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SLOPING FLOAT BREAKWATER: INTERIM DATA SUMMARY.(U)
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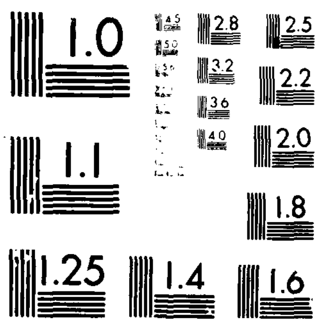

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CONVERSION OF UNITS

1 foot (ft)	=	0.3048 meter
1 nautical mile	=	1,853 meters
1 knot (kt)	=	0.5147 m/sec
1 pound (lb)	=	4.448 Newtons
1 kip	=	4,448 Newtons
1 lb/ft^2 (psf)	=	47.88 N/m^2
1 long ton	=	1,016.1 kg

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The sloping float breakwater consists of a row of bargelike pontoons moored so that, at rest, the shoreward ends, which are ballasted, rest on the seafloor while the seaward ends, which are buoyant, project slightly above the water surface. Ammi barges and NL pontoon structures have been proposed as breakwater modules.

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CONTENTS

INTRODUCTION

This Technical Note summarizes data from previous reports (Refs 1-5) on the sloping float breakwater.* (The most recent of these reports is dated November, 1978.) This concept for a floating (actually, semi-floating) breakwater has application as a transportable breakwater, particularly when the requirements include (1) transport by ship, (2) a reasonably high level of effectiveness for ocean waves with dominant periods up to at least 7 seconds, and (3) installation in relatively shallow water (coastal waters). The sloping float breakwater has also been called the inclined pontoon breakwater.

The Navy has a potential requirement for a ship-transportable breakwater as an adjunct to the Container Off-Loading and Transfer System (COTS) being developed by the Naval Facilities Engineering Command. With this system, a containership moored in an exposed location (outside a harbor) could be expeditiously off-loaded and the cargo transferred ashore. Breakwaters for sheltering elements of the system would be located in depths of water ranging from 20 feet to 60 feet or more. In particular, sloping float breakwaters are being considered for protecting small, moored craft (e.g., lighters, barges, work platforms); for some of these craft, waves with periods as small as 2 or 3 seconds can be troublesome.

The sloping float concept was proposed by LT D. A. Patrick, CEC, USN, who obtained data on wave transmission in wave-tank tests at the University of California in 1951 (Ref 1). This research was supported by the Office of Naval Research and the Bureau of Ships. In Patrick's tests, the float represented an NL pontoon structure 175 feet long – the longest standard pontoon string – located in water depths of 30 feet, 45 feet, and 60 feet. The float was not an exact model, and the effects on

*The body of this Technical Note contains previously reported data, exclusively. Just prior to printing, an appendix was added to present some new data - specifically, a revised cost estimate and some data on the effect of a breakwater on container throughput at an elevated causeway.

performance of various properties of the float and the mooring were not fully investigated; therefore, the data on performance were regarded as preliminary. However, the results were sufficiently encouraging for Patrick to recommend confirmatory full-scale operational tests and three-dimensional model tests. Data from Patrick's tests are summarized further on.

The results of an intensive literature survey of concepts for breakwaters that are potentially transportable were reported in 1971 (Ref 2). The survey indicated that the sloping float concept was more efficient than other concepts of comparable simplicity. Therefore, it was considered a prime candidate for development into a transportable breakwater for ocean applications. Initial steps were taken toward developing a general performance prediction technique. This effort was renewed in 1977, and interim findings concerning the development of a mathematical model (Ref 3) and wave-tank experiments with an Ammi pontoon model (Ref 4) were reported in 1978. The experimental results are summarized further on.

Aspects of the logistic burden of transportable breakwaters - ocean transportation, installation, and cost - were examined in Reference 5. The data pertaining to sloping float breakwaters are summarized further on.

The experimental wave transmission data indicate that floats 90 feet long reduce the significant height* of local-wind-generated waves by more than 50% when the dominant wave period is less than about 7 seconds and the water depth is less than about 30 feet. Thus, Ammi pontoons or NL pontoon barges or causeway sections, if adapted to this purpose, may be considered for ocean applications. Moreover, it was estimated that at least thirty of these pontoon structures could be carried on the hatch covers of a LASH bargeship. Thirty pontoons, 90 feet by 21 feet, would form a ribbon-type breakwater with a sea-to-shore dimension of 90 feet and an axial length of about 700 feet; 700 lineal feet of breakwater

*The significant wave height is the average trough-to-crest height of the highest third of the waves passing a given point in a given interval of time. This wave height is exceeded in about 13% of the waves.

is sufficient to shelter a localized area such as an LCU berth at a finger pier. At much lower speeds (2 to 4 knots, compared to about 20 knots for a LASH), roughly 2,000 lineal feet could be carried on a 100- by 400-foot ocean-going barge.

In waters deeper than 30 feet, the floats must be longer than 90 feet to maintain the same performance; for example, in 45 feet of water the length of the float must be about 110 feet. Increased length tends to compromise transportability. Therefore, suggestions have been made for design modifications that are expected to maintain performance in depths up to about 60 feet and, at the same time, increase the number of lineal feet of breakwater that can be carried on a LASH from about 700 feet to 3,000 feet ±600 feet.

In view of the positive findings, research is being continued. Areas of concentration at this time are (1) the development of a prediction technique for wave transmission and mooring forces for arbitrary float properties (length, mass, etc.), water depths, wave heights and lengths, and mooring system properties and (2) the examination of the operational characteristics of pontoon breakwaters through full-scale experiments.

THE SLOPING FLOAT CONCEPT

Description

The sloping float breakwater is a wave barrier that consists of a row of moored, flat slabs or panels whose mass distribution is such that in still water each panel rests with one end on the bottom and the other end protruding above the water surface. The upper end is the seaward end (see Figure 1).

Various panel constructions are possible. Current interest is in a hollow, steel barge; both Ammi pontoons and Navy Lightered (NL) pontoon barges or causeway sections appear to have acceptable dimensions and mass.* Concept development thus far has been concerned with adapting these structures. Ballasting the float can be accomplished by flooding one end. In a transportable breakwater, the advantage of a water-ballasted module is that much of the required mass is the water, which is available at the site. For the steel barges, the mass that does not have to be transported is considerable; the ballast water may account for more than three-fourths of the total mass.

A proposed procedure for installation is to assemble floating (unballasted) modules at the surface and then admit water to the shoreward end of each float by venting. Flooding would proceed until the lower end rests on the bottom and the upper end settles to the level which produces the desired freeboard. Conventional moorings could be used.

A proposed modification of the original concept is to add legs to the float or otherwise create a gap between the lower edge of the float and the seafloor. The gap may be advantageous with regard to scour. The addition of legs is expected to increase the range of depths in which a float of a given length can be used.

Principle

Primarily, the sloping float is a reflecting barrier. With legless floats, incoming waves encounter a barrier that occupies the entire water column. Some wave energy may pass over the barrier (the freeboard is not expected to be high enough that overtopping is always prevented), and ordinarily some will pass under it. The latter amount will depend upon the height of the gap, certain float properties, and the spectrum of the incident wave energy. Also, in a row of sloping floats, some energy will pass through the gaps between floats; the proper spacing of floats is an aspect of system design that has not yet been determined.

*The Ammi pontoon is a welded steel unit, 90 feet by 5 feet by 28 feet, weighing about 100,000 pounds. NL pontoon structures are bolted assemblies of small (175 cu ft), welded steel pontoons; common sizes (90 feet by 5 feet by 21 feet) weigh about 130,000 pounds.

However, it appears that, normally, waves in the lee will exist largely because of the induced motion of floats, which is resisted by inertia, gravity, and the moorings.

WAVE ATTENUATION

Independent Variables (Nondimensional)

Some orientation may be gained by considering the most important variables involved in the wave transmission process. Figure 2 illustrates the two-dimensional case found in a laboratory wave-tank in which a rectangular, legless float occupies the full width of the tank. In addition to two-dimensionality, other idealizations assumed are as follows:

(1) The thickness of the float is unimportant in the sense that the mass of the float, the mass of the internal ballast, the force of buoyancy, and hydrodynamic forces are considered to be distributed uniformly over a plane that coincides with the lower surface.

(2) A restraint such as a mooring that maintains the general location of the float in the presence of waves has no effect on wave transmission.

(3) The incident waves are "regular;" that is, they form a single-frequency, constant-amplitude wave train.

For the conditions assumed, it is expected that the height of the waves in the lee of the barrier (H_t) depends primarily upon the values of the following independent variables (see Figure 2 for illustration):

H_i = height of incident waves
L = length of incident waves
h = depth of water
ℓ = length of float

w = weight of a unit length of float (total weight of float = $w\ell$)

ℓ_b = ballasted length

w_b = weight of internal ballast in a unit length of float (total weight of ballast = $w_b\ \ell_b$)

w_d = displacement of a unit length of float

In mathematical form, this functional dependence is expressed by

$$H_t = f(H_i, L, h, \ell, w, \ell_b, w_b, w_d) \tag{1}$$

It would be permissible to replace ℓ_b with the angle of inclination of the float at rest, α, because the condition of static equilibrium yields an independent relationship among the variables α, ℓ_b, w_b, ℓ, w, w_d and h;* however, ℓ_b will be retained here. If ballasting consists of filling one end with water and if the walls of the float and other structural elements occupy little space, as in the case of the steel pontoons, then $w_d \approx w_b$, and w_d may be dropped from Equation 1. By means of the principles of dimensional analysis, the functional relationship of Equation 1 can then be rewritten in terms of dimensionless ratios. Selecting the ratio of wave heights, H_t/H_i, as the dependent variable and calling this ratio the wave transmission coefficient, C_T, one can write

$$C_T = f(\ell/L, \ell/h, H_i/L, \ell_b/\ell, w_b/w) \tag{2}$$

Thus, C_T is a function of five other independent dimensionless ratios.** That is, the value of C_T depends upon the wavelength relative to the length of the float, the depth of water relative to the length of the float (a rough measure of the angle of inclination, α), the height-length ratio or "steepness" of the waves, and, in this thin-float case, two parameters governing the distribution of mass of the ballasted float (hence the moment of inertia and the location of the center of gravity).

*For a "thin" float, $\sin^2 \alpha = (w_d/w)(h/\ell)^2/[1 + (w_b/w)(\ell_b/\ell)^2]$.

**Some freedom in constructing the set of dimensionless ratios is permitted. Thus, other dimensionless ratios may validly appear on the right-hand side of Equation 2; for example, $2\pi\ h/L$ could replace ℓ/L.

It is noted that this formulation utilizes ℓ, the total length of the float. Part of the length extends above the water surface, producing a freeboard, e, which can be determined from

$$e = \ell \sin(\alpha) - h \tag{3}$$

Equation 2 merely identifies possible independent variables. To define the indicated function of five variables, mathematical modelling and physical measurements are required. Digital-computer calculations are required if the function is to be defined for all combinations of the independent variables that are of interest. Physical measurements in controlled experiments are needed to verify elements of the mathematical model, to gain insight into the dynamics of a sloping float in waves, and to provide data for preliminary evaluation and design. A mathematical model is now under development. For the present, data from two sets of laboratory experiments are the means for predicting wave height reduction by a sloping float.

1951 Experiments

In Patrick's experiments (Ref 1), the float, which was 2.92 feet long, 0.96 foot wide, and 0.083 foot thick, was tested in regular waves and in water depths of 0.50, 0.75, and 1.00 foot. The ballast consisted of strips of lead. The density of the ballasted portion was just equal to the density of water. It is estimated that for equivalent internal ballasting with water the value of w_b/w would be about 1. The length of the mooring line was six times the depth; other properties were not specified.

Typical results are shown in Figure 3. These results pertain to two cases – Patrick's cases VII and IX – which differed only in the location of the point where the mooring line was attached. Most of Patrick's data pertained to cases (including VII and IX) in which a "cutoff panel" was affixed to the under side of the float*. Data from preliminary tests had indicated that the addition of the cutoff panel improved performance. However, the improvement was not great.

Figure 3 is a representation of Equation 2 over the ranges of the variables covered in the tests - a considerable range of values of ℓ/L and H_i/L and three values of ℓ/h, with fixed values of ℓ_b/ℓ and w_b/w. In Figure 3, the value of the transmission coefficient (C_T) is seen to depend rather strongly upon the values of ℓ/L and H_i/L, but not upon ℓ/h, within the range tested, nor upon the point of attachment of the mooring. Because the parameters w_b/w and ℓ_b/ℓ were held constant, their importance cannot be judged from these tests alone.

In Figure 3, it is seen that the curve for $H_i/L = 0.04$, which represents waves of moderate steepness, crosses the line for $C_T = 0.2$ at about $\ell/L = 0.8$. $C_T = 0.2$ represents excellent performance; that is, 4% of the wave energy is transmitted. It is seen that this was achieved for $L/h = (\ell/h) \div (\ell/L) = 3.2/0.8 = 4$ (using a nominal, realistic value for ℓ/h). A previous review of performance data for dozens of breakwater concepts (Ref 2) showed that few floating breakwaters of "reasonable" size and simplicity produced 96% energy reduction when the wavelength was as great as 4 times the depth.

