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FLOATING BREAKWATER PERFORMANCE COMPARISON

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ABSTRACT

Wave-transmission and mooring-force data of the Tethered-Float Breakwater and Pole-Tire Breakwater (PT-Breakwater) were compared, and the basic costs (without mooring system) of two equivalent breakwaters determined. It was found that, for short-fetch applications, the PT-Breakwater was an order of magnitude less costly than the Tethered-Float Breakwater. The PT-Breakwater is a more effective wave-energy filter than a Tethered-Float Breakwater of equal size. For open ocean conditions neither of these breakwaters has so far been proven to be economically feasible.

1. INTRODUCTION

An increasing demand for mooring space and the simultaneous depletion of suitable construction sites that are naturally sheltered from wave action creates a need for artificial low-cost protection of marinas and harbors [11]. Floating breakwaters are frequently chosen to provide this protection, particularly in locations where large water depths, poor foundation conditions or large seasonal water-level changes have to be considered [1]. Although the basic concept of using floating structures as wave-attenuation devices is certainly not new [4,11], the idea of utilizing automobile tires or tethered floats as major functional components is [16,12]. The Floating-Tire Breakwater and Tethered-Float Breakwater are two innovative breakwater concepts that have received considerable attention in recent years from researchers, users and the public press and, as a consequence, are increasingly considered in the solution of wave-protection problems. For short-fetch applications (fetch less than approximately 10 km), or semi-protected regions, both appear to be technically and economically feasible [3,6,9]. For large-fetch exposed locations this has not been demonstrated to date.

In the endeavor to meet a particular wave-protection problem with a functional cost-effective engineering design, the practicing engineer is generally faced with the important task of assessing the relative merits of several technically feasible solutions. Using the available data on the tethered-float and floating-tire breakwaters, such an assessment is difficult to perform. It is our aim here to provide needed information on the relative cost, wave-attenuation performance and mooring forces associated with these structures. Additional factors such as breakwater size, useful life, aesthetics, maintenance and repair are certainly involved, but the two primary design factors to be considered here are the wave-attenuation performance and cost of the basic structure. For a specified degree of wave attenuation, the coastal engineer should be able to estimate and compare the cost of alternative structures able to provide this protection. Using presently available data, this cannot be done in the case of the tethered-float breakwater (TF-Breakwater) and floating tire breakwater.

The generic name of floating-tire breakwater is generally applied to three types of floating structures using pneumatic tires as construction components: the Wave-Maze Breakwater [8,10,16], the Goodyear Breakwater [3,5,7], and the Pole-Tire Breakwater [5,6]. For purposes of this report, the most recent entry into the field, the Pole-Tire Breakwater (PT-Breakwater) was chosen as a basis of comparison for the Tethered-Float breakwater (TF-Breakwater). This is particularly appropriate since the PT breakwater has exhibited very promising survival capabilities and wave-damping characteristics in waves up to 2 m in height during recent tests (1979) at the U.S. Army Corps of Engineers Coastal Engineering Research Center.

2. BASIC DESIGN FEATURES

Most breakwaters function primarily as wave reflectors. Although some of the intercepted wave energy is indeed dissipated upon the structure, the larger portion is generally redirected seaward again. The converse is true for the breakwaters considered here: they are predominantly dissipators of wave energy. Most of the incident wave energy is transformed into turbulence within and around the many components of these structures, while only a small portion is reflected. For the PT-Breakwater, ten times as much energy is typically dissipated as is reflected [5].

In the TF-Breakwater the basic energy dissipation units are oscillating spherical floats that are individually tethered to a rigid submerged frame. The frame, shown in Fig. 1, is ballasted to provide proper float submergence and transmits all wave-induced loads to the mooring system. A portion of the incident wave energy is converted into turbulence by the pendulum-like wave-induced oscillations of the tethered buoyant floats. The tethered float constitutes a tuned, selective wave-energy filter. Waves that are able to excite the float into high-amplitude oscillatory motions, out of phase with the wave water-particle motions, experience substantial levels of drag-related turbulent energy dissipation. Relatively long waves that cause the float to move in phase with the wave water-particle motions experience little decrease in energy, as do, on the other end of the spectrum, very short waves that are not able to set the float into motion at all. Some important design features of the TF-Breakwater are [14,15]:

1) Optimum tether length in deep water is approximately 10% of the peak energy wave length of the spectrum.

