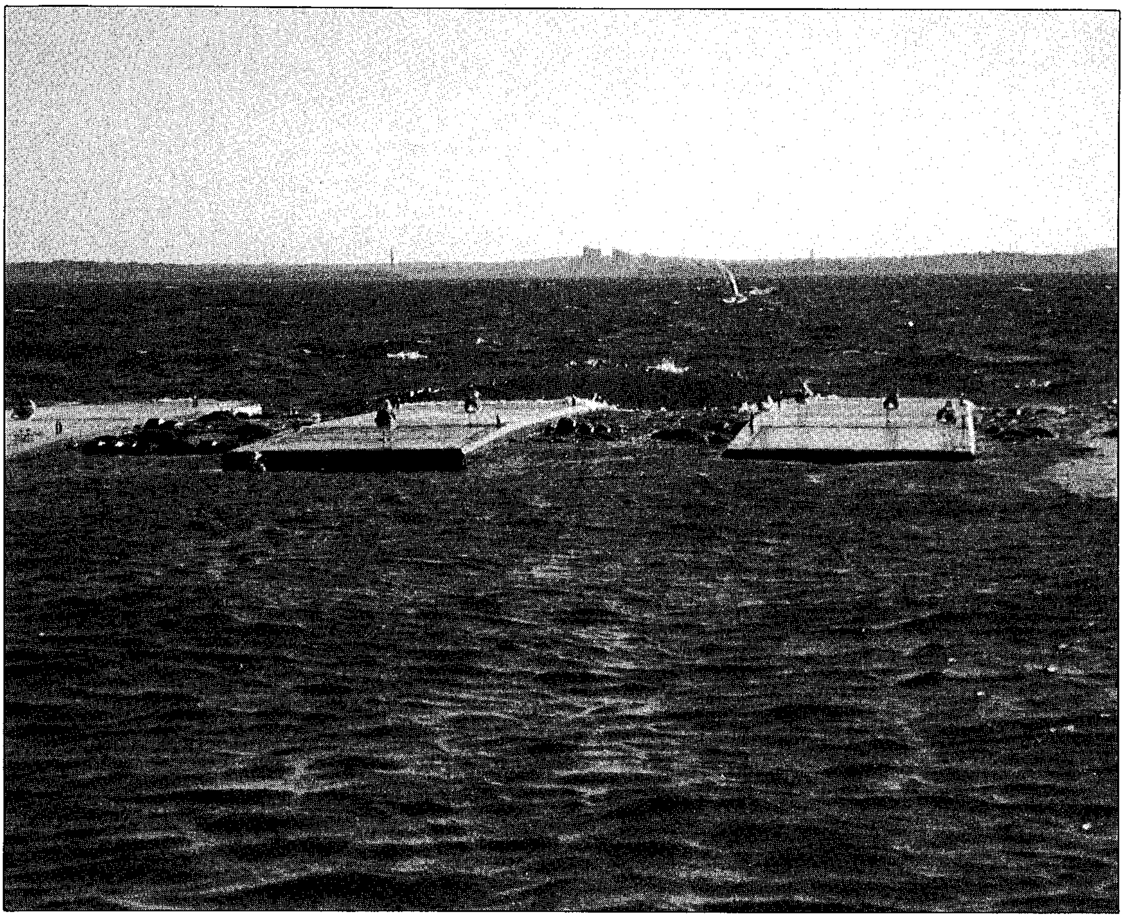

FIGURE 7. A raft type floating breakwater in action at Spinnaker Island Marina, Hull Bay, Massachusetts. Hull units are precast concrete with rigid foam floatation. Units are interconnected with chains. Tires serve as buffers and increase energy dissipation between units. (Photo by Eric Foote, Sandcastle Associates.)

wave height by better than 50 percent. Figure 7 shows such a FBW in action at Spinnaker Island in Hull Bay, Massachusetts.

Transmission coefficient data is often presented in terms of the breakwater width or beam, B, to wave length ratio, or B/L. This scale has been added to Figure 6 for the FBW shown in Figure 7, which illustrates the comparatively good performance of this FBW for $B/L \geq 1.0\pm$, and which diminishes rapidly as the wave length increases.

Figure 5 also indicates that a catamaran or prism (reflecting) FBW requires only approximately one-half of the width of a raft FBW to provide the same degree of wave protection. Reflecting FBWs are typically effective up to $B/L = 0.5\pm$, and are of little use beyond $B/L = 0.2$. The curves for the Friday Harbor, Washington, and Tenakee, Alaska, FBWs were smoothed from data presented by Adee, and Adee, Richey and Christensen.[4,20] These FBWs have proven to be among the most successful of permanent FBW installations. The Friday Harbor FBW was constructed of continuous timber decking and cross-structure on polyolefin floats. The Tenakee FBW consists of rigid foam-filled concrete units post-tensioned together to form modular cells. The raft type curve shown in Figure 5 is based on model test data at 1:10 scale.[25] The curves for the rectangular prism have been scaled from Isaacson and Fraser for two different widths to illustrate the effects of increasing B for a given FBW type.[23] The curve for the wider FBW indicates that it will provide greater protection under the survival storm condition. For most conditions, B/L is the key parameter in predicting FBW performance.