Further insight into sloping float performance is gained by applying Figure 3 to numbers representing a prototype float. Thus, fixing the float length at 90 feet, one may use Figure 3 to determine, for instance, the wave period at which 50% reduction of the wave height is obtained. (For greater wave periods, reductions of less than 50% would be obtained.) Table 1 shows the result of such a computation. It is seen that the wave periods in Table 1 are large enough that a 90-foot-long float could be considered useful in ocean applications.

The only practical use for Table 1 is to gain a rough idea of the ranges of water depth and wave period for which a 90-foot-long float

*This panel was, in effect, a small wall projecting 0.23 foot downward from, and at a right angle to, the lower surface of the float. The thickness of the panel (wall) was the same as the thickness of the float, 0.083 foot. The panel extended transversely the full width of the float. In cases VII and IX, the cutoff panel was located near the upper end of the float, the distance from the end of the float to the face of the wall being 0.146 foot.

with the mass distribution of the test structure would be useful. Table 1 has limited application because (1) the scaling-up of test results employed to construct the table, while reasonable, is not verified, (2) the mass distribution of the test structure is unknown, and (3) ocean waves with periods around 7 seconds are not "regular" and are better described as "random."

Random Waves

The prototype breakwater would be used for protection against local-wind-generated waves rather than against long swells propagating from distant storms.* Therefore, an attempt was made to adapt the data for regular waves (Figure 3) to the prediction of performance in random waves - specifically, fully-developed, wind-generated seas as represented by the Pierson-Moskowitz spectrum. This was done by assuming that the wave transmission process is linear** and that the curve in Figure 3 for $H_i/L = 0.04$ represents the frequency response function. Then the spectrum of the transmitted waves, $S_T(\omega)$, could be estimated from the spectrum of the incident waves, $S(\omega)$, by means of $S_T(\omega) = C_T{}^2(\omega)S(\omega)$. With the incident and transmitted spectra known, the respective significant wave heights, $(H_s)_i$ and $(H_s)_t$, can be computed.

The results of computations for a particular float length and water depth are shown in Table 2. The equations and relations used are as follows (all length dimensions are in feet):

$\ell = 90$

$h = 30$

$\omega_p = 2\pi/T_p$, where T_p is the wave period, in seconds, corresponding to the peak of the wave spectrum

*Ineffectiveness against long waves is evident in Figure 3 and Table 1 and is typical of all floating breakwaters of reasonable size.

**Dependence of C_T upon wave height can be deduced from Figure 3, indicating the process is not linear.

$$\omega^2 = \frac{2\pi g}{L} \tanh\left(\frac{2\pi h}{L}\right)$$

$C_T = f(\ell/L)$, by Figure 3 with $H/L = 0.04$

$$S(\omega) = \frac{0.0081\, g^2}{\omega_p^5}\left(\frac{\omega}{\omega_p}\right)^{-5} \exp\left[-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right]$$

$$S_T(\omega) = C_T^2\, S(\omega)$$

$$(H_s)_i = 4\sqrt{\int_0^\infty S(\omega)\, d\omega}$$

$$(H_s)_t = 4\sqrt{\int_0^\infty S_T(\omega)\, d\omega}$$

Reduction of Significant Wave Height (%) $= 100\,\{1 - [(H_s)_t/(H_s)_i]\}$

It is emphasized that the numbers in columns 8, 9, and 10 of Table 2 are very crude estimates, because of the assumption of linearity and the arbitrary selection of a function, $C_T(\omega)$. Still, it is believed that "ballpark" answers were obtained. Assuming that the numbers are correct, a 50% reduction of the significant wave height would be accomplished in a depth of 30 feet when the dominant wave period is about 7 seconds. Furthermore, the trend shown in Table 1 indicates that, in Table 2, the wave period for 50% reduction would be greater than 7 seconds if the depth were smaller than 30 feet, and vice versa.*

1978 Experiments

It became evident that an adequate assessment of the sloping float concept would require a broader data base, so work was begun in 1977 to develop a general performance prediction technique. Development of a

*The reduction of effectiveness in deeper water can be circumvented up to a point by means of a longer float. For example, in Reference 5 it is shown that the values in column 8 of Table 2 are almost duplicated for a depth of 45 feet if the length of the float is 106 feet.

mathematical model was undertaken by Raichlen and Lee (Reference 3 is a preliminary report), and a first series of wave-tank experiments were accomplished by Raichlen (Ref 4). These experiments provided data for use in verifying the mathematical model and in designing an ocean experiment with an Ammi pontoon (length, 90 feet; width, 28 feet; thickness, 5 feet; weight, about 100,000 pounds).

In Raichlen's experiments, a float, which was 3.60 feet long, 3.0 feet wide, and 0.208 foot thick, was tested in regular waves and a water depth of 1.0 foot.* The mass of the model was distributed so that the total weight, center of gravity, and moment of inertia represented a 90-foot by 28-foot pontoon weighing 95,200 pounds,** with approximately the lower 72 feet filled with 649,000 pounds of seawater. The value of w_b/w was about 8.5; thus, the mass distribution was notably different from that of Patrick's experiments.

Figure 4 shows the experimental results expressed in prototype units for the case in which the mooring line was attached 30 feet from the upper end. In Figure 5, the data for this attachment point are compared to data for two other attachment points, with the same wave height (6 feet). Evidently, the position of the mooring point is not very important. Patrick had made a similar observation.

The data of Figure 4 were transformed and replotted in Figure 6 (the solid lines). For comparison, the curves of Figure 3 (Patrick's data) were transferred to Figure 6 (the dashed lines). In general, the performance in Raichlen's experiments was superior. For example, when the wave height is 6.5 feet, the wave period 7 seconds, the water depth 25 feet, and the float length 90 feet, the wave steepness (H_i/L) is 0.0366 and the ratio ℓ/L is 0.506; for these values of H_i/L and ℓ/L, C_T from Raichlen's experiments is 0.38, while that from Patrick's experiments is 0.59. The difference is due apparently to the different masses and mass distributions of the floats. It is concluded that performance in

*At a model scale of 1:25, the thickness of the model represents 5.21 feet, which differs slightly from the true thickness, 5 feet; this deviation was not considered significant.

**The float was considered to be an adequate model of the Ammi pontoon despite the 5% discrepancy in weight.

random waves could be better than that shown in Table 2. That is, either greater wave height reduction in 30-foot depth or else equal wave height reduction at some depth greater than 30 feet could be achieved with a 90-foot float. However, additional experiments, with both regular and random waves, are needed in order to adjust Table 2 for the effect of the mass of the float and for error introduced by the ad hoc computational procedure.

Raichlen also conducted experiments in which two small blocks prevented the float from resting on the floor of the wave tank. The gap thus created between the floor of the wave tank and the bottom of the float at rest was 4.75 feet (prototype), or 19% of the depth. Figure 7 shows the experimental results. Table 3, derived from Figures 4 and 7, shows how much C_T changed because of the gap. The values of the wave period in Table 3 pertain only to a 25-foot water depth. The increase in the value of C_T, generally around 0.1, is probably acceptable; however, this should be judged after Table 2 is amended.

MOORING FORCES

Raichlen (Ref 4) obtained data on the tension in the mooring line. Measurements of tension were made along with the measurements of wave transmission in the experiments with the model Ammi pontoon. Without adequate data, the selection of an appropriate line to be modeled required some guesswork, inasmuch as the tension that is developed depends upon the elasticity of the mooring, which depends upon the length, material, construction, circumference, and number of lines. It was decided to consider first a mooring composed of one 150-foot-long line per 28-foot float (see inset in Figure 8); the line simulated a double-braided polyester rope, 8 inches in circumference, with a nominal breaking strength of 200,000 pounds. A spring was fabricated which modeled the highly nonlinear tension-elongation characteristic of this rope. A best estimate of the correct strength and elasticity of the mooring was desired in order to avoid losing time and money building and testing an inappropriate nonlinear spring.

The measurements defined the curves in Figures 8 and 9. These graphs show the maximum tension in the line for a given combination of wave height and wave period. Salient features of these results are (1) peak tensions at moderately long periods (10 to 12 seconds) for the no-gap condition, (2) shift of the peak tensions to shorter wave periods when the float rested on blocks, 4.75 feet high, (3) reduction of tension due to the gap for only the highest waves (H_i = 10 feet), and (4) tensions that are probably excessive for wave heights greater than 6 to 8 feet at the periods of maximum tension.

Figures 8 and 9, which pertain to regular waves, may be used directly to estimate tension for only the pure-swell case. For random waves, the significant value of the force (average of the greatest one-third of the momentary peaks) was estimated (Ref 4) for two cases of waves represented by Pierson-Moskowitz spectra, as follows:

	Case 1	Case 2
Wave period at peak of spectrum (sec)	7.00	9.85
Significant wave height (ft)	6.4	12.8
Maximum height expected in 3 hr (ft)	12.8	25.5
Significant force (kips)	29 to 62	52(?) to 108
Maximum force (kips)	72 to 155	-- to 267

From these results it appears that one 8-inch polyester rope is inadequate.

Some data on mooring tensions had been obtained previously with a mooring restraint that was linear and much "softer" than the 8-inch polyester (Ref 3).* For this soft spring, the maximum tension for a wave height (H_i) of 3 feet was 9.5 kips (at a wave period of 9 seconds), compared to a maximum of 34 kips in the polyester line at H_i = 3 feet. Thus, it appears possible to reduce the peak tensions below those found for the polyester rope by using a more compliant line; however, the line should be of comparable strength. Greater length and different material are options. The latter is preferable, and additional tests with a more compliant rope (double-braided nylon) are scheduled. A more compliant restraint will, of course, allow more movement of the float.

*The stiffness (spring constant) was 935 lb/ft (prototype). For comparison, the stiffness of the nonlinear spring representing the polyester rope was 36,000 lb/ft (prototype) for tensions above 40 kips.

UTILIZATION IN A TRANSPORTABLE BREAKWATER

Module Designs

Some aspects of the logistic burden of transportable breakwaters were examined in Reference 5. Findings in that report concerning sloping float breakwaters are summarized in this section. These findings pertain to the three proposed module designs illustrated in Figure 10. Features of these designs are as follows:

Design S1. The module is a 3x15 (21- by 90-foot) NL pontoon barge or causeway section, modified to include mooring attachments and a piping system (see Figure 11) for ballasting and deballasting the float.

Design S2. The module is a 28- by 90-foot float with 30-foot legs. Two constructions for S2 were considered, designated S2a and S2b (see Figure 10). In S2a the legs are retractable. With legs retracted for transporting the breakwater aboard ship, the space required is the same as for design S1. The objective behind this concept was to increase the operational depth above that of S1 without increasing the transportation requirement and without decreasing effectiveness significantly. The float could be a 4x15 assembly* of P-series pontoons. In S2b the legs are not retractable. Instead, the concept calls for two submodules that are hinged or are otherwise connected for operation. The objective behind this concept was to increase the operational depth as in design S2a and also to increase "transportability" by decreasing the length of the module in its shipping configuration. The floats of design S2b could be 4x10 and 4x5 assemblies of P-series pontoons.

Design S3. The module is a 28- by 120-foot float with 40-foot legs. The concept calls for two submodules, hinged or otherwise joined, with retractable legs mounted on one submodule. The objective behind this concept was to increase the operational depth above that of design S2 while maintaining the same outside dimensions as the S2b module in

*4x15 is not a standard NL pontoon-barge size.

the shipping configuration. The floats could be 4x10 assemblies of P-series pontoons.

It is emphasized that S2 and S3 are hardly more than conceptual designs and that, while the sloping float has been shown to be attractive in terms of performance, details of structural form have not been established. For example, the question has been asked whether or not sufficient moment resistance in the legs can be obtained; an investigation could show that other designs are preferred.

Estimates of cost and other factors of a logistic nature depend upon the design of the module. The estimates that follow are based on designs S1, S2, and S3.

Transportation

For short distances, it is practical to tow the modules. However, to transport a breakwater overseas would require an ocean-going barge, a well-deck ship,* or a barge-carrying ship (LASH or SEABEE). Table 4 summarizes the number of lineal feet of breakwater that could be carried on a barge or on the two bargeships.

Transportation by barge is relatively slow. It has the further disadvantage, with regard to military contingencies, of requiring special equipment or procedures at the destination. For ordinary barges, a crane would be required to off-load pontoons. The static lift would vary from 30 to 130 tons, depending upon the particular module or submodule. For a barge-mounted crane, the maximum radius would be about 200 feet if its location relative to the cargo barge (100 feet by 400 feet assumed) is fixed, or about 120 feet if the crane barge is moved back and forth along the side of the cargo barge. The radius would be much smaller if the crane were carried on the cargo barge, replacing a number of breakwater modules, and if it could be moved along the centerline of the barge. A crane would not be required if special ballast-down barges were used. Although the use of such barges has not been examined, it is

*Only a new design for a well-deck ship, such as the TRIMARINER, could carry more than about 600 lineal feet. This class of ship has not been considered further.

apparent that special procedures or equipment for removing and separating stacks of pontoons would be required.