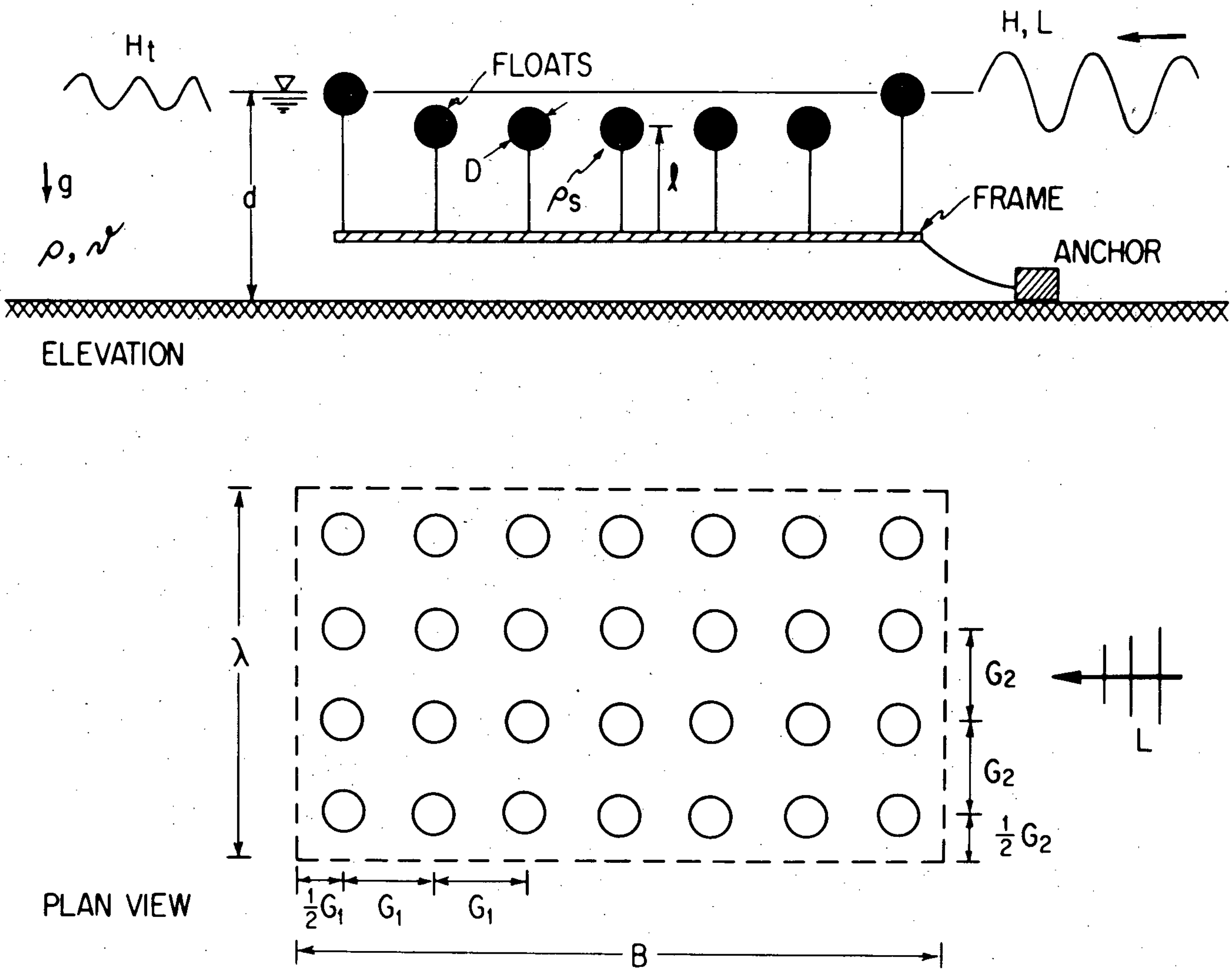

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Fig. 1. Definition sketch for Tethered Float Breakwater.

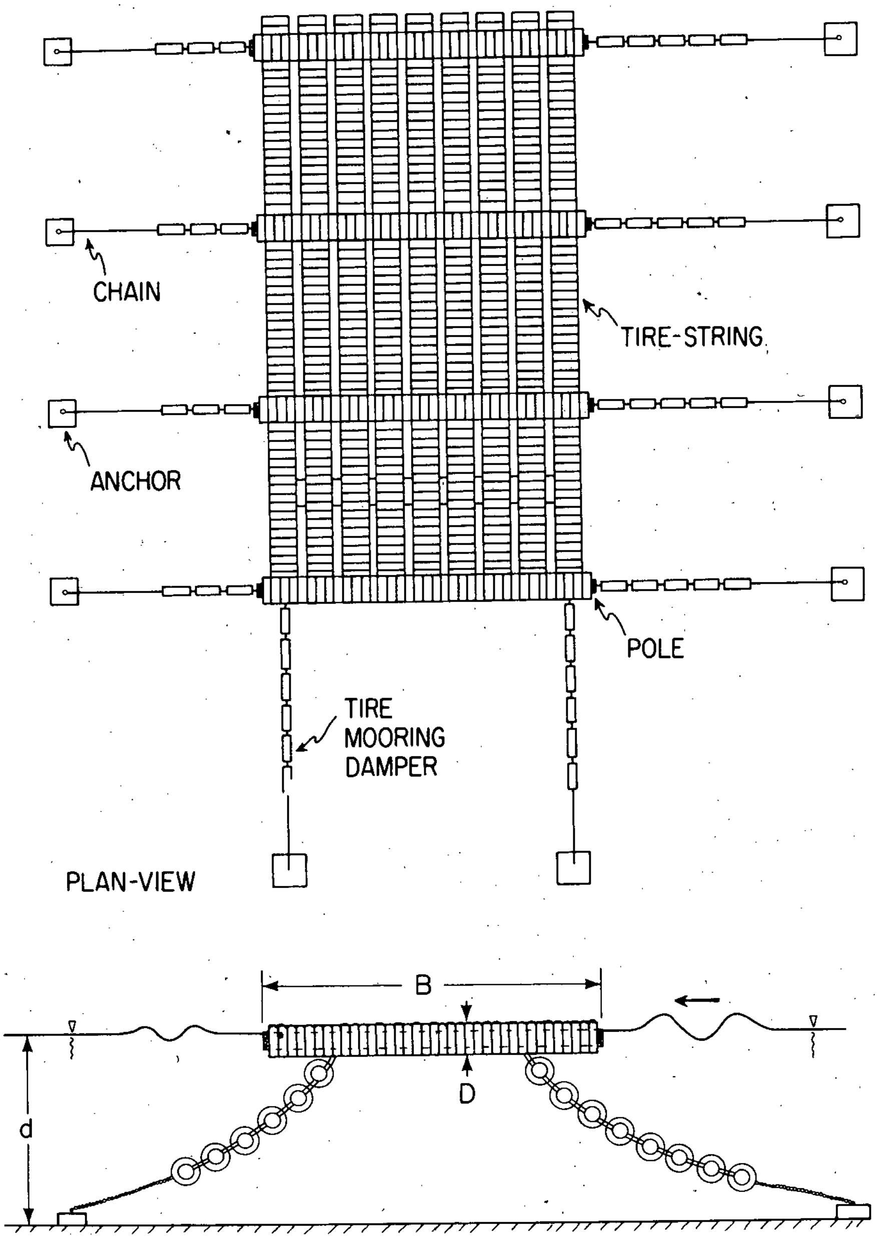

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Fig. 2. Schematic of Pole-Tire Breakwater.

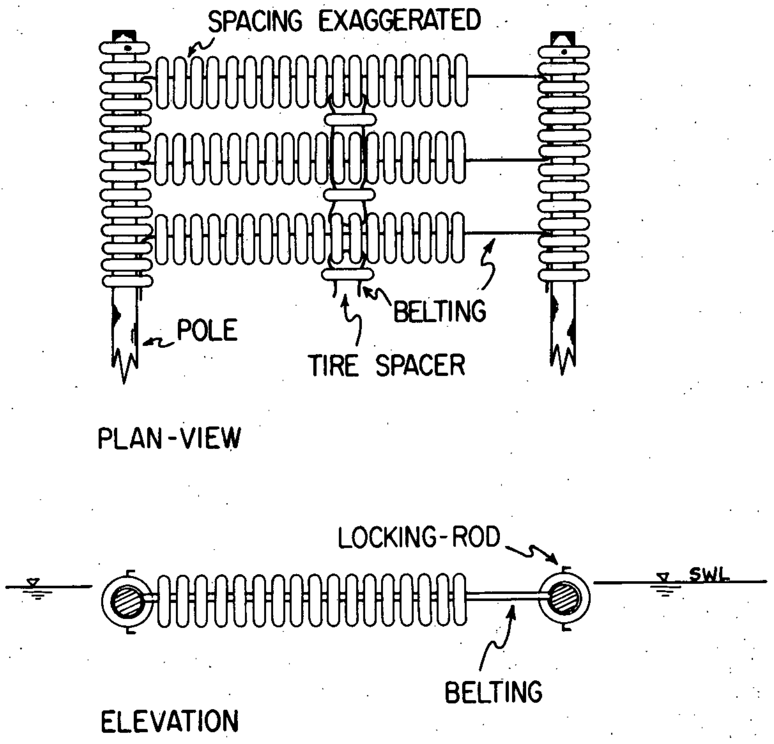

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Fig. 3. Basic tire arrangement in Pole-Tire Breakwater.