The transmission coefficient is also a function of other important non-dimensional parameters that must be considered in evaluating model test results; *i.e.*, $C_t = f(B/L, H/L, d/D, B/D, B/\lambda)$ for the case of a freely floating body. The effects of the mooring line restraint in terms of anchor scope, $S_c = l_c/d$, mooring spring constant, k, and relative density must also be considered.[23,24] Of these non-dimensional parameters, wave steepness, H/L, water depth to draft ratio, d/D, and the degree of mooring restraint are generally the most important. Increasing wave steepness and mooring tautness typically decrease the value of C_t. To maximize FBW effectiveness, the minimum length of the FBW, λ, should be at least 3 to 5 times the maximum wave length that must be attenuated, depending on the width of shadow zone (protected area inside of the FBW) required and the end boundary conditions. End boundary conditions refer to whether waves are free to pass around either end of the FBW, or whether one end connects with the shoreline or other structure, or tails off into shallow water.

Buoyancy & Stability

The FBW hull must possess sufficient reserve buoyancy to support the weight of its mooring chains at high water (including the downward component of the mooring force), plus additional weight from fouling growth, possible water absorption by concrete, wood or flotation materials, ice, navigation lights and appurtenances, *etc.*, and remain stable under the moving weight of inspection personnel. Excess freeboard (the height of the hull above the water line), except as otherwise required for visibility and reducing wave overtopping, is discouraged, since it may increase heave and roll motions as well as wind and wave exposure. Minimum trim and list requirements will vary with the structural type.

Basic hydrostatic data to be calculated for hull units include displacement (Δ = total weight of the FBW unit), center of gravity and buoyancy, moment to trim one inch and pounds per inch immersion from which the metacentric height can be calculated, which in turn can be used to calculate the free natural periods of heave and roll in accordance with standard naval architecture texts. Hulls, pontoons and buoyancy chambers should have floodable spaces, except those areas intended for ballast, filled with a rigid (closed-cell foam) buoyancy material. The overall mass density of the FBW structure should be as high as possible to minimize motion response.

Mooring Loads & Anchor System

The evaluation of mooring forces is a key, complicated aspect of FBW design. As a matter of practical design, upper bound values of the maximum horizontal mooring force must be estimated. The mean value of mooring force for a given sea condition should also be considered so that appropriate factors of safety can be applied to the mooring hardware. According to Dean and Harleman, the maximum horizontal force on a moored object in oscillatory waves can be characterized by $F_{Hmax} = [(\gamma HD)/2] * C_F$.[26] The mooring force coefficient, C_F, is a function of wave frequency and the object's geometry: $C_F = f(B/L, H/L, d/D, B/D, l_c/d, k)$.

If F_H can be properly described as a function of wave frequency, or B/L, then a spectral analysis of the wave forces can be performed, as illustrated in Figure 8 which presents a hypothetical example for a rectangular prism FBW. The response amplitude operator, or transfer function curve, was smoothed and normalized from averaged test data in periodic waves (as presented by Yamamoto), and indicates a peak spectral response at approximately $B/L = 0.20\pm$.[24] The value of F/H_i was adjusted after a comparison with other data.

Since real waves are short-crested (*i.e.*, of finite length along their crests), the total mooring force on the FBW will be a function of wave crest length to FBW length, or L_c/λ. Tratteberg presented data showing that the maximum wave force per unit length was reduced by a factor of approximately 5 when λ/L increased from 1 to 5.[27]