The carrying capacity of bargeships varies a great deal, as it depends upon both the type of ship and the design of the module. A SEABEE can accommodate 28-foot-wide modules more readily than 21-foot-wide modules; therefore, the latter were not considered for Table 4. For design S2a, the SEABEE has the greatest capacity. However, SEABEEs are few in number* and are not likely to be available.

When availability is considered along with capacity and speed, it is concluded that a LASH is the most suitable carrier. For designs S2b and S3, the capacity of a LASH ship approaches that of a SEABEE. The figures in Table 4 pertain to "LASH-compatible" designs. (The length of the module for designs S2b and S3, 60 feet, was chosen so that the modules could be stowed in the spaces normally occupied by the ship's barges. It was also assumed that the required procedures and structural details for stacking the modules in the hold would be developed.) The number of lineal feet (axial length of breakwater) that could be carried on the hatch covers of a LASH was estimated to be 750, 1,000, 700, and 700 for designs S1, S2a, S2b, and S3, respectively. Thus, the length of breakwater required to shelter a localized area, such as an LCU berthed at an elevated causeway, can be carried on the hatch covers. The figures for the total number of lineal feet of breakwater on a LASH, which are listed in the last column of Table 4, include the foregoing quantities carried on hatch covers.

Installation

Figure 12 illustrates a proposed layout for a breakwater. Floating modules would be connected and temporarily held in position by tugs. The modules would then be connected to moorings which have been preset. The valves in the manifold headers on the floats (see Figure 11) would then be opened in quick succession, beginning at one end. The valves

*Three in the U.S. merchant fleet.

would be reached from a warping tug or small boat. The rate of flooding would be controlled by the size selected for the ports and by valves in the air system. When flooding is complete, the moorings would be adjusted.

Time schedules for installing 600, 1,200, and 1,800 lineal feet are shown in Figure 13. The installation times are about 3, 4-1/2, and 6 days. These rates - about 8, 10, and 12 modules per day, respectively - are slower than the rates at which modules can be unloaded from transport vessels. Therefore temporary storage of modules will be required if the transport ships are to be unloaded as rapidly as possible. It is assumed for the present that these rates pertain only to sea state 1.

These installation rates are expected to apply to design S2a as well as to S1. Installation times for designs S2b and S3 are estimated to be 33% to 50% greater than for S1.

Cost

For design S1, the cost of new construction utilizing 3x15 NL pontoon sections with minor modifications was estimated (in 1977) to be $80,000 for one module (Ref 5). Moorings for a water depth of 30 feet would add a little more than 10%. Thus, the uninstalled cost would be about $90,000 per module, or about $3,500 per lineal foot. (This figure is based on the assumption that the average spacing between floats is about 3.5 feet, as in Figure 12; this spacing is not definite, as it depends upon the selected design of the moorings and connectors.) For designs S2 and S3, very rough estimates are $5,500 and $7,000 per lineal foot.*

SUMMARY

Representative performance for sloping floats in random waves is shown in the following table, which is adapted from Reference 5. The wave height reduction figures are estimates based on measurements of performance in regular waves in laboratory tests.

*A more recent estimate for design S1 is $6,000 per lineal foot (1979 dollars). See the appendix. Proportionate increases for S2 and S3 may be assumed.

Wave Spectrum[a] Peak Period (sec)	Significant Wave Height[b] (ft)	Sea State	Reduction of Significant Wave Height (%) for -	
			Water Depth, 30 ft Float Length, 93 ft	Water Depth, 45 ft Float Length, 106 ft
4	2.1	2	90	90
5	3.3	3	78	80
6	4.7	3	63	65
7	6.4	4	50	50
8	8.4	5	40	35
9	10.6	5	32	27
10	13.1	6	26	21

[a]Pierson-Moskowitz wave spectrum for fully developed sea.

[b]Exceeded by 13% of the waves.

These data show that floats as short as 90 feet produce a useful degree of wave height reduction for dominant (spectral peak) wave periods up to at least 7 seconds and that, therefore, floats of manageable size have ocean applications. The dimensions of existing Navy pontoon designs (Ammi barges and NL pontoon causeway sections) are appropriate for an ocean system, and development of the sloping float breakwater at present is focused on the adaptation of these structures.

Although the performance data tabulated were derived from the original (1951), preliminary laboratory tests by means of an approximate calculation, it is believed that they are indicative of the performance that can actually be obtained. A promising note is that later (1978) experiments in which the properties of an Ammi pontoon were modeled yielded notably better performance than the original experiments. The table above has not been revised to reflect this better performance; however, revision is planned for the time when an appropriate mathematical model (i.e., a more accurate technique for predicting performance in random waves) is available.

The experiments have indicated that sloping floats are most efficient if the angle of inclination is less than about 20 degrees. Thus, 90-foot floats, such as causeway sections, would be used most effectively in depths less than about 30 feet. Similarly, 106-foot floats would be used most effectively in depths less than about 45 feet.

The sloping float breakwater has potential as a ship-transportable breakwater. The difficulties of handling floats and transporting them on ships increase as their length increases. Therefore, two untested design concepts (legged floats) have been proposed as means for increasing the depth in which a float of given length provides a useful level of effectiveness. At the same time, these proposed concepts would increase significantly the number of lineal feet of breakwater that could be carried on a ship (specifically, a barge-carrying ship).

It was found that at least 700 lineal feet of breakwater composed of 90-foot floats could be carried on the hatch covers of a LASH. This length corresponds to 30 3x15 NL pontoon structures or 24 4x15 NL pontoon structures stacked three high. Stacking the pontoons five high may be possible, but the implications have not all been examined. For short, low-speed hauls, at least 2,000 lineal feet could be carried on an ocean-going barge. A LASH is self-contained, but barge-transportation would necessitate special procedures and accessory equipment for off-loading floats at the destination. To increase the capacity of a LASH from about 700 lineal feet of breakwater to 3,000 feet ±600 feet, special legged-float designs have been proposed to permit stowage in the hull.

It was concluded that a sloping float breakwater would be a useful adjunct to the Container Off-Loading and Transfer System (COTS). A breakwater 700 feet long would be enough to shelter a localized area, such as the berth at the end of an elevated causeway or an isolated, spread-moored platform and adjacent, small, floating craft. Two thousand lineal feet would shelter a number of moored LASH or SEABEE barges.

An important area of investigation is the mooring system. Data on mooring forces were obtained in the 1978 tests of a model Ammi pontoon, which was moored in regular waves. The mooring simulated the resistance of one double-braided polyester rope, of 8-inch circumference, per 28-foot-wide pontoon. The maximum mooring line tension was found to be excessive for some of the larger wave periods when the wave height was greater than about 7 feet. Remedies are available. For example, the use of a more compliant material will reduce the peak tensions; accordingly, double-braided nylon will be modeled in the next set of experiments.

Because of favorable results of performance and utilization studies, research is continuing. The three general areas of effort are (1) mathematical modeling of wave transmission properties and mooring forces to enable logistic assessments and optimum design for various wave climates, water depths, float properties, and mooring-system properties; (2) laboratory experiments to validate elements of the mathematical model and to perform model tests and (3) ocean experiments to evaluate structural and operational aspects of a full-scale system.

ACKNOWLEDGMENT

In the preparation of Reference 5, from which much of this material was drawn, Mr. Robert J. Taylor of CEL provided invaluable assistance, including the preparation of mooring plans and installation schedules.

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Table 1. Limits on Wave Period for 50% Attenuation of Regular Waves (1951 Data)

Water Depth, h (ft)	Maximum Wave Period, T (sec), for C_T = 0.50, ℓ = 90 ft, and --			Value of ℓ/h
	H_i = 3.6 ft	H_i = 6.4 ft	H_i = 8.7 ft	
25	7.6	6.9	6.3	3.60
30	7.0	6.4	6.0	3.00
35[a]	6.6	6.1	5.7	2.57

[a]Values of T for h = 35 ft obtained by extrapolation, as ℓ/h = 2.57 is outside the range tested.

Table 2. Predicted Performance (1951 Data) of Legless Sloping Float Breakwater in Random Waves (Pierson-Moskowitz Spectrum)

[Float length = 90 ft, water depth = 30 ft.][a]

Wind			Incident Waves				Reduction of Significant Wave Height (%)	Transmitted Waves	
Speed (kt)	Minimum Duration[b] (hr)	Minimum Fetch[b] (nautical miles)	Dominant Wave Period[c] (sec)	Sea State	Significant Wave Height[d] (ft)	Maximum Wave Height[e] (ft)		Significant Wave Height[d] (ft)	Maximum Wave Height[e] (ft)
24	14.0	130	9	5	10.6	22.1	30	7.4	16
21	11.3	91	8	5-	8.4	17.6	38	5.2	11
19	8.8	61	7	4	6.4	13.5	48	3.3	7
16	6.6	40	6	3	4.7	10.0	61	1.8	4
13	4.7	25	5	3-	3.3	7.1	76	0.8	2

[a]Table adapted from Reference 5.

[b]From Reference 6.

[c]T_p, the wave period corresponding to the peak of the wave spectrum.

[d]Exceeded by 13% of the waves.

[e]Expected in 6-hr interval (Ref 7).

Table 3. Effect of Gap on Wave Transmission; Gap Height = 4.75 Ft, Water Depth = 25 Ft

Wave Height (ft)	Change[a] in Value of C_T for --			
	T = 5.3 Sec	T = 7.0 Sec	T = 9.0 Sec	T = 12.0 Sec
2	-0.02	+0.08	+0.14	-0.03
4	+0.01	+0.11	+0.13	-0.03
6	+0.06	+0.10	+0.06	+0.04
8	-0.01	+0.05	+0.04	+0.08
10	-0.12	+0.04	0	+0.08

[a]Plus sign (+) indicates C_T with gap greater than C_T without gap.

Table 4. Capacity of Vessels for Ocean Transport of Sloping Float Breakwater Modules[a]

Breakwater Module		One Barge[b]		One SEABEE		One LASH[c]	
Design	Width (ft)	Number of Modules	Axial Length of Breakwater (ft)	Number of Modules	Axial Length of Breakwater (ft)	Number of Modules	Axial Length of Breakwater (ft)
S1	21	112	2,800	d	d	30	750
S2a	28	84	2,800	154	5,100	30	1,000
S2b	28	63	2,100	115	3,800	70-110[e]	2,300-3,600
S3	28	63	2,100	115	3,800	70-110[e]	2,300-3,600
Transport Speed (knots)		4		20		22	

[a]Table from Reference 5.

[b]100 by 400 feet.

[c]Range of values corresponds to the range of capacities of LASH ships.

[d]Values not estimated.

[e]Includes 21 modules on hatch covers.