Plate 1. PT-Breakwater before testing at Coastal Engineering Research Center, Ft. Belvoir, Virginia: truck tires/steel pipe on left and automobile tires/telephone pole on right.

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Plate 2. Assembly of PT-Breakwater.

2) Best performance in deep water is attained with floats totally submerged approximately one-quarter diameter beneath the surface. Some floats must pierce the surface in order to provide reserve buoyancy.

3) Ballast frames must be flexibly interconnected and frames must be kept small with respect to the peak energy wavelength. This is necessary in order that both frame and floats follow the sea surface and thus prevent emergence of floats in the wave trough (avoiding associated shock loadings during resubmergence).

4) A flexible terminator or boot must be provided at the base of the tether in order to reduce bending stresses and ensure reasonable life expectancy of the tether assembly.

5) Reasonable diameters of the TF-Breakwater will be of the same order as the significant wave height.

In the case of the PT-Breakwater the basic energy dissipation units and major structural components are discarded pneumatic tires (truck, automobile, earthmover, etc.). These are interconnected and, in conjunction with a rigid longitudinal member (telephone pole, steel or concrete pipe, etc.), form an integral part of the structure, as can be seen in Figs. 2 and 3 and Plates 1 and 2. The PT-Breakwater is essentially a dense mat composed of a large number of interconnected tires floating near the surface, with approximately 85% of the structure submerged. It functions predominantly as a wave-energy dissipator: most of the incident wave energy is transformed into turbulence in and around the many elements of the structure, with only a small portion being reflected. The breakwater is interconnected with conveyor belting [2], as shown schematically in Fig. 3.

3. LABORATORY DATA AND ANALYSIS

3.1 Experimental Conditions

Models of the TF and PT-Breakwaters were tested in the large wind wave tank (109 m × 4.5 m × 1.5 m) of the Hydraulic Laboratory at the Canada Centre for Inland Waters in Burlington, Ontario, shown in Fig. 4 and Plate 3. Additional full-scale tests of the PT Breakwaters were performed at the University of Delaware and the U.S. Army Coastal Engineering Center. Models of the TF Breakwater were constructed at two scales using 5 cm spherical styrofoam floats and 15 cm pressurized plastic balls. They were constructed according to guidelines given by Seymour [14,15]. Tires from a 1/8-scale model automobile were utilized in the construction of the PT-Breakwater models. Telephone poles were modeled from wooden hand-rail material.

In the test section shown in Fig. 4, the tank was subdivided into three channels (1 m, 1 m, and 2.5 m wide) so that two breakwaters as well as the undisturbed incident wave could be monitored simultaneously. For each breakwater the transmitted wave and mooring force on the seaward mooring line were recorded. Waves were generated with a programmable piston-type wave machine. Most experiments were performed with regular

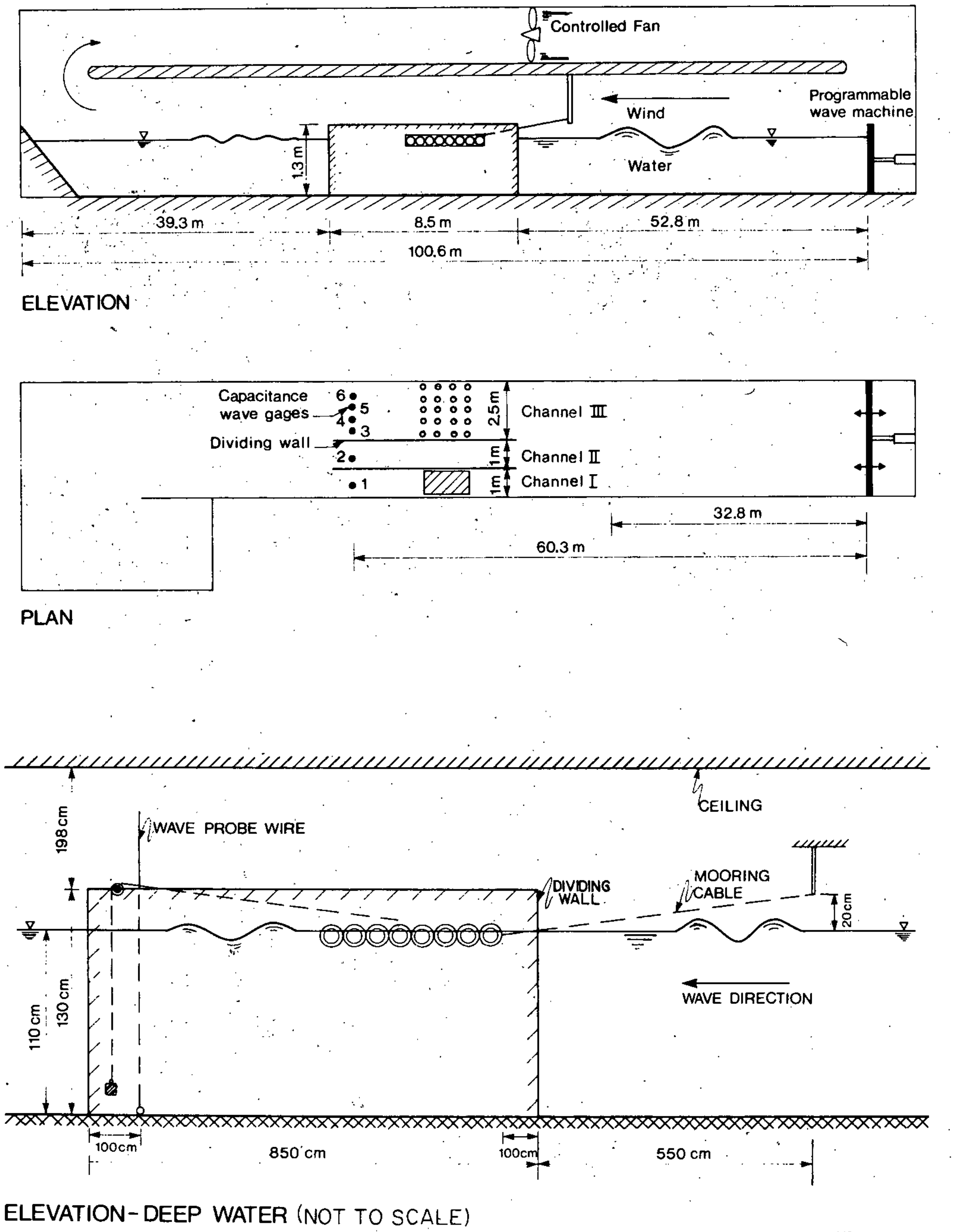

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Fig. 4. Schematic diagram of wave tank at the Canada Centre for Inland Waters.