Wave crest length, L_c, in deep water seldom exceeds three times the wave length

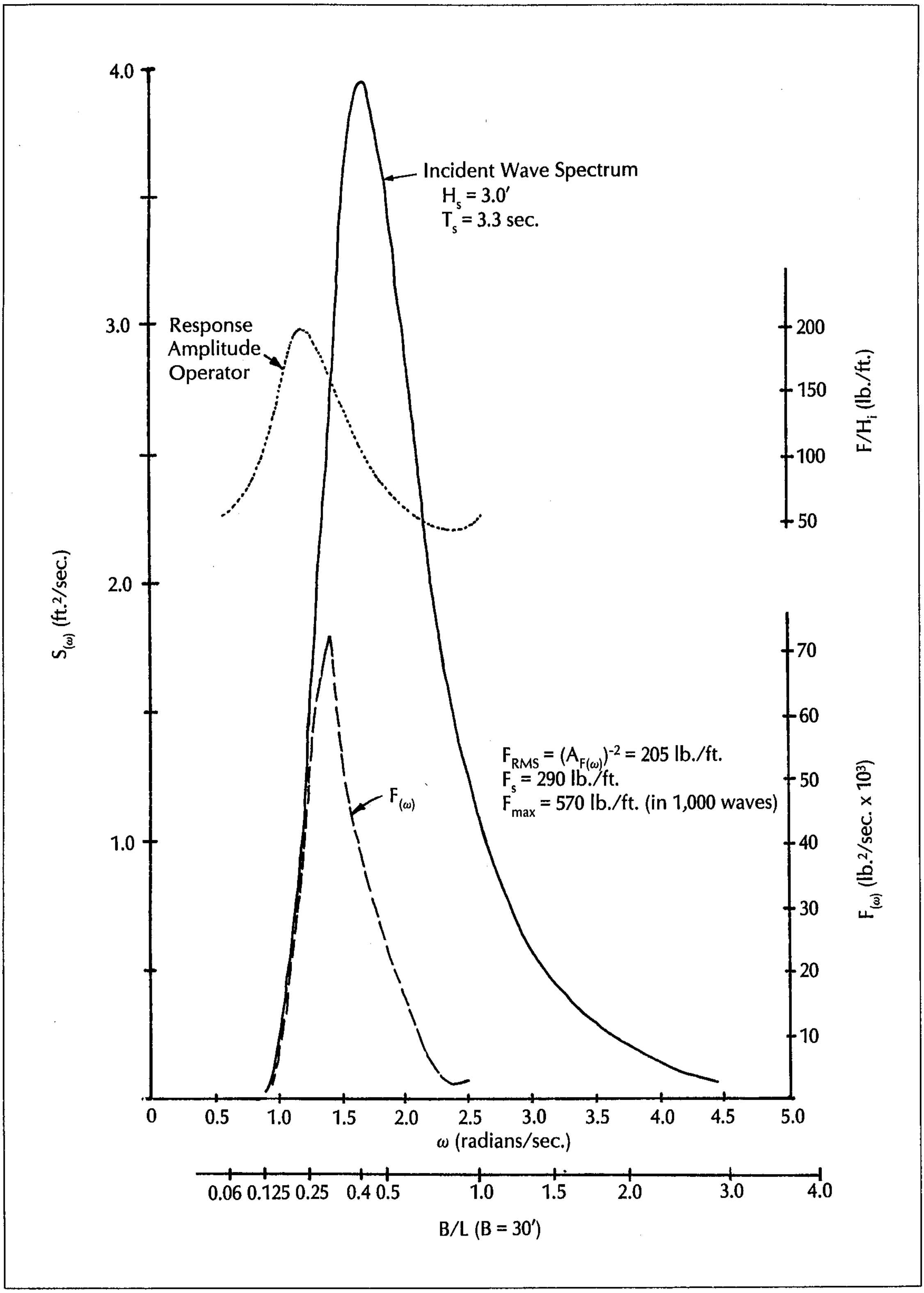

FIGURE 8. Wave force spectra for a rectangular prism — hypothetical example.

where L_c defines a trough-to-trough wave length normal to the direction of wave propagation.[28,29] Averaging H along L_c, the total force from a given wave can be roughly estimated by multiplying the force per unit length times L. At certain sites, however, refraction and shoaling effects may result in waves of greater L_c.

For solid reflecting FBWs that are relatively rigidly moored, possess a value of d/D greater than 2±, and experience waves of moderate steepness, a reasonably conservative estimate of F_H can be determined by $F_H = \gamma H_i D$. Results from this equation compare favorably with calculations based on Sainflous method for wave forces on rigid vertical walls where a truncated pressure diagram is used commensurate with D.[8,30] The total force is then estimated by $F_{HT} = \gamma H_i DL$.

Both of these equations should be applied with caution and be used for preliminary estimates and comparison purposes only. There is no exact closed form solution for wave mooring forces and these formulas are not necessarily conservative under certain conditions, such as for waves of maximum steepness, shallow water, shoaling conditions and where resonant effects are possible. The central problem in applying any such formula is determining the maximum wave height and steepness that is likely to occur. Therefore, generous factors of safety for all mooring system components is warranted.