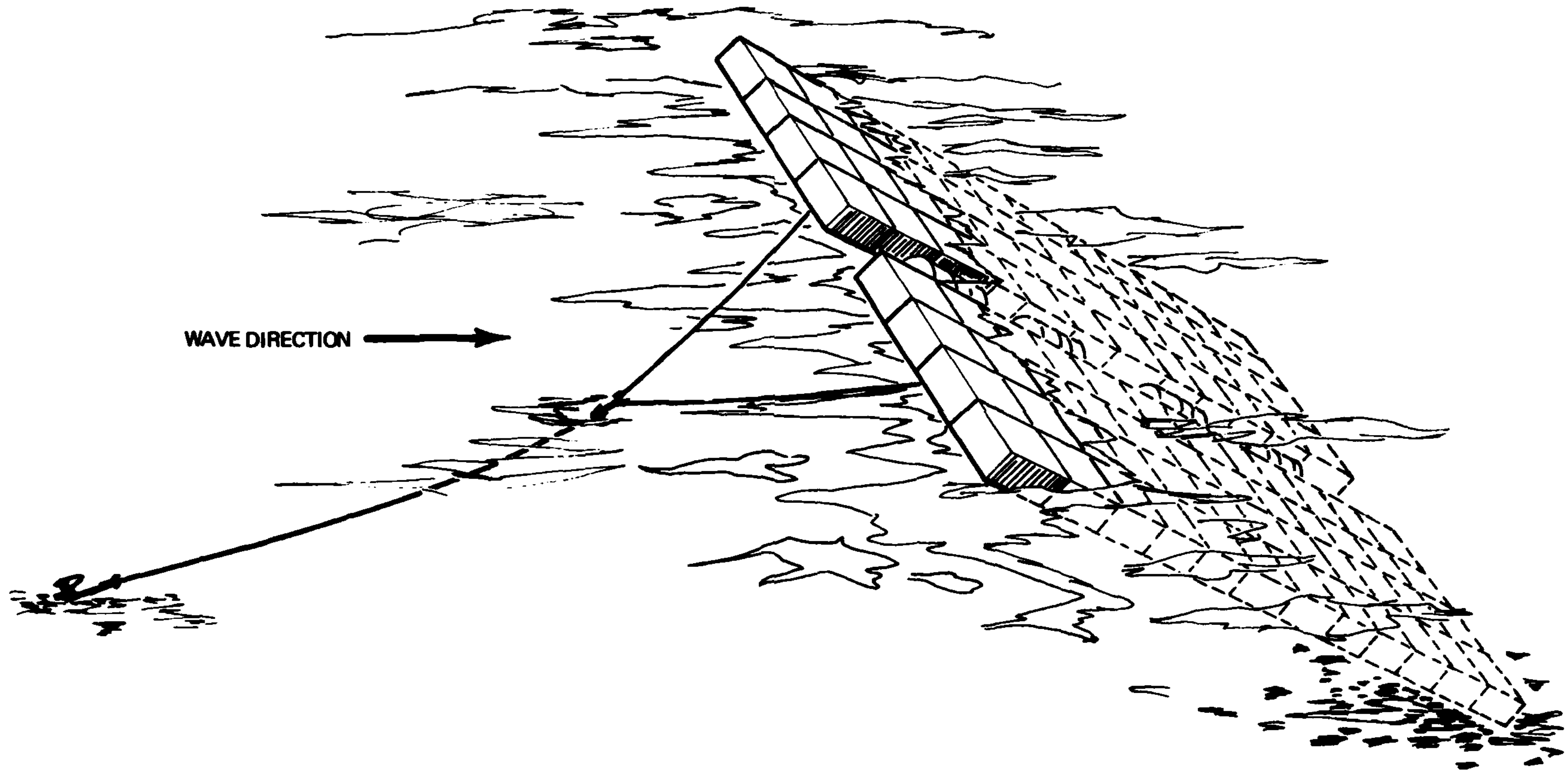

Figure 1. Two modules of a sloping float breakwater (from Ref 5).

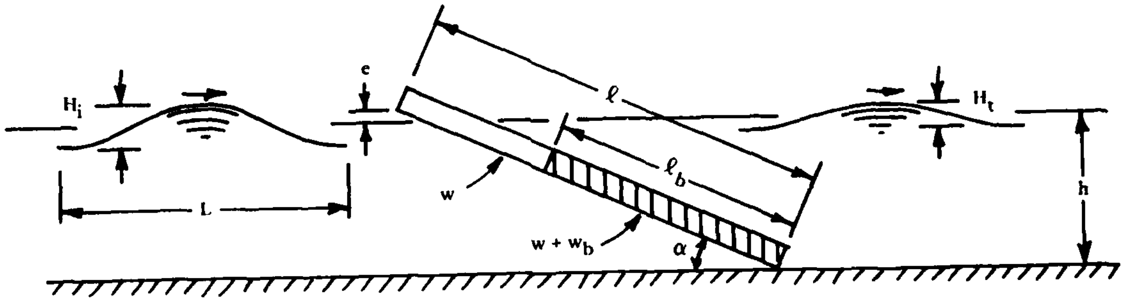

Figure 2. Definition sketch.

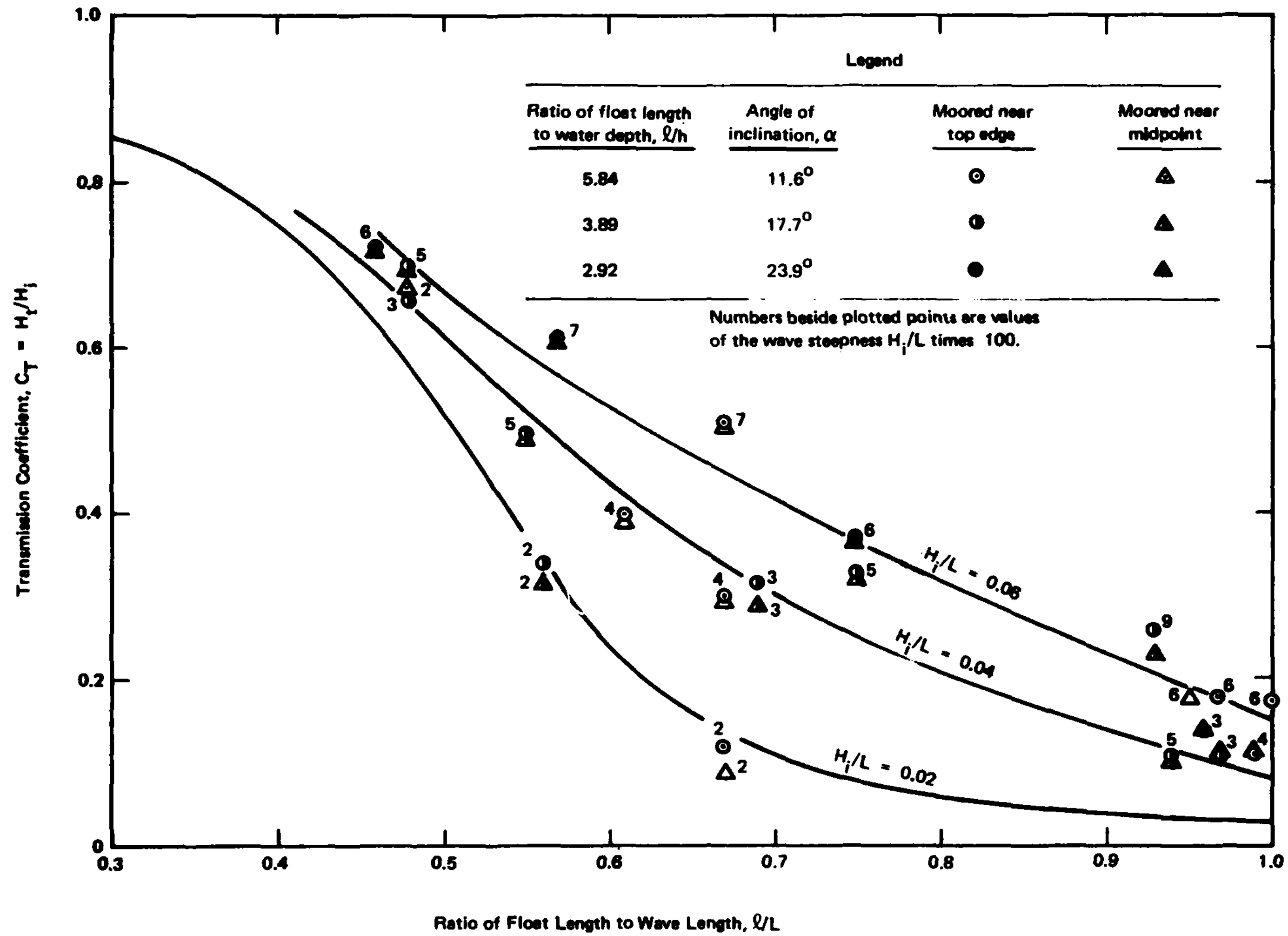

Figure 3. Wave transmission for a sloping float in regular waves; laboratory data of Patrick, 1951, cases VII and IX (adapted from Refs 1 and 5).

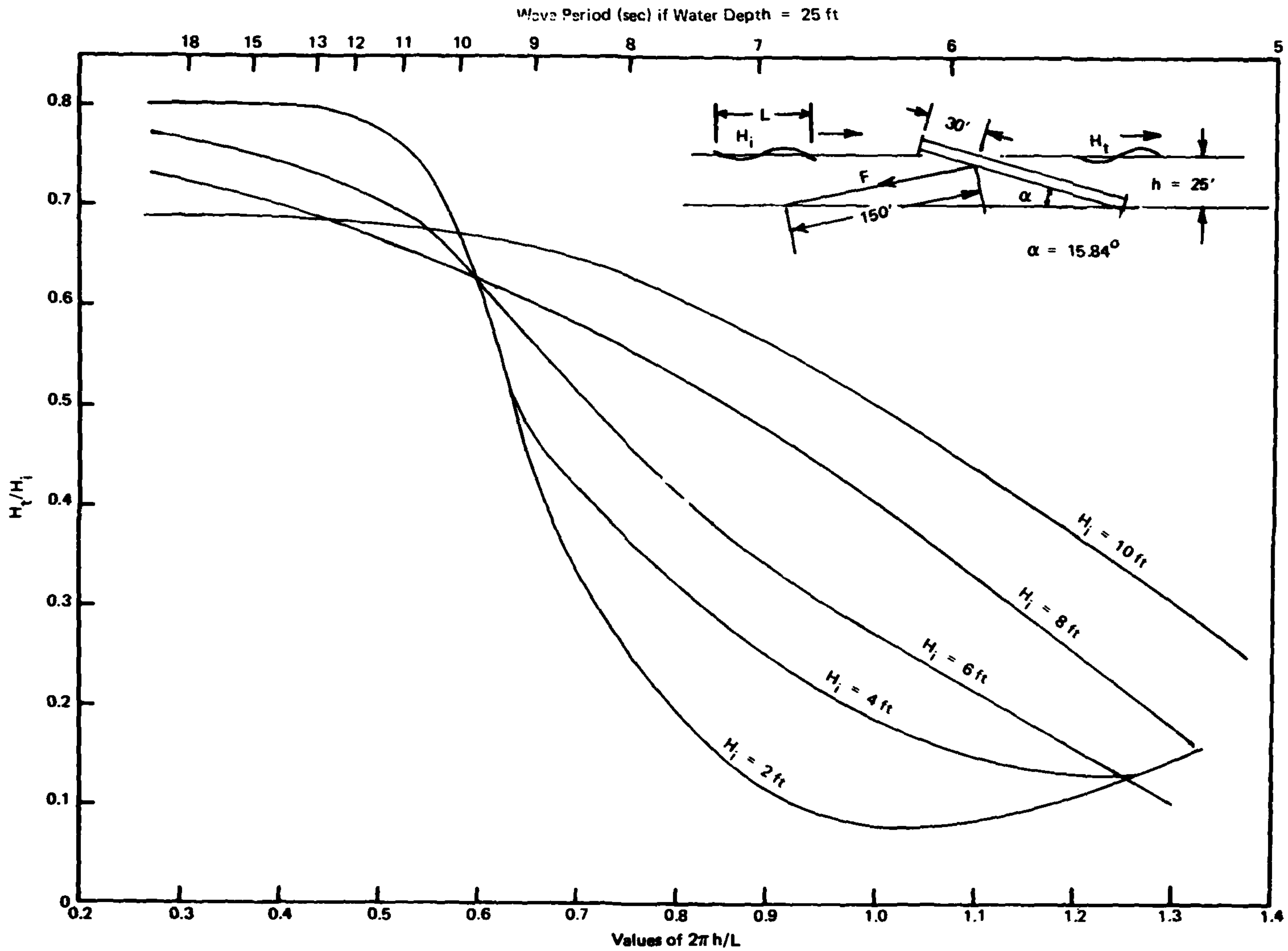

Figure 4. Wave transmission for a sloping float (Ammi pontoon) in regular waves; laboratory data of Raichlen, 1978 (from Ref 4).

