

This paper is to be published in the Proceedings of Breakwaters '88, Institution of Civil Engineers, United Kingdom.

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**SOME NORTH AMERICAN EXPERIENCES
WITH FLOATING BREAKWATERS**

by

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January 1988

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MANAGEMENT PERSPECTIVE

Floating breakwaters offer a relatively inexpensive alternative for protection from wave attack at marinas or other shore facilities. This paper collates recent field experience with laboratory experience. In so doing, designers can have increased confidence as to the range of wave conditions for which floating breakwaters are realistically applicable.

PERSPECTIVE - GESTION

Le brise-lames flottant constitue une solution relativement peu coûteuse pour protéger les ports de plaisance et autres installations riveraines contre l'action des vagues. Ce mémoire rassemble les résultats d'expériences récentes effectuées sur le terrain et d'expériences en laboratoire. Ainsi, les concepteurs pourront avoir une meilleure idée de la gamme de conditions de vagues pour lesquelles les brise-lames flottants peuvent être utilisés avec succès.

RÉSUMÉ

Ce mémoire fait état d'expériences effectuées sur le terrain avec des brise-lames flottants au cours des 10 à 15 dernières années sur les côtes est et ouest de l'Amérique du Nord. Il existe des préférences régionales : sur la côte est, le type le plus courant est le brise-lames constitué de pneus, tandis que sur la côte ouest, on préfère les brise-lames de béton (à flotteur simple ou double). Les caractéristiques générales de ces deux types de brise-lames sont décrites, accompagnées d'un exemple. Sur la côte est, les expériences ont été faites en eau douce et en eau salée, tandis que sur la côte ouest, elles l'ont été plutôt en eau salée.

SYNOPSIS. This paper discusses field experience with floating breakwaters during the past 10-15 years on the East and West Coasts of North America. Regional preferences exist; on the East Coast the most common type is the floating tire breakwater, while on the West Coast concrete units (single pontoon or catamaran) are prevalent. General features of both categories are discussed, and one example of each is presented. East Coast experience is divided between freshwater and saltwater sites; saltwater sites are most common on the West Coast.

INTRODUCTION

1. Floating breakwaters must be sited with care. The local wave climate must be assessed to see if a floating breakwater is indeed feasible and then the breakwater must be sized to provide adequate wave attenuation. The degree of wave protection sought is somewhat subjective and varies with type and size of craft. Guidelines have been proposed for wave conditions in sheltered harbors (ref.1). For example, for head seas and a design wave period between 2 and 6 seconds (more than spanning the range of application of floating breakwaters) a "good" wave climate is one for which 0.3m waves are exceeded no more than once per year.

2. Until the early 1980's, operational problems with floating breakwaters were often the rule rather than the exception. A number of problems are listed here; many are common to both types of breakwaters:

- Inadequate buoyancy, including effects of biofouling.
- Connections between modules and/or individual components of the breakwater.
- Mooring and anchoring systems.
- Corrosion of connections and mooring lines.
- Accumulation of litter and debris.
- Boat-wake transmission, diffraction, and reflection; boat waves may be as large as wind waves at the site.
- Unplanned multiple use; this condition may or may not be anticipated, often is recreation oriented, and may lead to questions of safety.

FLOATING TIRE BREAKWATER

3. The predominant type of floating breakwater that has been used on the Great Lakes and the East Coast of the U.S.A. has been the floating tire breakwater (FTB). More specifically, a design developed in the early 1970's by the Goodyear Tire and Rubber Company and now known as the Goodyear FTB design, has been by far the most common floating breakwater. In a 1982 survey of floating breakwater projects in the eastern United States (ref.2) 75 percent of all identified floating breakwater projects were Goodyear FTB's. FTB's dissipate wave energy primarily by transforming it into turbulence within and around tires; wave reflection is minor.

4. The Goodyear design consists of modules, each containing 18 tires, interconnected to form a flexible mat as shown in Figure 1. State-of-the-art construction guidelines are available (ref.3). Many early Goodyear FTB installations failed for two main reasons: lack of sufficient reserve buoyancy and inappropriate choice of module binding and fastening materials (ref.2).