Theoretically in an oscillatory wave, the value of F_H on the seaward moorings would be the same for the leeward moorings. However, the seaward moorings are generally more heavily loaded in proportion to the reflected wave height, H_r, except at low values of $B/L \leq 0.2\pm$, where little reflection occurs and the FBW follows the wave contour. For a raft FBW, the seaward chains will always be considerably more highly loaded than the leeward chains, while the maximum mooring forces will commonly be an order of magnitude less than those on a corresponding solid FBW. For a raft FBW, the mean wave force can be calculated in terms of the "radiation stress" associated with the excess wave momentum flux, as given by Galvin and Giles.[31] This force is proportional to H_i^2 and is similar in nature to the slow drift second order wave forces observed on larger moored vessels.[32] The wave drift force has a net resultant in the direction of wave propagation and is additive to the oscillatory wave force against solid FBWs. However, the drift force is usually quite small, on the order of approximately 5 percent of the oscillatory wave force and is of greatest consequence in relatively short steep waves.

Extreme mooring loads are theoretically possible under resonant conditions if the entire FBW were subjected to waves with a relatively long crest length at, or near, a well-defined natural period of the mooring system. Under design wave conditions, this situation is unlikely to occur. However, FBWs exposed to long ocean swells or harbor surging, even of low amplitude, could exhibit resonant motions. The natural period in sway, T_{ns}, can be roughly estimated by:

$$T_{ns} = 2\pi * (\Delta'/kg)^{-2}$$

The virtual displacement of the FBW, Δ', includes the weight of "entrained" water (hydrodynamic mass) and is on the order of 1.3 to 2.5Δ. The mooring system spring constant, k, can be considered to be a function of the mooring chain geometry, using the catenary equations where chains are used. This formula for the natural period in sway does not yield perfectly accurate results due to viscous damping and other effects, but should be able to furnish reasonable estimates for preliminary evaluations.

Figure 9 illustrates the mooring chain tension *vs.* FBW excursion, ϵ, for a particular set of seaward and leeward chains subject to an initial pretension. The value of k can be estimated from the mean slope of the net disturbing force curve within the force range of interest. Calculations for a proposed catamaran hull FBW, with similar mass properties to those at Friday Harbor and Tenakee over a range of water depths and with varying assumptions regarding the added "virtual" mass and wave force, yielded a T_{ns} within the range of 8 to 26 seconds. Ocean swells are normally within the range of 8 to 20 seconds, and even though they may be of low amplitude, the residue from these