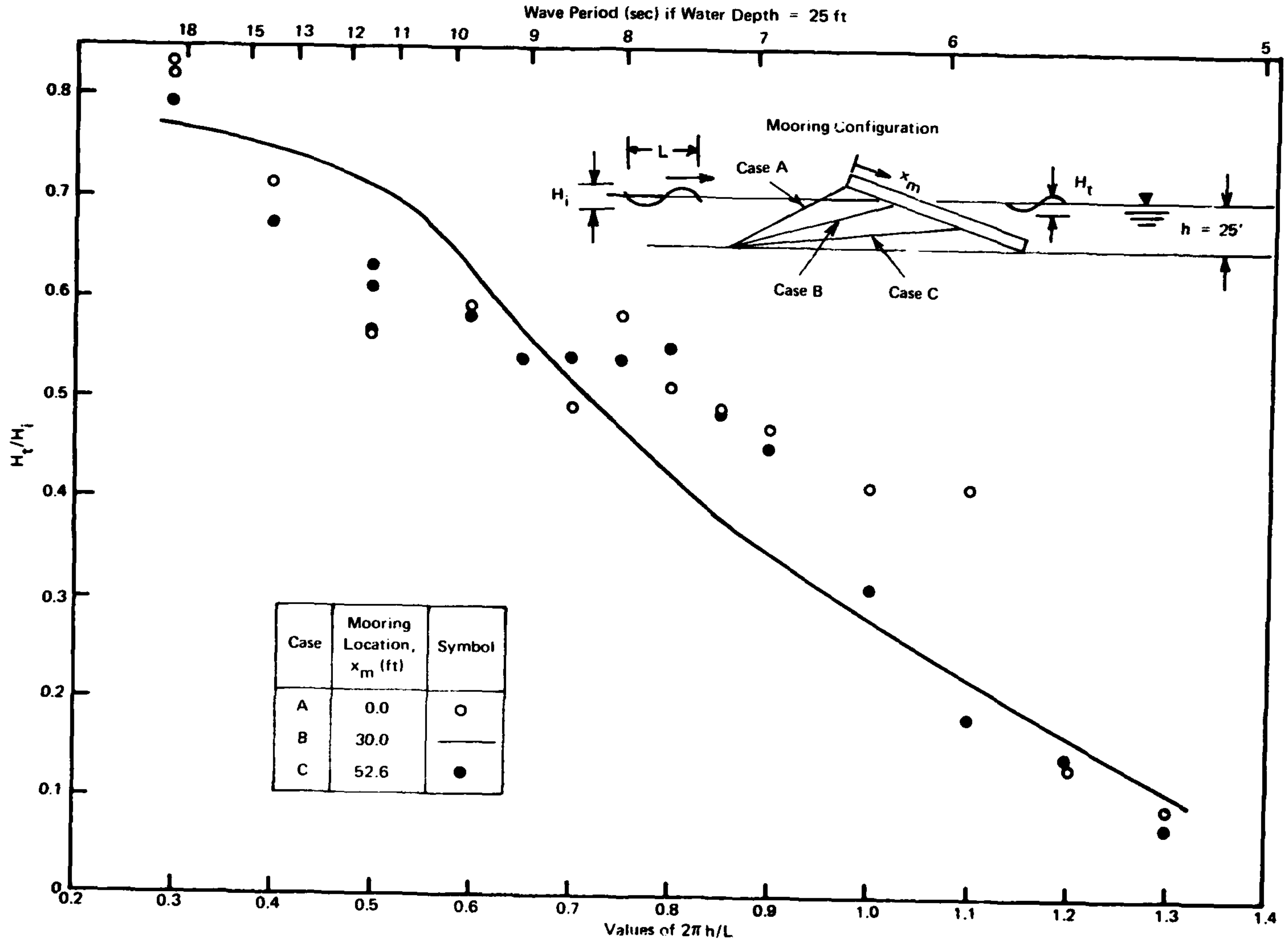

Figure 5. Effect on transmission coefficient of location of mooring line attachment, for H_i = 6 ft; laboratory data of Raichlen, 1978 (from Ref 4).

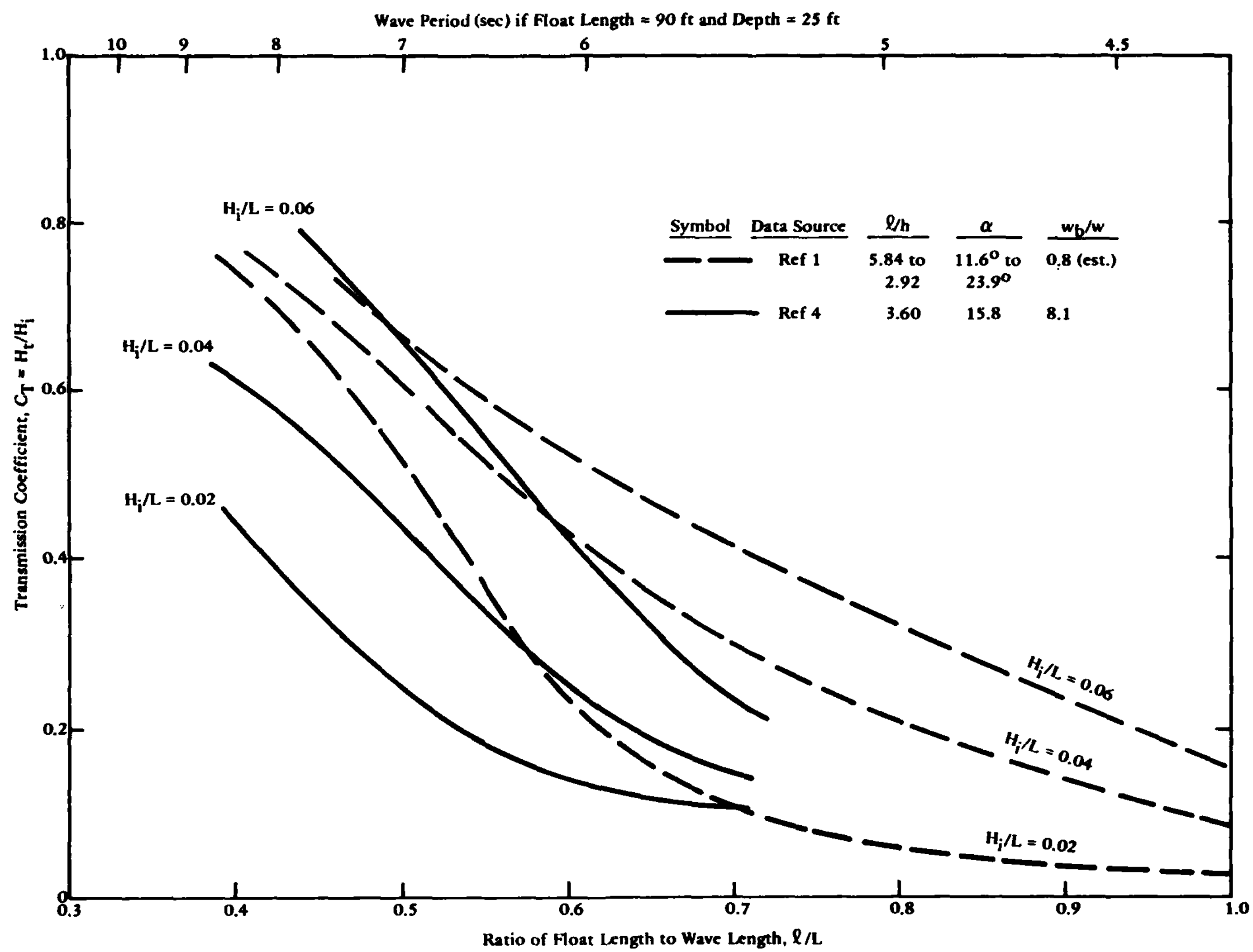

Figure 6. Wave transmission for a sloping float in regular waves; comparison of laboratory data of Patrick (dashed lines) and Raichlen (solid lines).

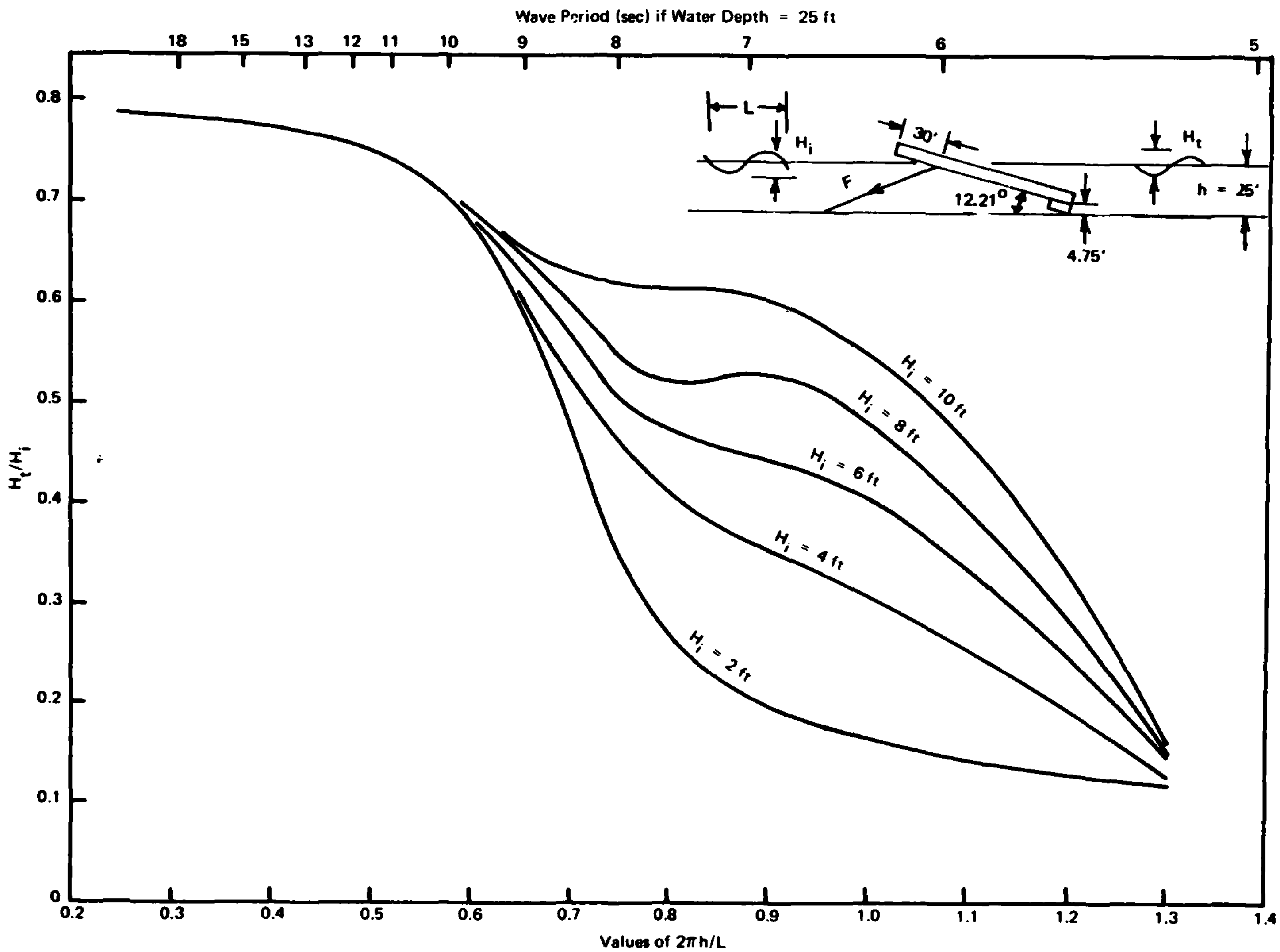

Figure 7. Wave transmission for a sloping float (Ammi pontoon) with 19% bottom gap; laboratory data of Raichlen, 1978 (from Ref 4).

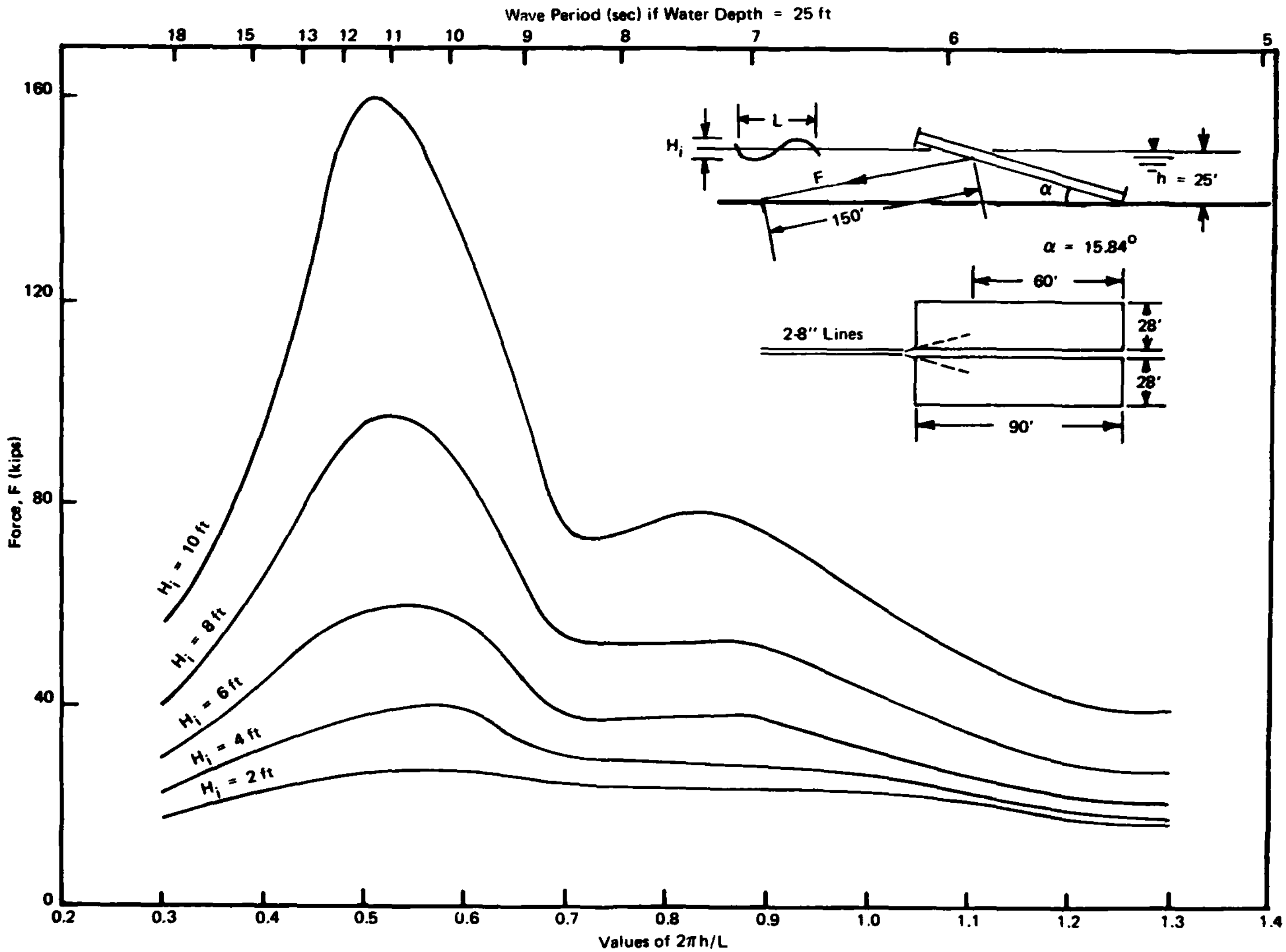

Figure 8. Maximum tension in mooring line (Ammi pontoon with one 8-inch-circumference, double-braided polyester line); laboratory data of Raichlen, 1978, for case of no gap (from Ref 4).