Plate 3. One-quarter scale model of TF-Breakwater in drained wave tank at Canada Centre for Inland Waters (model of Goodyear Breakwater in foreground).

waves, but machine-generated and wind-generated wave spectra were also investigated. In the case of irregular waves, the transmission coefficient $C_t = H_t/H$ and wave steepness H/L were evaluated using the peak-energy wave length and the average wave height as obtained from time-series analysis of the water surface elevation.

3.2 Dimensional Analysis

For the breakwater configuration shown in Fig. 1 we assume that the transmitted wave height H_t is an unknown function of the following variables:

$$H_t = f(H,L,d,\rho,\nu,g,D,\rho_s,\ell,B,\lambda,N) . \qquad (1)$$

Here H,H_t = incident and transmitted wave height; L = wave length; d = water depth; ρ = fluid density; ν = kinematic viscosity; g = gravitational acceleration; D = float diameter; ρ_s = float density; ℓ = tether length; B = beam dimension of breakwater; λ = length of breakwater; N = number of floats in breakwater. Note that the transmitted wave height H_t is assumed to depend only upon the total number of floats N, not their geometrical arrangement, as long as no interference between balls occurs. According to Buckingham's Pi Theorem, this is equivalent to the following non-dimensional relationship:

$$H_t/H = f[L/B,\ H/L,\ \ell/d,\ \ell/D,\ \rho_s/\rho,\ B/D,\ \lambda/D,\ \sqrt{B\lambda/ND^2},\ D\sqrt{gH}/\nu] \quad (2)$$

Note that the last term is a Reynolds number and that the next to last term is simply a measure of the float spacing, e.g., with $G_1=G_2$, $B=nG_1$, $\lambda=mG_2$ in Fig. 1 and $N = nm$ = number of floats; it follows that $\sqrt{B\lambda/ND^2} = G_1/D$. We simplify this expression by:

i) Keeping some terms the same in all models .... ρ_s/ρ, ℓ/D ;

ii) Considering only quasi-two-dimensional tests, i.e., no diffraction influences from ends .... λ/D ;

iii) Assuming that some parameters are of second-order importance if they are sufficiently large ... B/D, $D\sqrt{gH}/\nu$

For such experiments:

$$C_t = f[L/B,\ H/L,\ \sqrt{B\lambda/ND^2},\ \ell/d\ ] \quad , \qquad (3)$$

i.e., the transmission coefficient $C_t = H_t/H$ depends primarily upon the relative wavelength L/B, the wave steepness H/L, the effective float spacing $\sqrt{B\lambda/ND^2}$ and the relative draft ℓ/d. For the mooring force we obtain, similarly:

$$F/\gamma B^2 = f[L/B,\ H/L,\ \sqrt{B\lambda/ND^2},\ \ell/d\ ] \qquad (4)$$

For the PT-Breakwater, following procedures similar to those applied above, we may anticipate a relationship of the form

$$C_t = f[L/B,\ H/L,\ B/D,\ D/d] \qquad (5)$$

$$F/\gamma B^2 = f[L/B,\ H/L,\ B/D,\ D/d] \qquad (6)$$

where D now designates the tire diameter.

3.3 Wave-Attenuation Performance

In Fig. 5 the wave-height transmission ratio C_t has been plotted as a function of relative wave length L/B for three models of the TF-Breakwater. These models were constructed according to guidelines given by Seymour and are similar to structures tested in San Diego Bay, California [14,15]. An averaged wave-height transmission curve representing Seymour's predictive model [14] for several wave spectra with peak energies at L/B = 0.6, 1.0 and 1.7 has been included for comparison. Agreement in basic trends is evident, but measured C_t values are generally larger. Although Reynolds' numbers appear to be sufficiently high for proper modeling of float dynamics (and to maintain the turbulent character of the drag-related energy dissipation mechanism that governs at larger scales), it is possible that some Reynolds-number influences are being observed in the case of the small breakwaters. Seymour performed laboratory and field experiments on the TF-Breakwater and found his predictive model to be satisfactory [14]. For purposes of comparison it will be assumed that Seymour's predictive model describes the wave-transmission characteristics of the TF-Breakwater correctly.

In Fig. 6 the wave transmission curve for the PT-Breakwater is shown as a dashed line that increases monotonically as a function of L/B. This curve corresponds to $H/L = 0.04$ and is based upon extensive data, both model and full-scale. The data will not be included here because it is already well documented [5,6]. This performance curve was originally established using tires 8.4 cm in diameter, but has also been confirmed by full-scale experiments with truck and automobile tires 64 cm and 100 cm in diameter. A fundamental difference in the filtering characteristic of these structures is evident in Fig. 6: the TF-Breakwater is a tuned discrete filter that is most effective around $L/B = 0.7$, and becomes increasingly less effective at wave lengths other than this (either shorter or longer), whereas the PT-Breakwater is a monotonic filter that becomes increasingly more effective as the wave length decreases. It is apparent that the PT-Breakwater offers substantially more wave protection (lower C_t levels) than a TF-Breakwater of equal size.

3.4 Mooring Forces

The data presented here applies to a single-point mooring that provides an essentially horizontal restraining force on the seaward side of the breakwater, similar to the anchor line depicted in Fig. 1. Only the peak mooring force recorded during the experiment is reported (excluding wave-generator stop-start transients). Although accurate scaling of elastic properties and damping characteristics of the mooring system could not be assured, it was found that satisfactory agreement with full scale measurements existed for similar breakwaters tested in the past [5,6]. In tests with irregular waves the wave length corresponding to the spectrum energy peak is utilized in the wave length parameter L/B.

Mooring force data for the TF-Breakwater is plotted in Fig. 7 for large wave steepness ($H/L > 0.04$), and Fig. 8 for low wave steepness

($H/L < 0.04$). For comparison, the corresponding mooring force curve for the PT-Breakwater ($H/L = 0.06$, $D/d = 0.06$) has also been included in Fig. 7. It is evident that the peak mooring force for the PT-Breakwater is larger than that of a TF-Breakwater of equal size, but it should be recalled that such a PT-Brekwater is also more effective (Fig. 6). In previous studies [5] a useful empirical relationship for the peak mooring forces on a PT-Breakwater was determined to be

$$F/\gamma B^2 = 0.15(H/L)^2(L/B)\tanh(L/B) \quad . \qquad (7)$$

This indicates that for a given wave length and structure the peak mooring force grows rapidly as a function of wave height. Mooring force measurements performed by Seymour with waves of very low steepness are also included in Fig. 8. It is apparent that these forces are significantly higher than those from this investigation. The two force measurements at a low wave steepness of $H/L = 0.02$, for example, are as high as those for $H/L = 0.06$ in the present study.