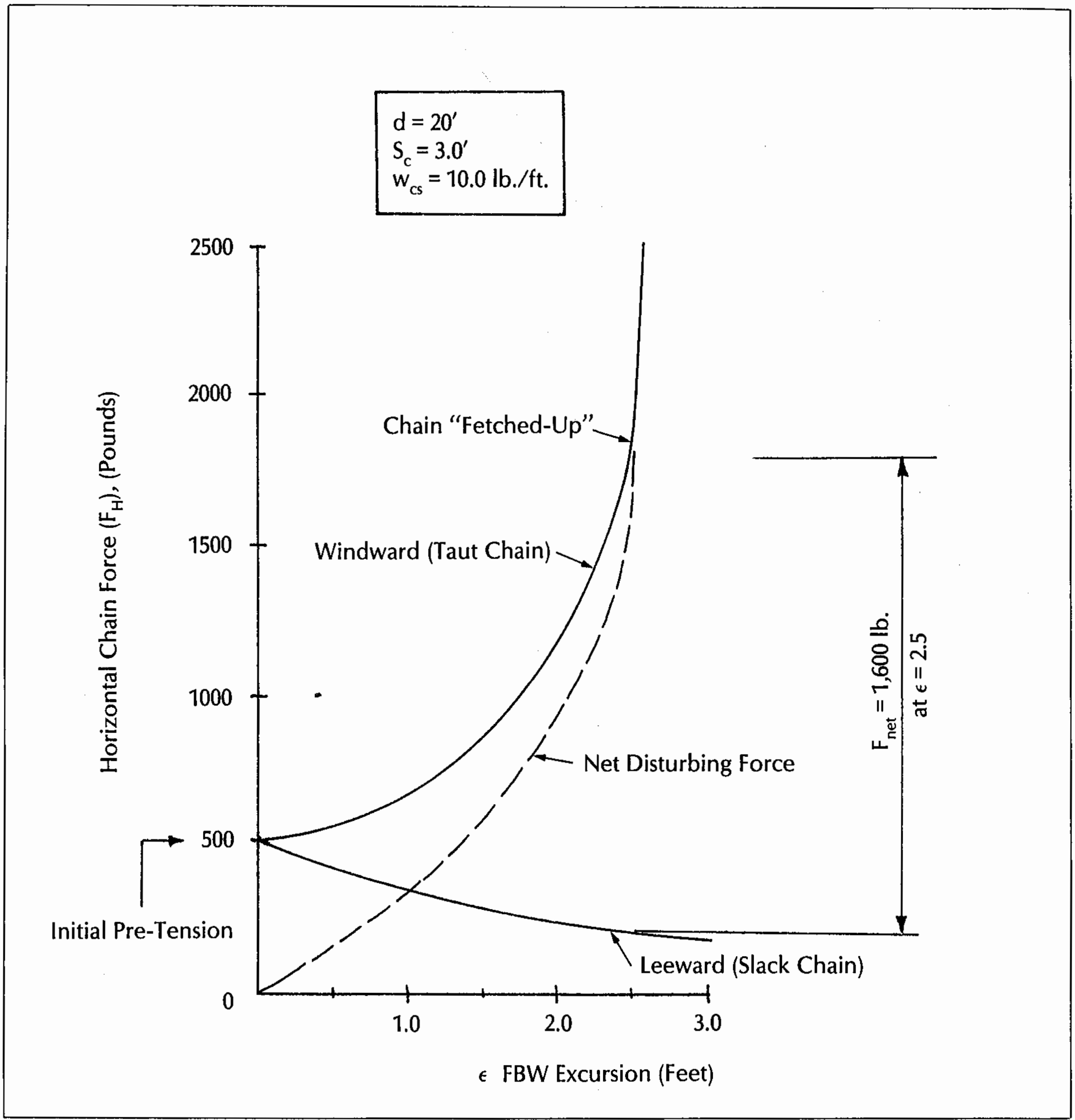

FIGURE 9. An example of horizontal chain force *versus* floating breakwater excursion.

swells within a bay or harbor may possess sufficient energy to cause harmonic swaying and, therefore, high mooring loads on a spread-moored FBW.

In addition to remaining secure under maximum mooring forces, the mooring system must keep the FBW "on station" with minimal excursions over a range of water depths, including extreme storm tide plus heave allowance. Mooring system hardware should possess a generous corrosion and wear allowance and means for adjustment and replacement. Figure 10 illustrates the cross-section of a catamaran hull FBW originally proposed for Spinnaker Island, showing the mooring system configuration. Chain lengths and anchor offset distances are dependent on the water depth at the anchor and were calculated so that all chains would "fetch up" nearly simultaneously and maintain $S_c = 3.0$ at mean high water.

Stake pile anchors driven into the bottom are preferred because of their holding power and their ability to be accurately located.

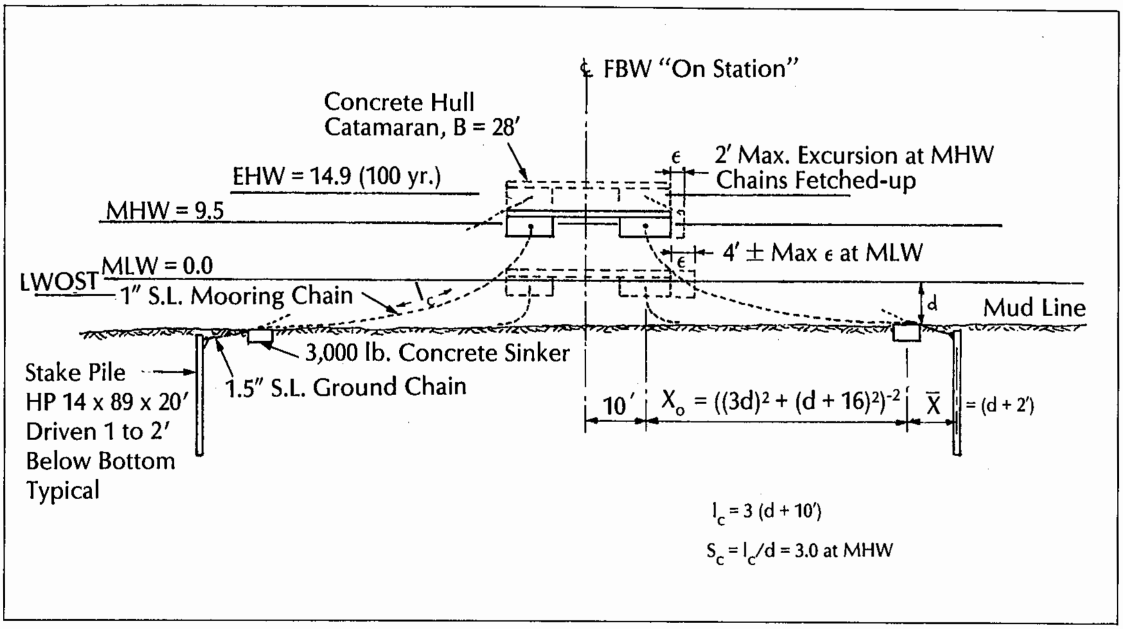

FIGURE 10. A cross-section showing the mooring system geometry for a catamaran hull floating breakwater originally proposed for Spinnaker Island, Hull Bay, Massachusetts.