5. Some early FTB's relied solely on air trapped in the tire crowns to provide flotation. It is now recognised that supplemental flotation must be provided to ensure continued flotation. The buoyancy of an FTB may decrease with time for the following reasons:-

- Increase in weight due to marine growth on the tires

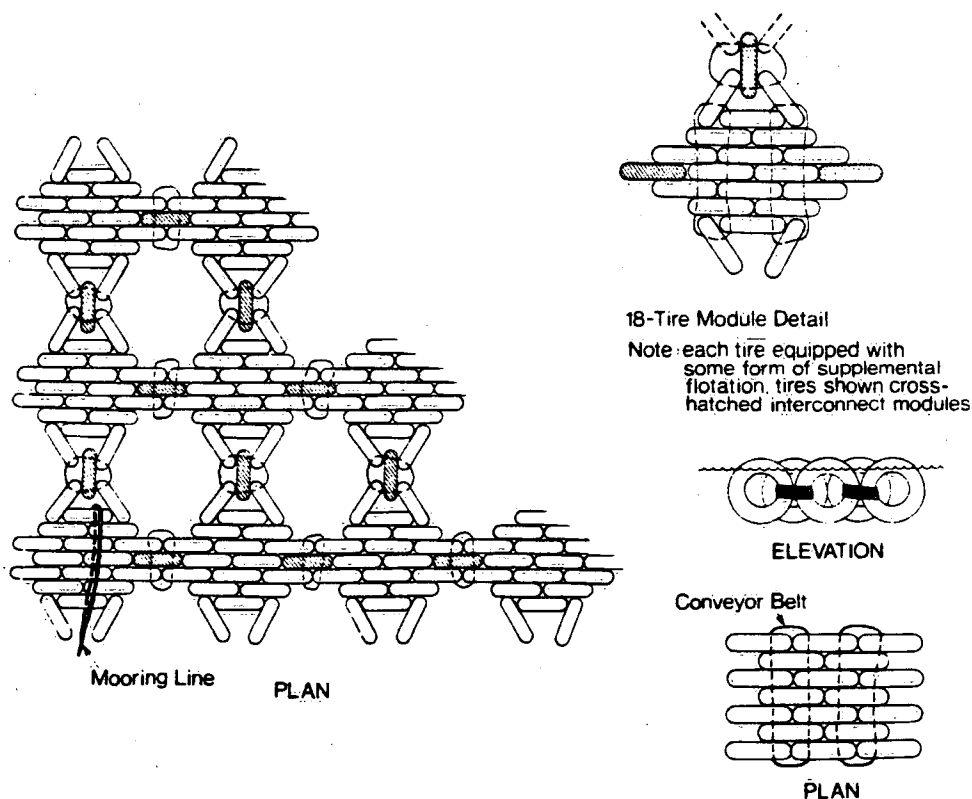


Fig.1. Arrangement of tires in a Goodyear FTB (ref.3)

- Increase in weight due to accumulation of sediment in the bottoms of tires.
- Loss of trapped air and/or effectiveness of supplemental flotation decreases, e.g. polyurethane foam in the tire crowns (the most common supplement) breaks up and/or absorbs water.

6. Field testing of module binding materials has led to recognition that conveyor belting is preferable in most situations (ref.4). The belting should be at least 12mm thick, 80mm wide, and should have 3 or more synthetic fabric plies. Overlapping conveyor belt ends can be fastened with a pattern of at least 2 bolts, nuts, and washers. Steel hardware is suitable for freshwater FTB's, while nylon hardware, dyed black, is more durable in saltwater.

7. Table 1 provides summary information on several successful floating breakwaters, 11 of which are Goodyear FTB's. All but one of the FTB's used conveyor belting for module binding. Except where noted, all breakwaters listed were still in use in late 1987. This list is not a complete catalogue of successful floating breakwaters in the region, but represents those familiar to the authors. From Table 1, several points may be noted for these installations:

- A-frame breakwaters have survived almost 20 years and are still in use.
- Goodyear FTB's have survived 10 years and are still in use.
- Maximum fetches are less than 20 km.
- Car tires have been used more frequently than truck tires in Goodyear FTB's.
- Three "old" Goodyear FTB's built without supplemental flotation are still being used successfully with regular maintenance to recharge the trapped air.
- Supplemental flotation has been provided in a variety of ways.

8. Most of the FTB's in the Great Lakes and East Coast regions have been installed to protect private marinas. Owners generally report satisfaction with them (refs.2,5). For FTB's built to state-of-the-art guidelines, the greatest maintenance requirements are removal of trapped debris and litter and removal and storage of the breakwater at locations where moving ice packs constitute a mooring problem. Occasional replacement of some belting and mooring lines is required.