4. COST COMPARISON

The following material is intended to be of assistance to the coastal engineer in a preliminary assessment of relative costs associated with the TF- and PT-Breakwaters. The principle of "equal wave protection" has been utilized here in order to arrive at meaningful, comparable cost figures for the different structures. This implies that the size of each structure was first fixed so as to provide equal levels of wave protection from the same incident wave. The associated breakwater costs were then determined using these dimensions. The resulting cost figures may therefore be meaningfully compared as costs associated with two equivalent solutions to a particular wave protection problem. Cost estimates are given for major cost-contributing components of the structure, the mooring system has not been included.

4.1. Equivalent Breakwaters

Figure 6 indicates that over practically the full spectrum of wave lengths L/B, the wave attenuation performance of the PT-Breakwater is superior to that of a TF-Breakwater of equal size. The only exception to this is a narrow band of essentially equal wave attenuation from $L/B = 0.65 - 0.85$. This narrow region would be of importance only in the case of monochromatic laboratory waves and not with regards to the broader wind-generated spectra encountered in actual design cases. In view of this disparity in wave attenuation performance, it is clear that one should not compare the cost of two breakwaters of equal size, for different "amounts of wave protection" would then be purchased with each structure. We therefore determine first how large a TF-Breakwater must be in order to provide approximately the same level of wave protection as a PT-Breakwater. In Fig. 9 a PT-Breakwater with beam B is compared to a TF-Breakwater with beam dimension $B_{TF} = 1.5B$, and from this conclude that approximate equivalence of wave protection has been attained. In the simple design procedure used here, the beam dimension of the TF-Breakwater is chosen so that the region of maximum effectiveness of the breakwater (the trough

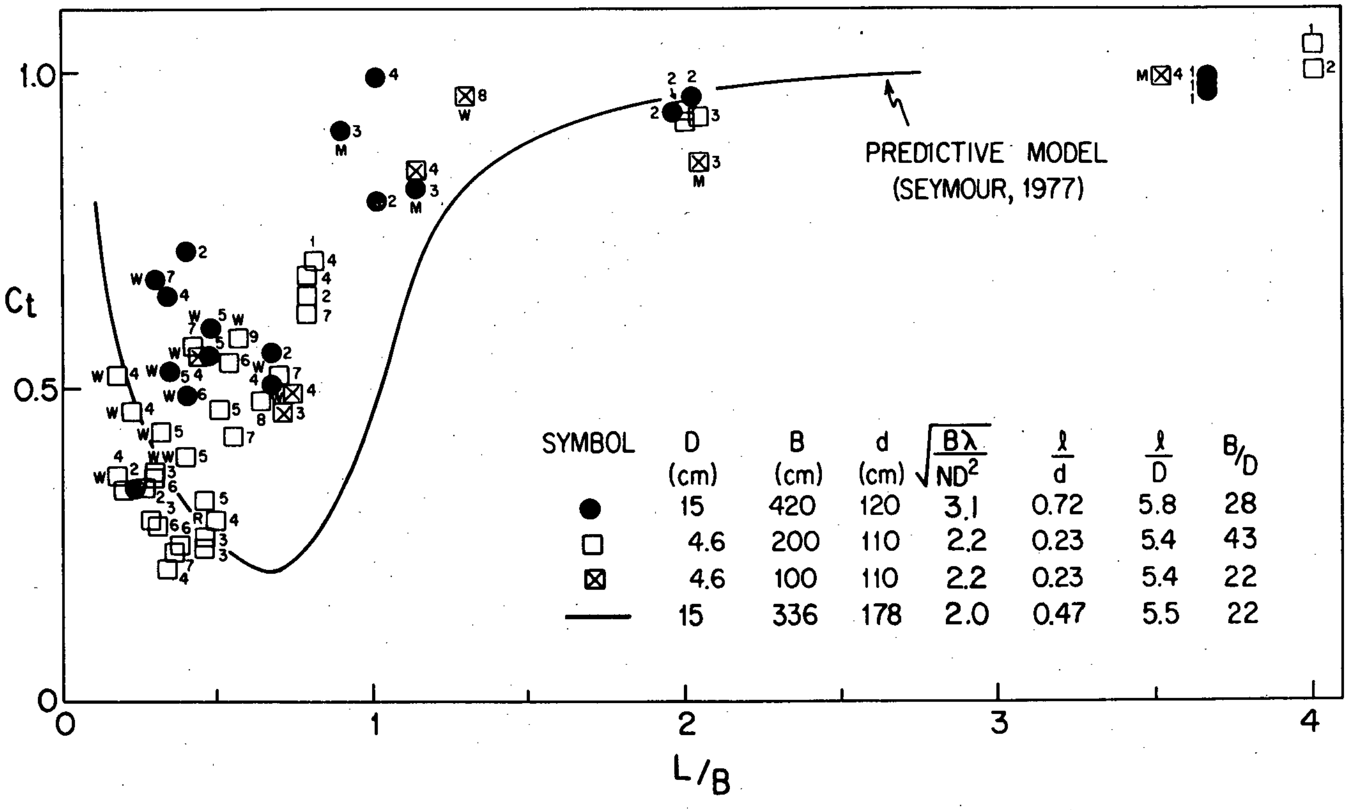

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Fig. 5. Wave-height transmission data for TF Breakwater.