Typical vessel type anchors must be dragged in order to set properly and, therefore, cannot be accurately located. Also, their holding power is highly variable with bottom conditions. Clump weights will usually be found to be the most practical and economical type of anchor for a raft FBW that has lower mooring force requirements than the solid type.

Other forces acting on the FBW mooring include wind, current, ice and impact from ice, flotsam, and inadvertent collision. Wind loads will generally be found to be small (less than 5 percent of peak wave loads) unless the FBW has a particularly high freeboard or vessels are moored to it. Dunham and Finn, and ASCE, outline methods for calculating wind loads.[34,35] Loads produced by steady currents can be calculated from the drag force equation, which for sea water and the current speed, V_c, in feet per second is reduced to $F_c = C_{cd}V_c^2A_p$, where F_c is the force in pounds and A_p is the projected area below the waterline in square feet. The value of C_{cd} is dependent on the water depth at shallow water sites and will increase on the order of 5 times its value at $d/D \geq 6$ when d/D is decreased to nearly unity.

For maximum tidal currents of less than one knot (1 knot = 1.69 ft./sec.), current loads will generally be small except for deep draft structures and low d/D. For stronger currents, loads will increase rapidly and the current velocity may have a dramatic effect on wave characteristics; *i.e.*, steepening waves in opposing directions and flattening and increasing the effective period of waves traveling in the same direction. Currents also increase the potential for trapping flotsam and ice, as well as increasing the potential for boats colliding with the FBW. For these reasons, the installation of FBWs at locations where currents regularly exceed approximately one knot should be avoided.

Ice may exert sizable loads on FBWs and may have a major influence on overall FBW design and configuration. For a spread-moored FBW frozen in solid ice, lateral forces will usually be small unless the entire ice sheet can move under the influence of wind and current shear stresses as a driving force. Figure 11 illustrates the horizontal force per unit length, F_i, of an FBW for an effective "mile of ice" driven against the FBW for varying wind and current speeds. F_i has been calculated from the drag force equations drawn from Määttänen, using shear stress coefficients