BURLINGTON, ONTARIO FTB

9. A large Goodyear FTB comprising 35,000 car tires (diameter $D = 0.64\text{m}$) was constructed at Burlington, Ontario in 1981. A 64 module x 9 module (129m x 18.9m) FTB section was monitored in the field during 1981 and 1982 (Figure 2). Waves were measured with four bottom-mounted pressure transducers, two on each side of the FTB test section. Wave-induced loads on the steel chain mooring lines were measured with two electronic load cells and four mechanical "scratch" gauges. The field monitoring programme has been documented (ref.6) and

Table 1. Summary information on some successful floating breakwaters in the Great Lakes and the East Coast U.S.A.

Location	Year Built	Max Fetch (km)	Max Depth (m)	Dimensions			Flotation	Comments
				Length (m)	Beam (m)	Draft (m)		
Thunder Bay, Ont.	1968	4.8	6.2	110	8.5	3.2	Pipes	Centrebored A-frame (ref.14)
Geosnoque, Ont.	1969	5.5	4	61	8.5	3.2	Pipes	Centrebored A-frame (ref.14)
Marlington, New Hampshire	1975	1.6	6+	46	6	0.5	Trapped air in tires	Goodyear - design car tire FTB, hauled onto beach each year for cleaning, replaced in 1985 by 2.4m beam concrete caisson (ref.2)
Westport New York	1978	7.2	7.5	200	8	0.5	Trapped air	Goodyear FTB, car tires, air compressor used as required to recharge tire crowns, 9.5mm steel chain used to bind modules (ref.2)
Charlevoix, Michigan	1979	16	8	240	12.8, 4	0.85	Sprayed polyurethane foam	Goodyear FTB, car and truck tires, constructed on ice, wood dock on top part of FTB
Cotnamet, Massachusetts	1980 1982	1.8 1.8	3.6+ 3.6+	17 122	6 6	0.5 0.5	Poured polyurethane foam	Goodyear FTB, car tires, prior installation in 1976, failed in 1978 due to flotation and binding material problems (ref.2)
South Portland, Maine	1980	13	9+	250	10, 6	0.5	Trapped air	Goodyear FTB, car tires, air compressor used several times/year to recharge tire crowns (ref.2)
Burlington, Ont.	1981	4.4	12	490	18, 10	0.5	Sprayed polyurethane	Goodyear FTB, 35,000 car tires (ref.7)
Lorain, Ont.	1981	6	3	183	24	0.5	Styrofoam blocks in polyethylene bags	Goodyear FTB, 20,000 car tires, to be removed in fall of 1987 due to completion of rubblemound breakwater
Cobourg, Ont.	1982	6	6	50	10	0.5	Sprayed polyurethane	Goodyear FTB, car tires
Erie, Pennsylvania	1982	3.2	3	37	12	0.5	Foamed pipes, poured polyurethane foam in some tires	Experimental pipe-tire floating breakwater
Mariners, New Jersey	1984	1.6	2.5+	120	10	0.5	Styrofoam wedges	Goodyear FTB, car tires, replaced floating concrete caisson that had failed
Barber Springs, Michigan	1985	7.2	4.3	113	10	0.5	Preformed foam	Goodyear FTB, car tires, constructed on ice, wood dock on top of part of FTB
Dallertille, Ont.	1985	2.2	4	120	12	0.5	Sprayed polyurethane	Goodyear FTB, car tires