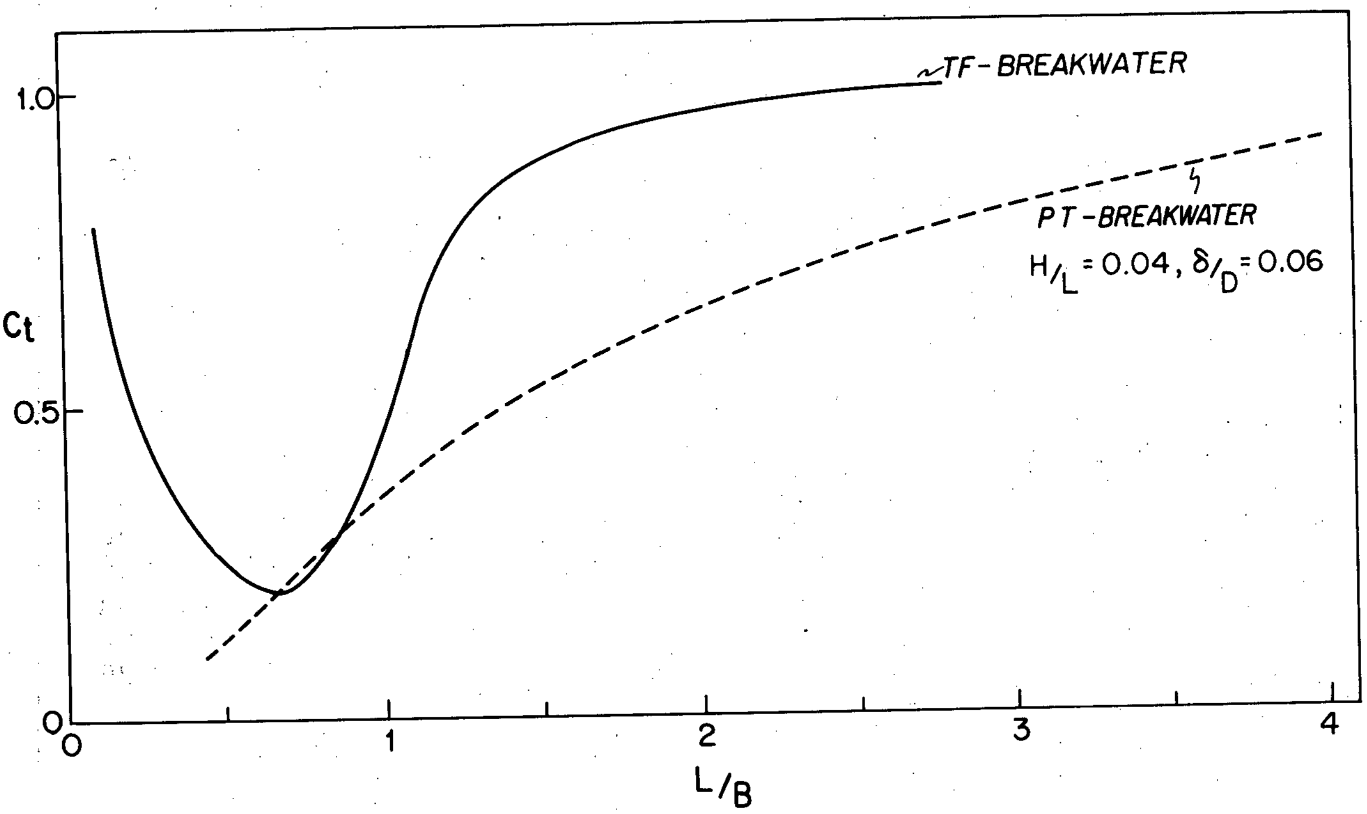

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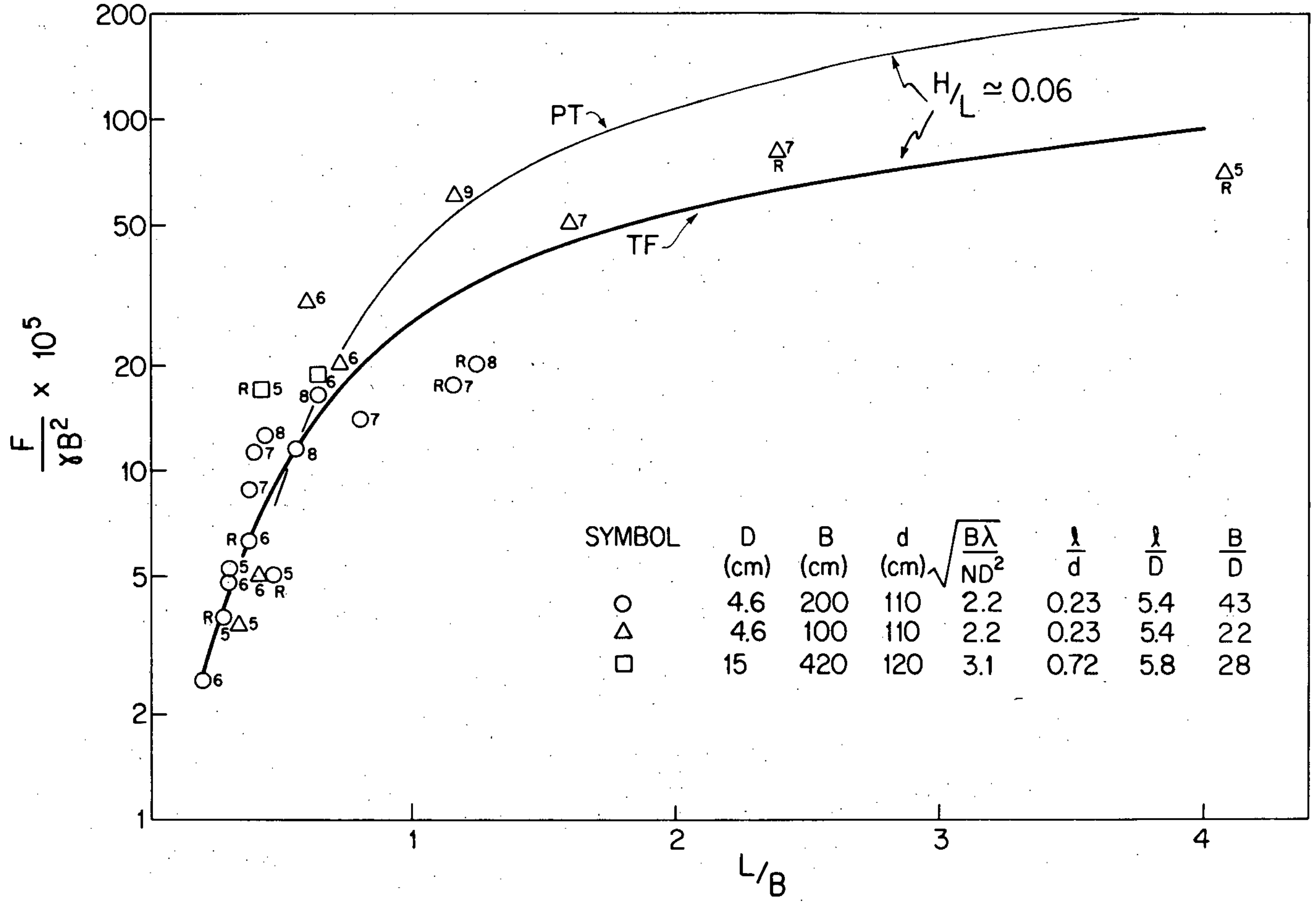
Fig. 6. Wave transmission curves for TF and PT Breakwaters of equal size.