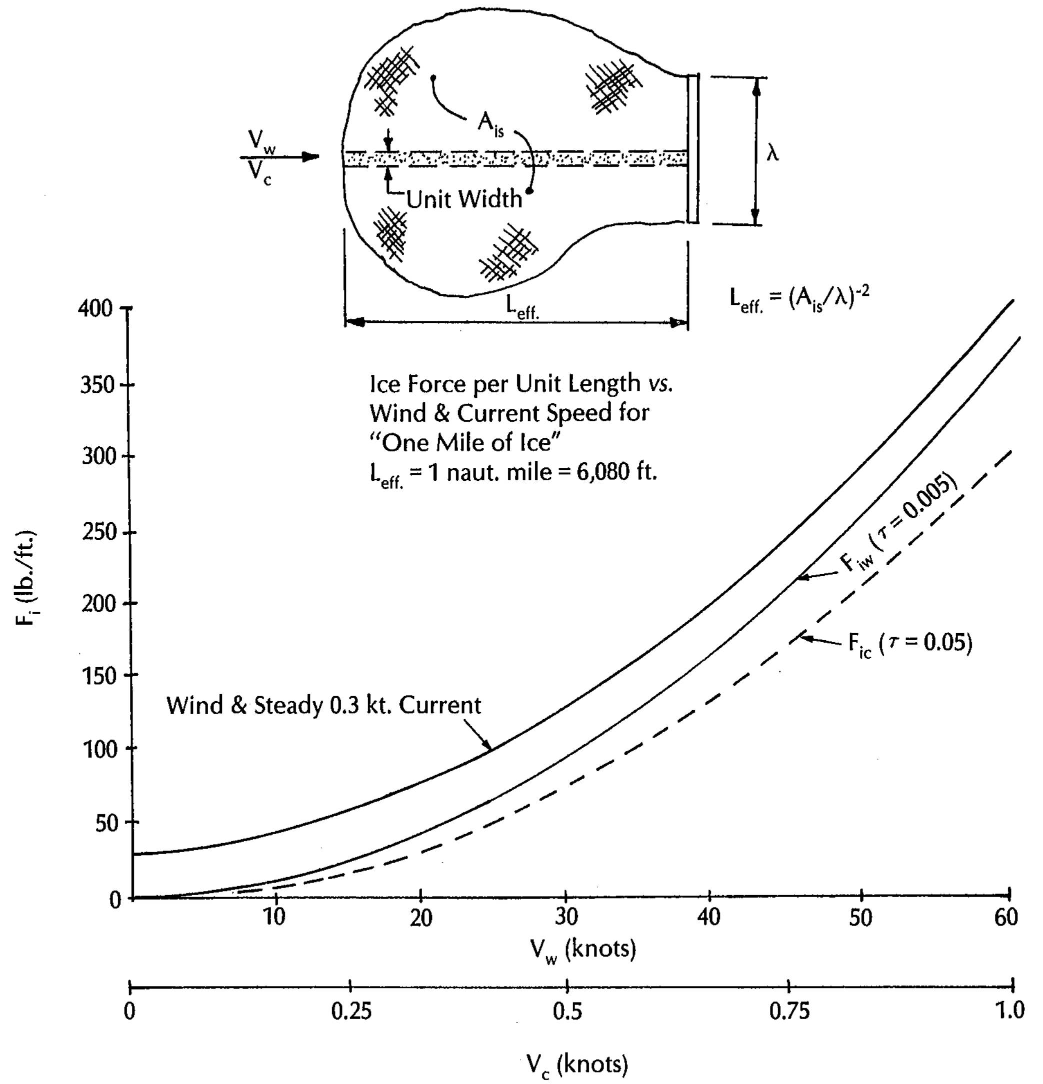

FIGURE 11. Lateral thrust of an ice sheet driven by wind and current against a solid type floating breakwater.

within the mid range.[36] The figure reveals that an ice thrust can easily be on the same order of magnitude as peak wave loads. More significantly, the ice thrust will act simultaneously across the entire length of the FBW, whereas the total wave force will act over a smaller area proportional to the incident wave length. Rigidly fixed (pile anchored) FBWs should be avoided where lateral ice movements are possible. Noble presents a useful discussion on the effects of ice on ice-bound floating objects not subject to moving ice.[37] Impact forces due to ice, flotsam or collision can be estimated by kinetic energy principles if a mass and a relative velocity can be assigned to the impacting body. The California Department of Boating and Waterways provides useful information on calculating the berthing impacts of small craft.[38]

Structural Design

Structural design for wave loadings should follow the basic principles of naval architecture. Concrete is often the material of choice for hull construction due to its durability, mass, damping and impact resistance. Gerwick provides useful design information for concrete hulls oriented toward rectangular shapes.[39] Tsinker and Lee, *et al.*, furnish additional design information.[40,41] Hutchison presents a method of analysis adaptable to microcomputer use for the distribution of mooring loads and structural stresses under short-crested seas.[42]

Connections between sections has proven to be perhaps the most problematical of structural details. Solid hulls should be constructed as long as possible, thus minimizing the number of connections and the relative amplitude response of the individual sections to wave action. In some cases, it may prove more satisfactory to provide the ends of adjoining sections with copious fendering rather than attempt a rigid connection. Where the FBW design calls for long lengths of individual sections, post-tensioning of concrete pontoons (as was employed on the Tenakee FBW)[1,2] is probably the most practical solution. For individual hull components such as pontoons, launching or handling stresses may exceed design sea loads. By comparison, the raft FBW poses minimal structural design requirements, since the individual hull units need only be designed for wave hogging and sagging moments and shears, mooring force distribution, and handling stresses.

The importance of providing ample allowance for the effects of corrosion, wear and fatigue on a FBW cannot be overemphasized. Although a nominal design life of twenty to twenty-five years can be assumed for a permanent FBW installation, it is practically impossible to provide a design that will not require periodic maintenance. The mooring system and the section connection components may need to be replaced or repaired every five to ten years. Indeed, a FBW experiences significant wear over the course of its life. For example, for a single event such as a storm of twelve hours duration with an average wave period of four seconds, the FBW structure and mooring system will typically experience over 10,000 load cycles.

Construction & Installation

Mobility and adaptability to on-site construction, and rapid and simple field assembly, should be key construction features considered in the design process. Local site conditions, accessibility and availability of suitable materials may be the determining factors along with relative costs in selecting a particular FBW type. Further consideration should be given to how easily inspection can be performed and how easily wear-prone parts can be replaced in order to reduce future maintenance requirements and costs.

The rectangular prism FBW is the most massive, even if it is constructed using more reasonably sized modules. Therefore, as a practical construction matter and unless a building basin is handy to the site, this type of FBW would be constructed by ballasting an existing barge or car float, fitting it with mooring and connection hardware, and providing it with long-term corrosion protection. The problems of finding a barge of suitable size, outfitting it, and then towing it with its attendant insurance costs, generally make this option more expensive and problematical than it would appear at first glance. Furthermore, unless properly ballasted, a barge will have high windage and low aesthetic appeal, and will experience the highest mooring loads of the alternative types.