+ Water depth at high tide
* FTB exposed to diffracted lake waves

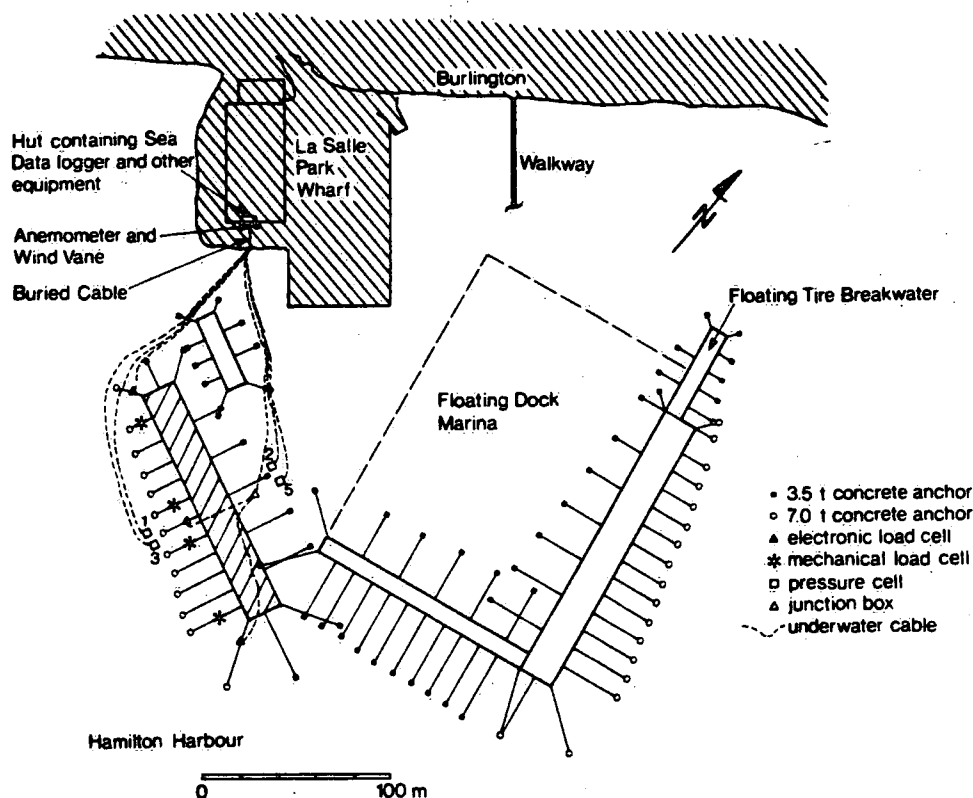


Fig.2. Layout of instrumentation for Burlington, Ontario, field monitoring study (ref.6).

breakwater construction details given (ref.7).

10. Spectral analysis of the pressure records led to the wave transmission design curve in Figure 3. It is in good agreement with earlier two-dimensional model tests (refs.8,9,10,11). The record of largest waves gave $H_{m0} = 0.65\text{m}$ and $T_p = 2.8\text{s}$. For practical purposes, a breakwater is seldom required unless wave attenuation of 50% or more is needed. Figure 3 shows that to obtain a wave transmission coefficient C_t of less than 0.5 the Goodyear FTB beam must be at least 1.2 times the design wavelength ($L/B < 0.85$). If the tire diameter is more than one-third of the water depth (d), lower C_t values may be obtained but reliable design data are not yet available.

11. Wave-induced mooring loads on FTB's have been found to increase with increasing wave height and length and decreasing water depth. From electronic measurements on the central seaward mooring line, peak mooring loads ($F_{\max}\cos\theta$) per unit length (ℓ), where θ is the angle between the mooring line and a perpendicular to the front face of the FTB and ℓ is the length of breakwater frontage restrained by the mooring line, are plotted versus the incident characteristic wave height in Figure 4. Also plotted are results from six-module-beam two-dimensional prototype scale tests in 4m of water (ref.8), for which the regular wave height has been substituted for H_{m0} .

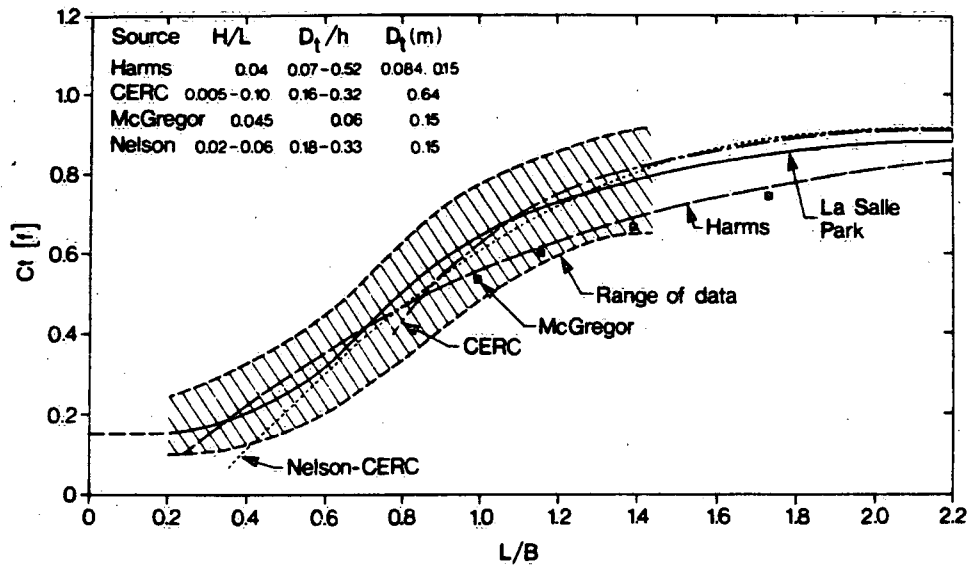


Fig.3. Wave transmission results from Burlington, Ontario, compared with results from other investigators (ref.6).