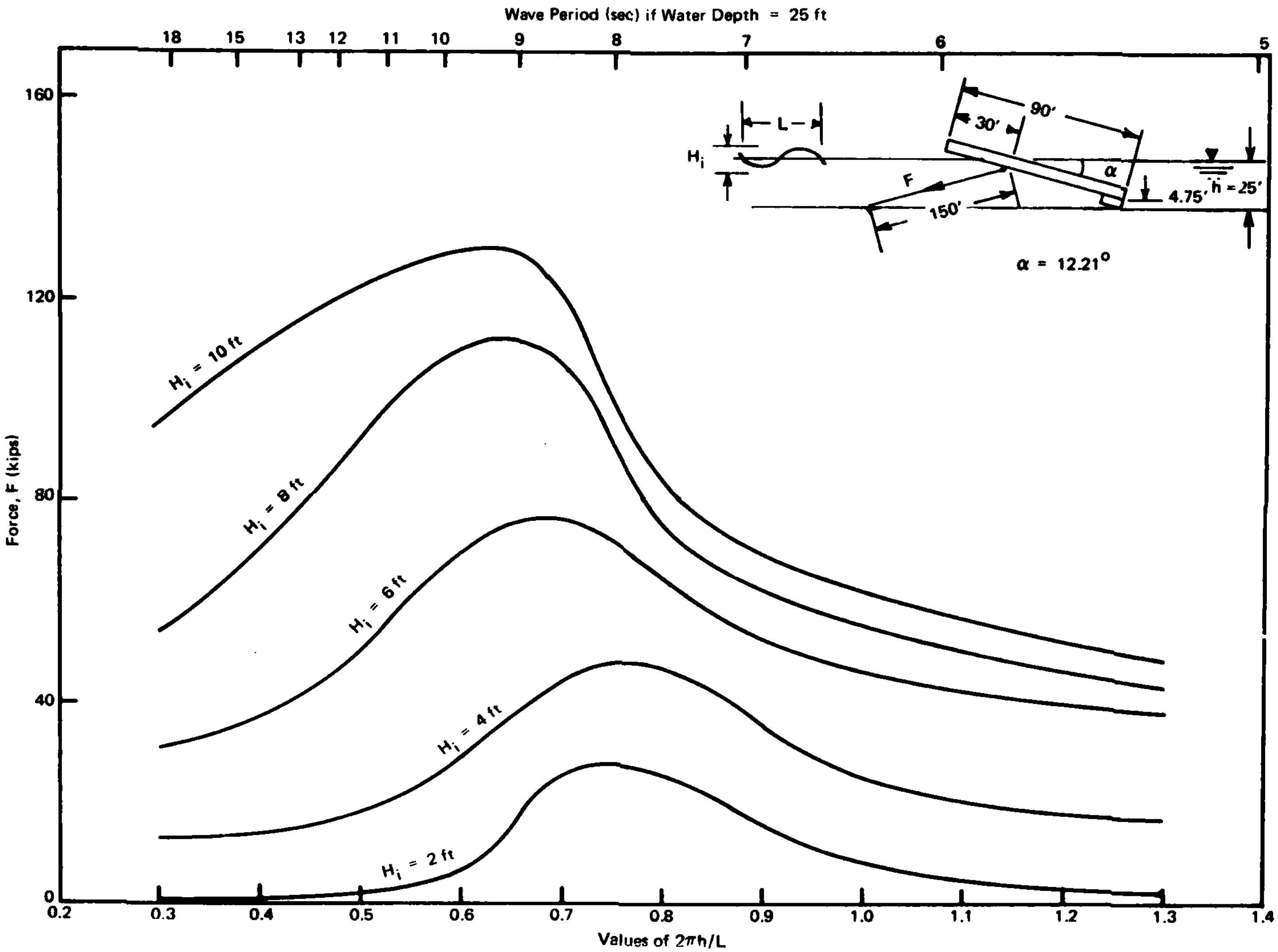

Figure 9. Maximum tension in mooring line (Ammi pontoon with one 8-inch-circumference, double-braided polyester line); laboratory data of Raichlen, 1978, for case of 4.75-foot gap (from Ref 4).

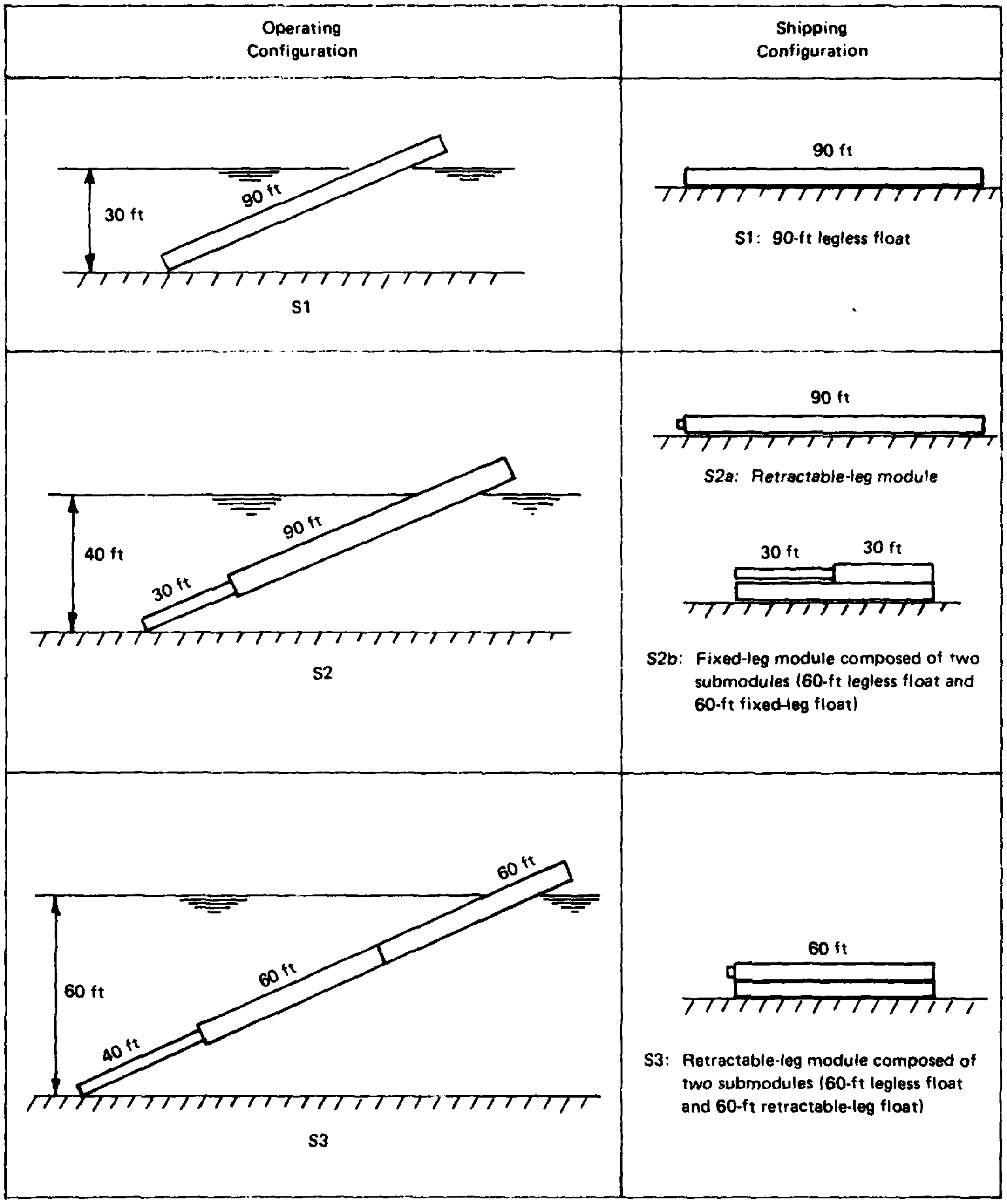

Figure 10. Sloping float breakwater: proposed module designs (from Ref 5).

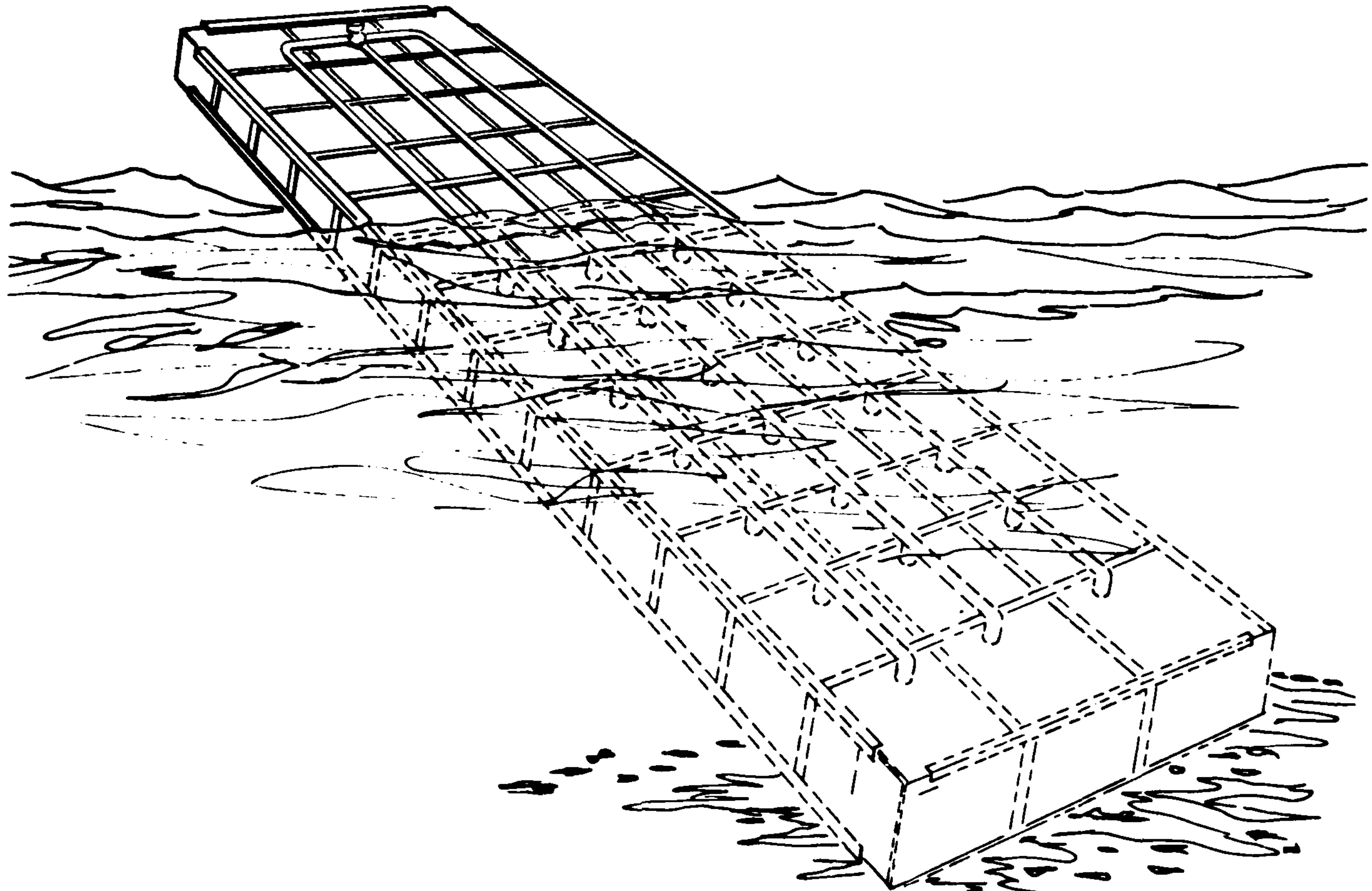

Figure 11. Piping for ballasting and deballasting NL pontoon structures (from Ref 5). (Note: For clarity of illustration of the principle, the piping is shown located on the top of the float. In practice, the "deck" of the structure would be clear, with add-on piping (quick-disconnect hoses) and fittings located in the spaces between individual pontoons and main line (hose) running along one side of structure. It is possible to have piping leading only to the lowest three rows of pontoons.)