The catamaran, or caisson, offers the advantage of modular construction. The sizes of the modules are amenable to on-site construction, are easily transported over land or water, and can be field assembled without undue difficulty. Their greatest design problem is in their structural connection details. They are effective attenuators and derive the maximum mass moment of inertia per unit displacement.

As a solution to the general problem of field assembly, portability and flexibility of adding or deleting units to vary the overall length, the raft represents an optimum solution. Connection problems have been solved by eliminating the need for direct connection. Mooring forces are commonly low, thus reducing anchor system requirements. A raft FBW has the further advantage of permitting flexibility for the breakwater's overall configuration. For example, a raft FBW can be curved in plan dimension to maximize sheltering characteristics. The primary disadvantage of this type, however, is its lower effectiveness than the reflecting, solid FBWs. Although this diminished effectiveness can be compensated by constructing wider units, this extra width may encroach on otherwise usable berthing space or channel lines. In addition, individual raft units may be subject to harmonic pitching motions under certain conditions, thus further reducing their overall effectiveness. However, for most applications, a raft FBW will hold a cost advantage, which will likely diminish somewhat with increasingly severe exposures (*i.e.,* longer waves to be attenuated).

The actual cost at a given site will vary with such factors as design wave conditions, water depth, bottom conditions, site accessibility and materials availability. The cost of the barge solution would depend on the availability, and condition, of a barge. Navigation aids such as lights, day marks and radar reflectors will likely be required and must be approved by the U.S. Coast Guard and the local harbor master. Proscriptive and warning signs should also be considered as local conditions warrant.

Summary

Floating breakwaters may provide limited, but sufficient, wave protection for small craft facilities subject to short period wind waves. They may provide an economical and environmentally acceptable alternative to traditional bottom-supported structures. Since their overall behavior, and mooring and structural loads, are not well understood, their application should be approached with caution. For installations that will be considered to be permanent, the problem of long-term maintenance must be given substantial consideration.

The evaluation of wave transmission characteristics and mooring loads form the central focus of the design problem. For relatively shallow lakes, bays and harbors with wave fetch exposures generally under three or four miles, a solid prism or catamaran/caisson FBW with a 20- to 30-foot beam, or a rigid raft with a 35- to 50-foot beam, will be required to achieve suitable wave attenuation. Ultimately, the acceptability of FBWs depends on the level of wave action maintained within the "protected" area and how this "protection" is perceived by the end users.

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The following symbols are used in this article:

A_{is} = Area of ice sheet
A_p = Projected area of FBW below the waterline normal to flow
$A_{S(\omega)}$ = Area under spectral density curve
B = Beam, or width of the floating breakwater
C = Wave celerity
C_{cd} = Coefficient of current drag
C_F = Wave force coefficient
C_t = Wave transmission coefficient, or H_t/H_i
C.G. = Center of gravity
d = Water depth
d_{avg} = Average water depth
D = Draft, or depth of floating breakwater below water
EHW = Extreme high water
f = Wave frequency, or 1/T
F = Force
F_c = Current force
F_e = Fetch length
F_H = Horizontal component of wave force
F_{Hmax} = Maximum value of horizontal component of wave force
F_{Hnet} = Net horizontal component of mooring chain force
F_{HT} = Total mooring force
F_i = Ice force
F_{ic} = Ice force due to current shear stress
F_{iw} = Ice force due to wind shear stress
F_{RMS} = Root mean square value of force
F_{max} = Maximum value of a given force
$F_{(\omega)}$ = Wave spectral force density function
g = Acceleration of gravity, 32 ft./sec.^{2}
H = Wave height
H_i = Incident wave height
H_r = Reflected wave height
H_s = Significant wave height
H_t = Transmitted wave height
k = Mooring force spring constant
l_c = Length of mooring cable
L = Wave length
L_c = Wave crest length
L_{eff} = Effective length of ice sheet per unit width
LWOST = Low water on spring tide
MHW = Mean high water
MLW = Mean low water
S_c = Scope of mooring line, or l_c/d
$S_{(\omega)}$ = Spectral energy density function
S.W.L. = Still water level
T = Wave period
T_n = Natural period
T_{ns} = Natural period of mooring system in sway motion
T_p = Spectral peak period
T_s = Significant wave period
V = Velocity
V_c = Current velocity
V_w = Wind velocity
w_{cs} = Submerged weight of chain per unit length
X = Distance sinker to stake pile anchor
X_o = Anchor offset distance
γ = Unit weight, 64 lbs./ft.^{3} for seawater
Δ = Displacement
Δ' = Virtual displacement
ϵ = FBW excursion
λ = Length of floating breakwater
τ = Shear stress factor
ω = Circular frequency, or $(2\pi)/T$