SYMBOL	D (cm)	B (cm)	d (cm)	$\sqrt{\frac{B\lambda}{ND^2}}$	$\frac{\ell}{d}$	$\frac{\ell}{D}$	$\frac{B}{D}$
○	4.6	200	110	2.2	0.23	5.4	43
△	4.6	100	110	2.2	0.23	5.4	22
□	15	420	120	3.1	0.72	5.8	28

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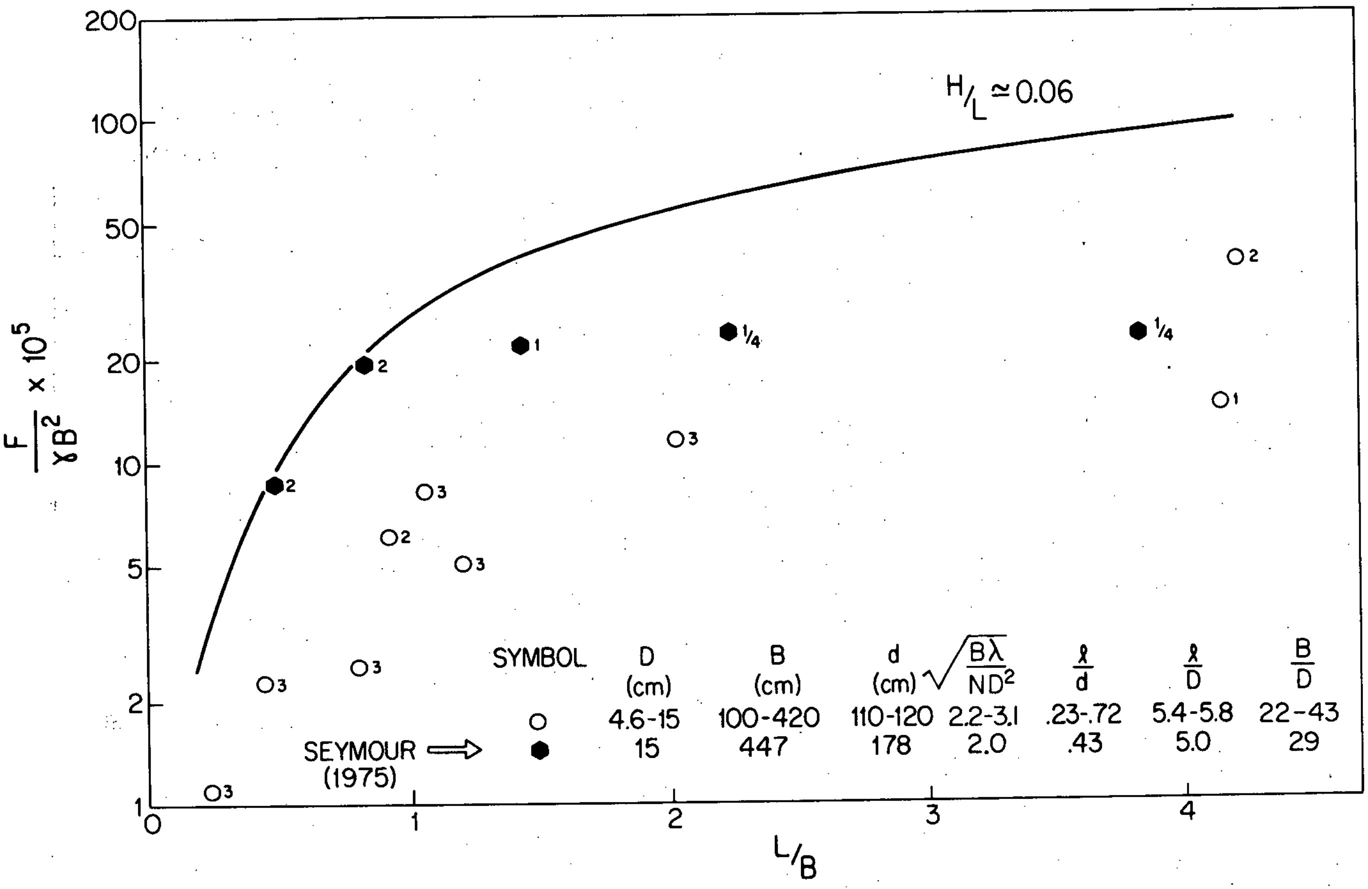
Fig. 7. Peak mooring force data for the TF Breakwater and $H/L > 0.04$ (curves for TF and PT Breakwaters, $H/L \cong 0.06$).



SYMBOL	D (cm)	B (cm)	d (cm)	$\sqrt{\frac{B\lambda}{ND^2}}$	$\frac{\ell}{d}$	$\frac{\ell}{D}$	$\frac{B}{D}$
○	4.6-15	100-420	110-120	2.2-3.1	.23-.72	5.4-5.8	22-43
SEYMOUR (1975) ⇒ ●	15	447	178	2.0	.43	5.0	29

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Fig. 8. Peak mooring force data for the TF Breakwater and $H/L < 0.04$ (curve for $H/L \cong 0.06$).