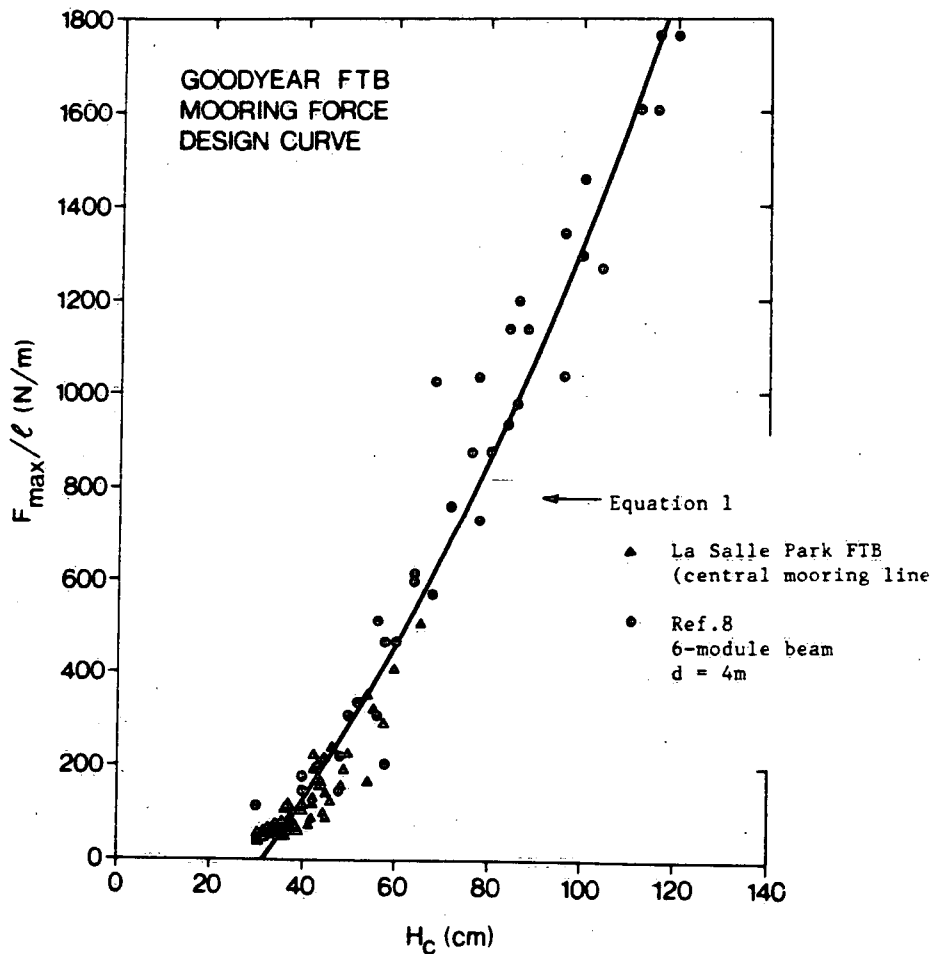


Fig.4. Peak mooring load data from Burlington, Ontario (ref.6) and six-module beam data (ref.8).

Agreement is surprisingly good. A second order regression analysis of the 64 field test points and 39 model test points gives

$$\frac{F_{\max} \cos \theta}{l} = -346 + 8.76 H_{m0} + 0.0789 (H_{m0})^2 \quad (1)$$

where $F_{\max} \cos \theta / l$ is in newtons per metre length and H_{m0} is in centimetres. Equation 1 should only be used for values of H_{m0} greater than 40cm and when D/d is less than 0.18.

12. Measured corner mooring line values of $F_{\max} \cos \theta / l$ were found to be significantly larger than those at the central mooring line. This is thought to be due to three-dimensional effects at the corner such as oblique wave attack and diffraction. For design purposes, it is suggested that $F_{\max} \cos \theta / l$ for a corner be estimated as twice the central mooring line load. Field experience with dragging anchors, especially at corners, substantiates this.