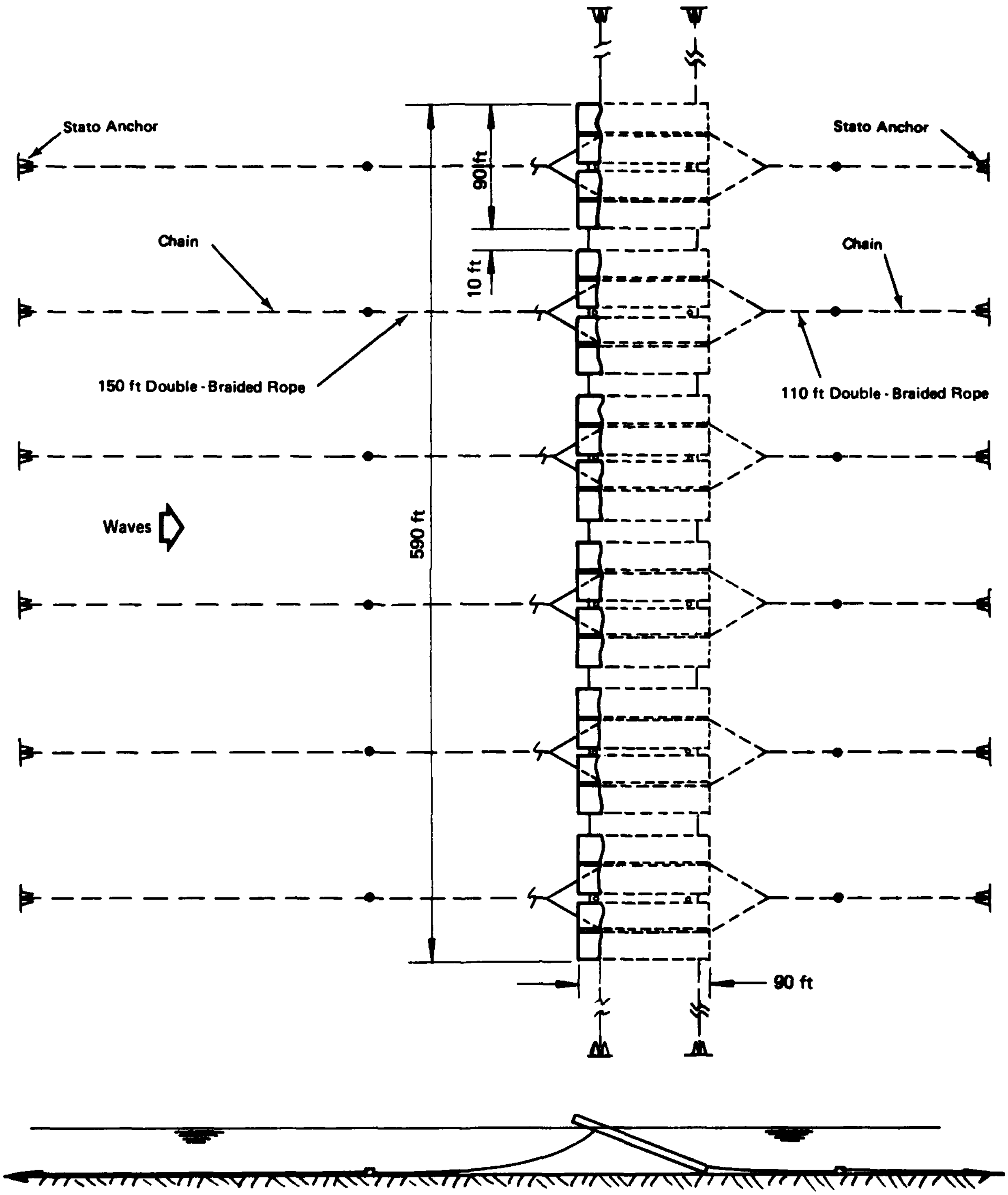

Figure 12. A preliminary layout for float breakwater, design S1 in 30-foot water depth (adapted from Ref 5).

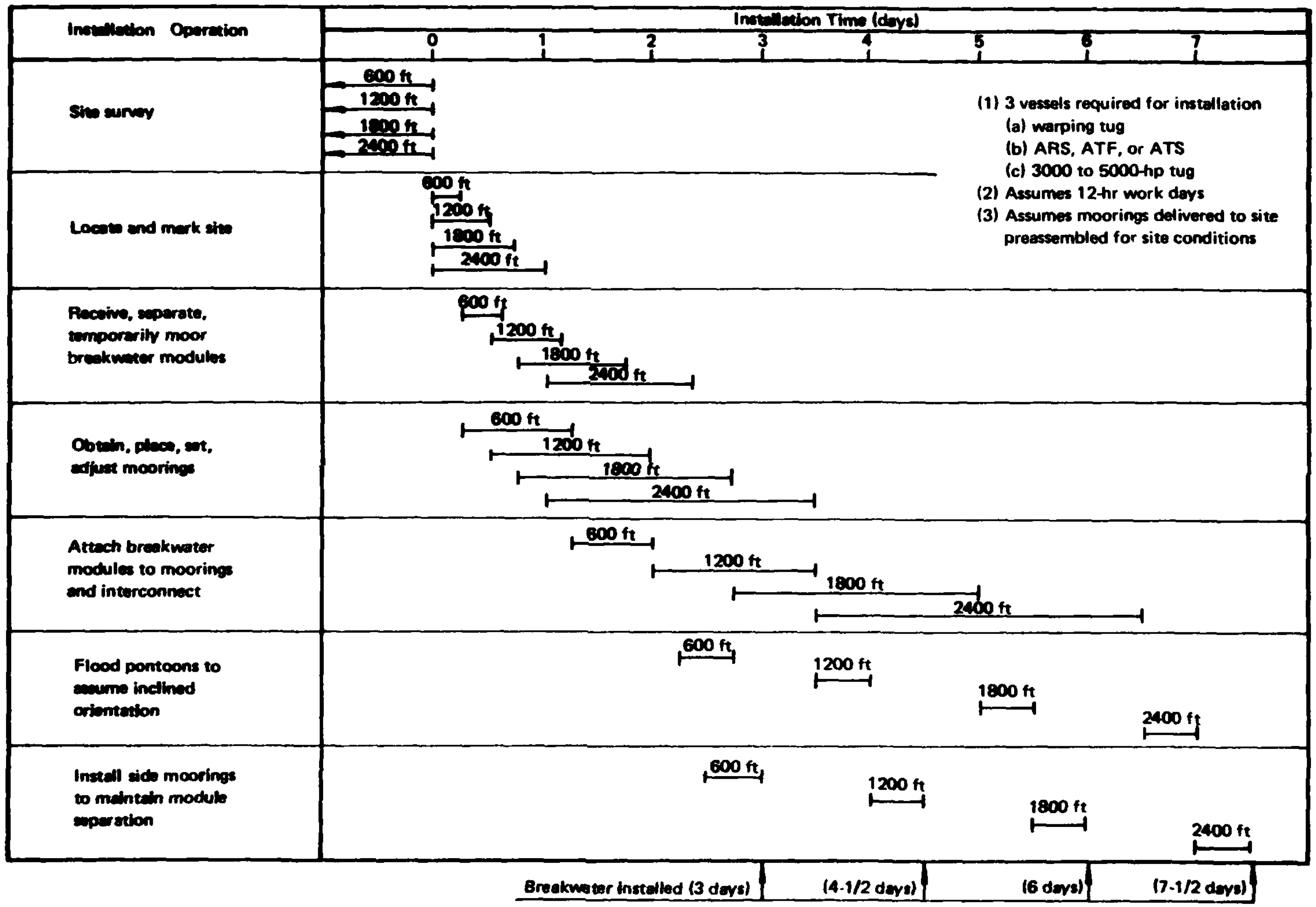

Figure 13. Installation schedule for various lengths of sloping float breakwater; 30-foot water depth (from Ref 5).

Appendix

COST-BENEFIT UPDATE

The body of this technical note is primarily a compilation of data that has already been reported elsewhere (Refs 1-5). A small amount of material of an editorial nature was included to lend coherence. The intent was to provide a status report which summarizes the research findings reported up through November, 1978. The areas of information covered are wave attenuation, mooring forces, and properties of sloping floats relevant to their use in an operational transportable breakwater. Special reference was made to transportable breakwaters for the Container Off-Loading and Transfer System (COTS).

This Appendix presents new data -- specifically, a revised cost estimate and information on the potential benefit of a sloping float breakwater to operations at the elevated causeway system (ELCAS) of the COTS.

COST UPDATE

An improved cost estimate for planning purposes is $6,000 per front foot (1979 dollars). This revision reflects the improved system definition now available as well as the effect of two years' inflation.

The system consists of floats of design S1 (3x15 NL pontoon sections), conventional drag-embedment anchors, and chain and synthetic-fiber rope moorings. The cost estimate includes minor structural additions to the pontoon sections for mooring-line attachment points, for piping for ballasting and deballasting some of the individual pontoons, and for interconnections between adjacent modules (tentatively, these are existing causeway-section side connectors).

The cost estimate is based on the revised, tentative mooring plan shown in Figure A-1. In general, floats would be moored in independent groups of six or eight. An increment of length of one moored element provides about 150 additional lineal feet of breakwater (if six floats per element) or 190 feet (if eight floats).

Figure A-1 also shows the breakwater deployed to shelter an LCU tied up at an elevated causeway. The axial length of breakwater shown -- 560 feet -- is an estimate for the minimum length acceptable. The required length depends upon the wave diffraction pattern (undetermined) and the variability of the direction of approach of the waves (unknown). The required length was estimated by assuming that the true extent of the sheltered area could be approximated by the area inside the lines forming the 45-degree angle. The length of breakwater also depends upon the stand-off distance. In Figure A-1 the distance from the end of the causeway to the toe of the floats is 200 feet. With these estimates for the sheltered area and the stand-off distance, the cost of a breakwater for an elevated causeway is estimated to be about $3,500,000 uninstalled. The major cost elements are the pontoon sections and the anchors, which make up 70% and 19% of the total, respectively.

BENEFIT

The benefit of a breakwater to the operation of an elevated causeway system can be expressed in terms of the improvement of productivity. Productivity may be measured by the number of TEUs* transferred in a 20-hour day. Table A-1 shows the stated goals for TEU throughput, and also threshold (minimum) values, for various sea states.

If it is assumed that the throughput goals in Table A-1 could always be met but higher goals could not be met, then the values in columns 1 and 2 of Table A-1 establish a relationship which shows how throughput varies with, and is controlled by, the sea state. This relationship is plotted in Figure A-2 (upper curve). The effect of a breakwater is to decrease the sea state; therefore, the use of a breakwater would result in increased productivity of an ELCAS. Table A-2 shows how much the

*TEU = 20-foot Equivalent Unit (ISO Standard 20- by 8- by 8-foot containers weighing up to 20 long tons).

Table A-1. ELCAS Throughput Goals and Thresholds[a]

Sea State	Throughput (TEUs per 20-hour day)	
	Goal	Threshold
1	250	160
2	220	150
3	140	100
4[b]	0	0

[a]From Reference 8.

[b]Reference 8 contains no data for sea state 4; it is inferred that the expected throughput is zero.

throughput (goal values) may be increased by a sloping float breakwater having the wave transmission characteristic indicated by columns 4 and 8 of Table 2. (This wave transmission characteristic is also shown in Figure A-3.)

Table A-2. Increase in ELCAS Productivity Due to a Sloping Float Breakwater if Attainable Values of Throughput Equal the Goals in Table A-1

Sea State (Incident Waves)	Throughput (TEUs per 20-hour day)		
	Without Breakwater	With Breakwater	Increase
1	250	250	0
2	220	250	30
3	140	240	100
4	0	166	166
5	0	0	0

If it is assumed that only the threshold throughput values in Table A-1 could be met, then the figures in columns 1 and 3 of Table A-1 establish another relationship between productivity attained and sea state. This relationship is also plotted in Figure A-2 (lower curve). For this relationship, Table A-3 summarizes, in the same fashion as for Table A-2, the increase in productivity attributable to the same breakwater.