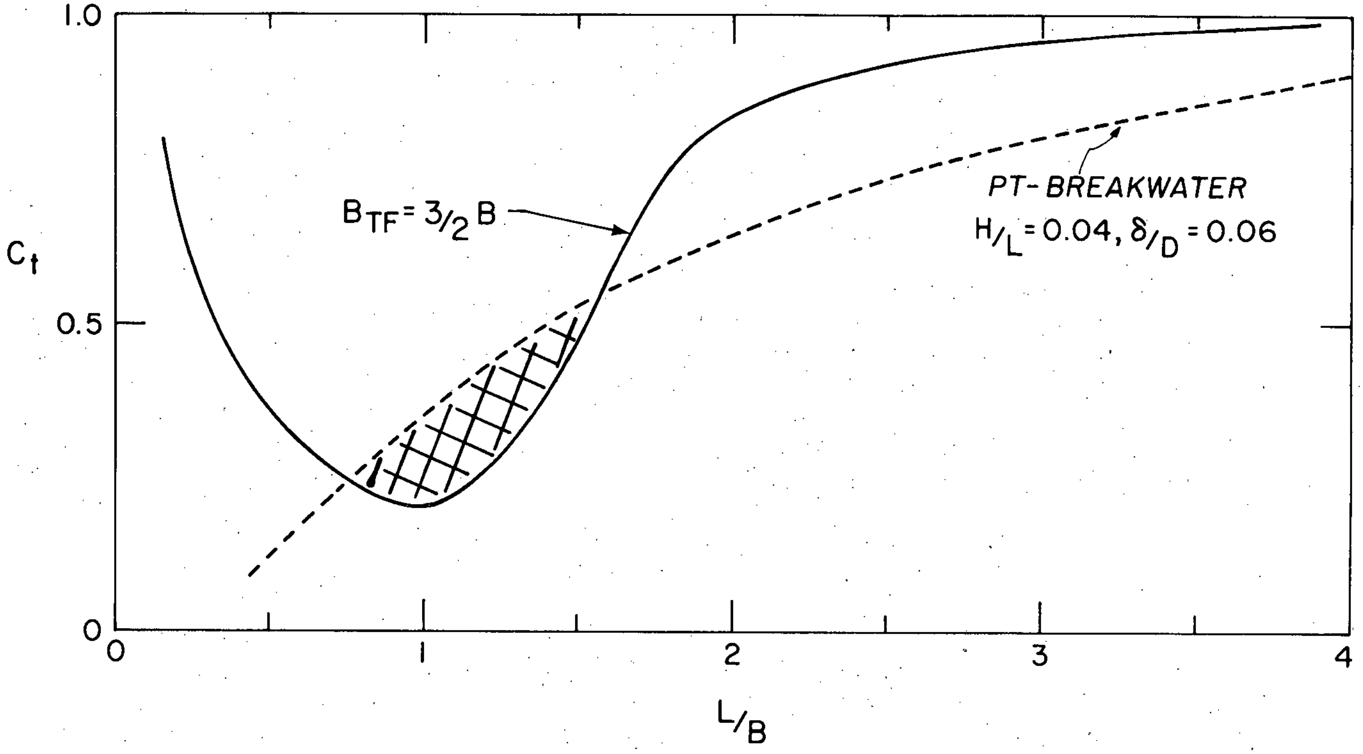

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Fig. 9. Wave transmission curves for PT Breakwater and larger TF Breakwater (B_{TF} = 3/2 B).

region at $L/B = 1$) corresponds to the design wave length or, equivalently, the peak energy wave length of the incident spectra. With this in mind, and recognizing that most short-fetch wave spectra are much broader than the cross-hatched region around the incident wave-energy peak at $L/B = 1$, it is reasonable to conclude that the two breakwaters are, for most practical purposes, equal in wave attenuation performance. The beam-size relationship to be used in the cost comparison is consequently $B_{TF} = 1.5B$, i.e., the TF-Breakwater requires a 50% larger planform area.

Considering the case of a design-wave period (or peak energy period) of $T = 3.0$ sec and a wave height of $H = 1.0$ m, and assuming deep-water conditions, one finds that $L = 14.0$ m and $H/L = 0.07$. This wave length should correspond to $L/B = (3/2)L/B_{TF} = 1.0$ in Fig. 9 in order to maximize the effectiveness of the TF-Breakwater. The beam dimension necessary to achieve this is consequently $B_{TF} = 3/2\ L = 21.0$ m. To attain comparable performance with the PT-Breakwater requires a beam dimension of $B = 1.0\ L = 14.0$ m. The corresponding peak mooring forces can be determined from Fig. 7 using $H/L = 0.06$ as an approximation. For both the TF-Breakwater ($L/B = 2/3$) and the PT-Breakwater ($L/B = 1.0$), the peak mooring forces turn out to be very nearly equal, $F = 780\ \mathrm{Nm}^{-1}$.

4.2 Cost Estimates

The following cost comparison is based predominantly upon the cost of major structural components required for assembly of the breakwater. Construction labor costs are also included, but mooring system costs and expenditures for construction equipment that may be utilized during assembly and launching are not. In the absence of site-specific data on mooring and launching costs, the total component cost figures given here become useful first approximations of the installed cost, particularly in the case of the TF-Breakwater for which the neglected cost items (mooring system and launching) are generally only a small fraction of the total.

Cost data for the TF-Breakwater were obtained from a 1977 "Feasibility Study to Evaluate the Commercial Market for a Tethered Float Breakwater System" [Maritime Administration, U.S. Department of Commerce]. Cost figures for the PT-Breakwater reflect recent construction experience (1979) with two breakwaters at the State University of New York in Buffalo: these utilized telephone poles and steel pipes 12 m in length in conjunction with automobile and truck tires, respectively. The utilization of automobile tires is financially attractive particularly because they can generally be obtained in large quantities at no cost. In the US the cost associated with the disposal of a truck tire is typically US $1 (landfill sites generally charge user fees and, to improve compaction, also demand that tire casings be cut up prior to disposal). Trucking and tire-recapping firms are consequently willing to not only supply tires, but deliver them to the breakwater construction site as well: in most cases they still save money. All cost figures were adjusted to 1980 levels by assuming annual price increases of 10%.

COMPONENT COST ESTIMATES: TETHERED FLOAT (TF) BREAKWATER

Module Dimensions : $B = 21.0$ m, $\lambda = 3.80$ m

Materials : Spherical floats ($D = 38$ cm, $\gamma = 0.04$ gm cm^{-3}),
Tethers and flexible tether terminals,
Steel ballast frames with flexible couplings
(3 frames 7.00 m × 3.00 m per module),
Concrete ballast.

Item	*Quantity*	*Unit Cost (US $)*	*Total (US $)*	*Cost per meter (US $)*
Float unit (float, tether, flex. terminals)	135	24.30*	3279.30	863.00
Ballast frame (incl. flexible couplings)	3	465.90*	1397.60	367.80
Concrete ballast	4.2 m^3	113.10*	475.20	125.00
Assembly (labor only)	14 hrs	6.00	84.00	22.10

Cost per meter of breakwater (excluding mooring system) = $1377.90

*Source: Ref. (9)

COMPONENT COST ESTIMATES: POLE-TIRE (PT) BREAKWATER

Module Dimensions : $B = 14.0$ m, $\lambda = 4.00$ m

Materials : Automobile tires (typically $D = 64$ cm),
Telephone poles (4 m spacing),
Conveyor belting (3-ply, 14 cm wide, 5000 N cm^{-1} breaking strength),
Nylon bolts, nuts, washers (13 mm or equivalent).

Item	*Quantity*	*Unit cost (US $)*	*Total (US $)*	*Cost per meter (US $)*
Tires	403	none	none	none
Tying material (conveyor belting)	180 m	0.90	162.40	40.60
Nylon bolts, nuts, washers	105	0.55	57.80	14.40
Telephone poles	1	50.00 (salvage @ 15% new)	50.00	12.50
Assembly (labor only)	18 hrs	6.00	108.00	27.00

Cost per meter of breakwater = $94.50
(excluding mooring system)

Note: The use of steel pipe (41 cm diam, 6 mm wall) and truck tires will increase the cost by approximately $130 per meter.

5. CONCLUSIONS

1) The Tethered-Float and Pole-Tire Breakwaters are technically feasible solutions to wave protection problems in short-fetch (say, less than 10 km) or semi-protected locations.

2) The Pole-Tire Breakwater is a more effective wave-energy filter than a Tethered-Float Breakwater of equal size.

3) In a typical short-fetch design case, a Tethered-Float and Pole-Tire Breakwater were found to compare as follows (for equal levels of wave protection):

a. The Pole-Tire Breakwater costs less than one-tenth as much as the Tethered-Float Breakwater.

b. Peak mooring forces are approximately the same.

c. The Pole-Tire Breakwater requires less space.

6. ACKNOWLEDGMENTS

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