13. The cost of the breakwater, including materials, labour and profit, was \$35 Canadian per square metre. The beam dimensions were 5 and 9 modules, giving an average cost per unit length of \$500 Canadian per metre.

CONCRETE PONTOON BREAKWATERS

14. Concrete units, the most common type of floating breakwater on the (northern) West Coast, have typically been installed in saltwater where depths are greater, tidal ranges larger, and tidal currents stronger than at sites of tire structures on the East Coast. Another difference is that commercial fishing vessels as well as pleasure craft use the protection provided. Multiple use, both planned and unplanned, represents another difference where breakwaters are operated by local port authorities (ref.12).

15. In semi-protected waters of British Columbia and the States of Washington and Alaska, experience over the past 10 years shows that satisfactory wave attenuation performance is obtained with concrete pontoon units of width from 4.5-6.5m and maximum draft of less than 1.5m when exposed to incident waves of height up to 1.0m and periods up to 3-3.25 seconds; transmitted wave heights for these conditions are generally an acceptable 0.3-0.4m or less. Conditions typical of sites where floating breakwaters might be used involve significant wave heights between 0.6 and 1.2m, with periods from 2 to 4 seconds. Wave attenuation is mostly due to reflection from the rectangular pontoons, so the sea surface is rougher on the windward side of the breakwater than for a tire unit.

16. Concrete floor, deck, and sides typically are 0.10-0.15m thick; end walls may be thicker, especially if individual modules are post-tensioned together to form a longer, rigid unit. Welded wire fabric is common for reinforcement. Styrofoam blocks typically are used for interior forming and provide positive buoyancy as insurance

against flooding. Anchor line lockers, hawse pipes, and other hardware tied into the form are an integral part of each unit. Monolithic units weighing nearly 1,000 tons have been built.

17. The configuration of anchor lines crossed beneath the breakwater, as shown in Figure 5, is typical to provide keel clearance for vessel tie-up. The clump weights (usually concrete blocks) shown in the drawing are intended to produce a more even anchor line tension over the full tide range and thus reduce horizontal excursions of the breakwater, particularly at low tide levels. Line scopes of 1 vertical to 4-5 horizontal are common. Anchor line tensioning provides a mechanism for adjusting freeboard and alignment.

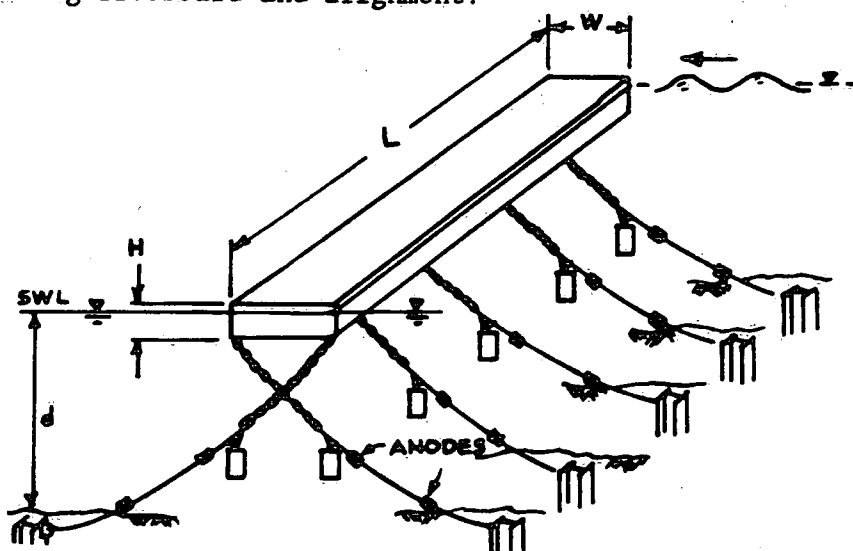


Fig.5. Schematic drawing of Friday Harbor breakwater

18. Connections between pontoons are a problem. Metal-to-metal connections have generally been unsatisfactory and often were under-designed. Connections incorporating large cylindrical rubber fenders appear more promising. More recent designs do not have connections between pontoons, which instead are fendered to protect against collision damage and depend upon anchor line restraint to hold them individually in position.