Table A-3. Increase in ELCAS Productivity Due to a Sloping Float Breakwater if Attainable Values of Throughput Equal the Threshold Values in Tables A-1

Sea State (Incident Waves)	Throughput (TEUs per 20-hour day)		
	Without Breakwater	With Breakwater	Increase
1	160	160	0
2	150	160	10
3	100	157	57
4	0	120	120
5	0	0	0

Table A-4 shows how the figures in column 3 of Table A-2 were computed; Table A-3 was constructed similarly. Because each sea state is represented by a range of significant wave heights, it was necessary to assume that the throughput figure corresponding to each sea state would actually be attained for the wave height at the middle of each range. Then it was assumed that the sea is composed of local-wind-generated waves that are represented by the Pierson-Moskowitz spectrum. For this spectrum, there is a unique relationship between the dominant wave period (that which corresponds to the peak of the wave spectrum) and the significant wave height -- namely, $T = 2.76\sqrt{H}$, with wave height in feet and wave period in seconds. Wave attenuation by the breakwater (column 5) is a function of this wave period (Figure A-3). Combining the figures in columns 3 and 5 of Table A-4 yields the figure in column 6; that is, the value of significant wave height behind the breakwater. Reference to Figure A-2 then yields the throughput value in the last column of Table A-4, which is the source for column 3 of Table A-2.

In summary, Tables A-2 and A-3 show that a significant increase in productivity is expected when the incident wave conditions are state 3 and state 4. The amount of the increase depends on the particular relationship between the sea state and the limit on throughput imposed by the sea state. Two such relationships were analyzed. In one, the sea-state limit on throughput was assumed to equal the throughput goal; in the other, the limit was assumed to equal the threshold value of throughput.

Table A-4. Computation of Throughput at an Elevated Causeway With Sloping Float Breakwater Installed

Wave Conditions Incident at Breakwater				Reduction of Significant Wave Height by Breakwater (%)	Wave Conditions at Elevated Causeway: Significant Wave Height (ft)	Throughput at Elevated Causeway With Breakwater (TEU/20-hr)
Sea State	Range of Significant Wave Heights (ft)	Median Significant Wave Height (ft)	Dominant Wave Period (sec)			
1	0- 1	0.5	2.4	99	0+	250
2	1- 3	2.0	3.9	91	0.2	250
3	3- 5	4.0	5.5	68	1.3	240
4	5- 8	6.5	7.0	48	3.4	166
5	8-12	10.0	8.7	32	6.8	0

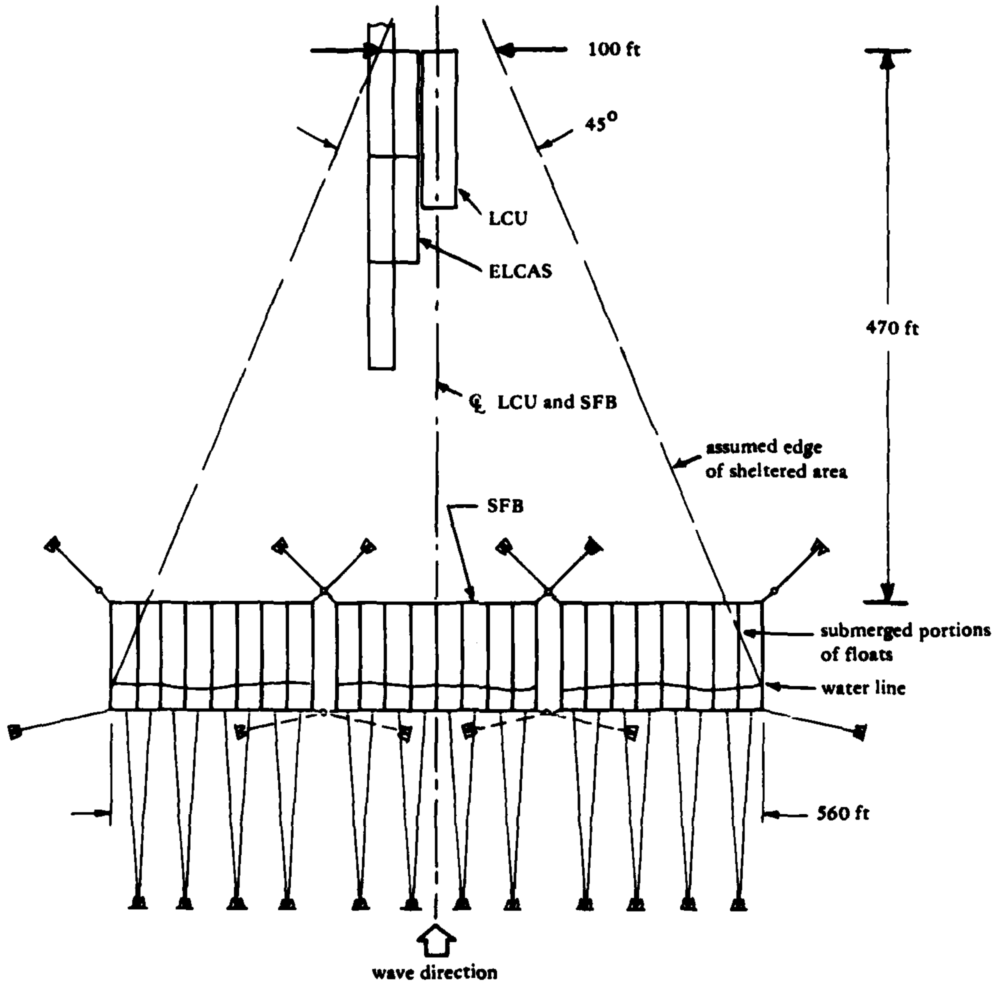

Figure A-1. Tentative layout for a sloping float breakwater (SFB) composed of 3x15 NL pontoon sections, with application to the elevated causeway system (ELCAS).

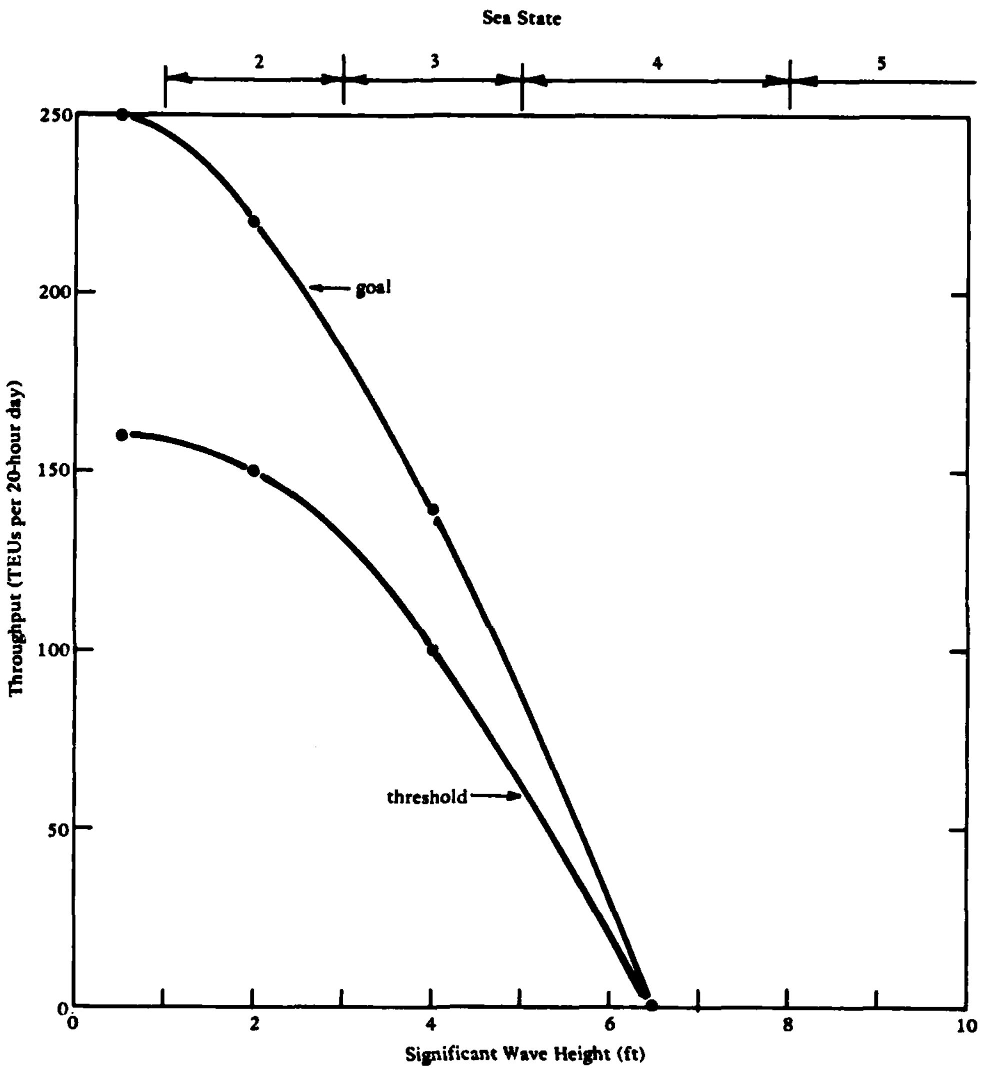

Figure A-2. Effect of sea state on ELCAS productivity (from Ref 8).

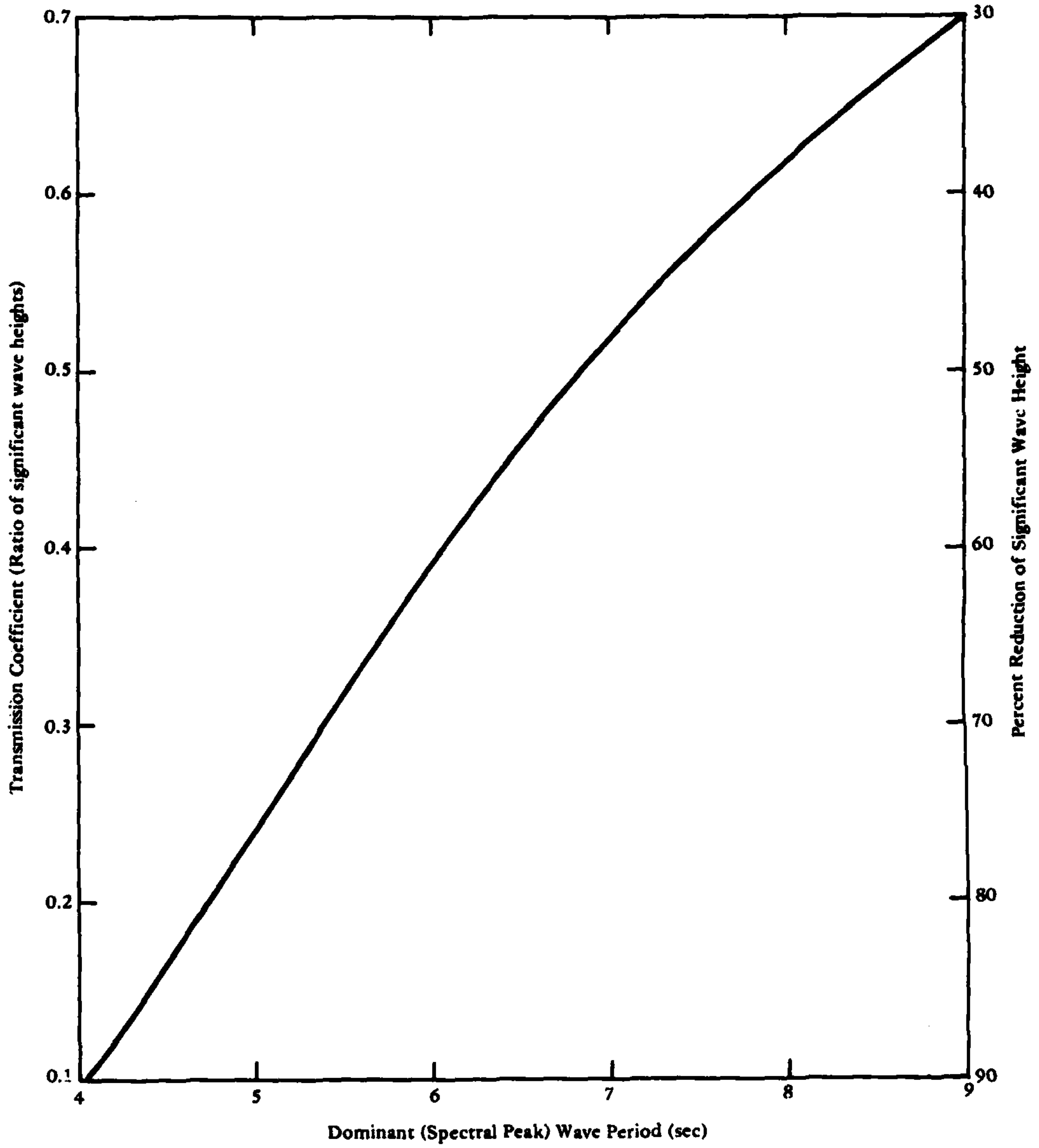

Figure A-3. **Estimated transmission characteristic for random waves (Pierson-Moskowitz spectrum) and for 90-foot-long floats in a depth of 30 feet (from Ref 5, Appendix F).**

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