19. The U.S. Army Corps of Engineers, the lead government agency in the United States in the design and analysis of floating breakwaters, considers a 50 year design life in estimating costs of concrete units if reasonable quality controls are maintained. Galvanized steel cable anchor lines are anticipated to have a 50 year life if protected by anodes which will have to be replaced once, perhaps twice, over this life span. Without a corrosion protection system, the service life of 0.025m anchor chain is between 5 and 10 years in a temperate marine environment (ref.13); chains may have to be replaced 5 times during a 50 year structure life.

20. Field observations (refs.12,13) have led to some other conclusions, among them:

- Any large concrete float attached to shore will be

used for temporary moorage by large vessels if there is a shortage of dock space. This possibility should be considered in the design. Additional wind loads caused by the sail effect of larger vessels moored on the windward side can lead to increased float excursion.

- Boat waves may be more significant than wind waves, producing larger forces and perhaps overtopping of the float.
- Inadequate freeboard can lead to frequent overtopping, causing a slippery deck which can be dangerous if access to the breakwater is allowed. Breakwaters with shore access become popular fishing piers.
- Electrical services, if provided on the breakwater, should be properly designed for the marine environment.

21. Prior to the 1970's most floating breakwaters in the Pacific North West tended to be makeshift, with the exception of the A-frame unit at Lund, British Columbia (ref.14). Table 2, while not all-inclusive, shows the trend toward larger concrete units. The Lund A-frame unit was replaced in 1987 by three fendered but unconnected concrete pontoons each approximately 45m long by 7.6m wide by 2.7m high.

PORT OF FRIDAY HARBOR MARINA BREAKWATER

22. The 580 boat marina at Friday Harbor is located on the eastern shore of San Juan Island in the inland waters of northwestern Washington. The breakwater consists of 5 rectangular post-tensioned pontoons; three are 91.5m long by 6.4m wide by 1.8m high with a 1.4m draft, and the other two are 91.5m long by 4.9m wide by 1.5m high with a 1.1m draft. Respective design waves are shown in Table 2. Water depth at the site varies between 12 and 15m at MLLW. Tides are mixed with a diurnal range of 2.3m; maximum currents at the site are less than 0.5 m/s. Breakwater anchors are 52 steel H-piles embedded in firm silts, sands, and clays. Anchor lines (Figure 5) consist of 35mm diameter galvanized bridge rope with 9m lengths of 32mm link chain at the upper end. A 1-ton (submerged) clump weight is attached 15m from the upper end of each anchor line, initial tension is approximately 45kN, and 3 large aluminum anodes are attached to each anchor line to prevent corrosion (ref.13).

23. Part of one of the smaller pontoons is composed of two smaller units, each 22.9m long. These initially underwent prototype field tests for 18 months at an exposed site in Puget Sound, off Seattle. Water depth at the test site was about 15m at MLLW, the diurnal tide range was 3.5m, and maximum currents exceeded 60cm/sec. Anchor arrangements were basically those used later at Friday Harbor. Wave attenuation and anchor line forces were measured. Details of the monitoring programme and results obtained have been presented (ref.15), and some are given here. Three configurations were tested:

- Floats rigidly connected (effective single pontoon

Table 2. Summary information on some successful floating breakwaters on the West Coast U.S.A. and Canada

Location	Year Built	Depth MLLW (m)	Dimensions				Design Wave		Anchors		Comments
			L (m)	W (m)	Draft (m)	H (m)	H ₀ (m)	T (sec)	Wt (tons)	Line Size	
Lund, Brit. Columbia	1964	21	110	7.6	3.7	5.5	1.4	2.8	13	25mm chain	Centreboard A-frame. Replaced by concrete pontoons in 1987 (ref.14)
Tenakee, Alaska	1972	15	110	6.4	1.1	1.5	0.9	4.0	26	35mm chain	Catamaran; 18.3m post-tensioned modules, 0.9 x 1.5 x 4.6m indiv. pontoons (ref.12)
Sitka, Alaska	1973	14	293	6.4	1.1	1.5	0.9	4.0	Stake Pile	35mm chain	Catamaran; 18.3m post-tensioned modules, 0.9 x 1.5 x 4.6m indiv. pontoons (ref.12)
Port Orchard, Wash.	1974	14	473	3.7	0.5	0.9	0.6	2.5	Stake Pile	12mm Nylon rope	Rectangle; 19.3m post-tensioned modules (ref.12)
U.Wash, Friday Harbor, Wash.	1979	18	119	4.6	0.9	1.4	0.9	3.5	27	25mm chain	Rectangle; 3 modules (refs 12,13)
Ketchikan, Alaska	1980	26	293	7.0	1.4	1.8	1.0	3.5	60.18	chain	Catamaran; 4 post-tensioned modules (ref.12)
Semiahmoo, Wash.	1981	6	1067	4.6	0.9	1.4	0.6-0.9		Stake Pile	25mm Nylon rope	Rectangle; 18.3m modules, clump weights on anchor lines (ref.13)
Brownsville, Wash.	1981	9	110	5.5	1.2	1.5	1.0	3.4	Stake Pile	38mm chain	Rectangle; 24 4.8m units post-tensioned together into a single unit (ref.13)
Olympia, Wash.	1982	4	213	4.9	1.2	1.7	0.6	2.8	Timber anchor piles thru sleeves in floats		Rectangle; 7 modules (ref.13)
Friday Harbor, Wash.	1984	18 12	302 183	6.4 4.9	1.4 1.1	1.8 1.5	1.0 0.8	3.2 2.6	Stake Pile	12mm Nylon rope	Rectangle; 3 modules, 1-ton clump weights Rectangle; 2 modules, 1-ton clump weights (ref.13)

length of 45.8m) with clump weights.

- Floats rigidly connected, without clump weights.
- Floats flexibly connected, without clump weights.

24. Data were treated by spectral analysis. A 0.08Hz low pass filter removed long period effects and a 1.0 Hz filter removed effects of short period phenomena such as ripples. Results of the spectral analysis were used to calculate significant wave heights, and transmission coefficients C_t were determined through comparison of incident and transmitted wave spectra. Waves were measured by resistance-wire wave staffs mounted on spar buoys having natural heave periods greater than 12 seconds. Anchor line forces were measured by load cells.

25. Wave transmission data are shown in Figure 6. The two-dimensional monochromatic wave laboratory model data (ref.16) were for a pontoon of equal width and draft. For the limited range of periods covered by the prototype data, agreement between prototype and model results was reasonable. The transmission coefficient centred on 0.4 but because of the limited range of wave periods no definite conclusions could be made about wave period, effects anticipated from model tests. Neither was there apparent influence of breakwater configuration.

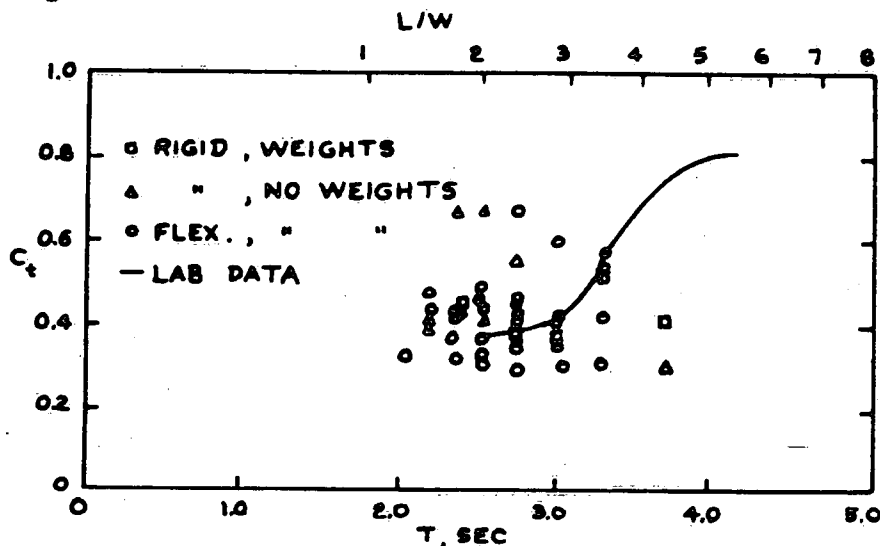


Fig.6. Wave transmission results from field monitoring study of concrete breakwater for Friday Harbor (ref.15) compared with model test results (ref.16).

26. Peak wave force (taken as statistical value of the highest one percent, after filtering) results are shown in Figure 7. There was no strong dependence upon wave height, nor for that matter (not shown here) on wave period. Forces shown are values in excess of the current drag and pretensioning, which was 22.4 kN in each of five lines with clump weights and 6.7 kN without. Force/unit length values were calculated assuming each anchor line carried one-fifth of the load and that incident wave crests were parallel to the breakwater face; the latter, due to breakwater orientation, was a reasonable

approximation and the breakwater was not long compared to wave crest lengths. Measured anchor line forces were much smaller than anticipated; pretensioning could have been the cause.

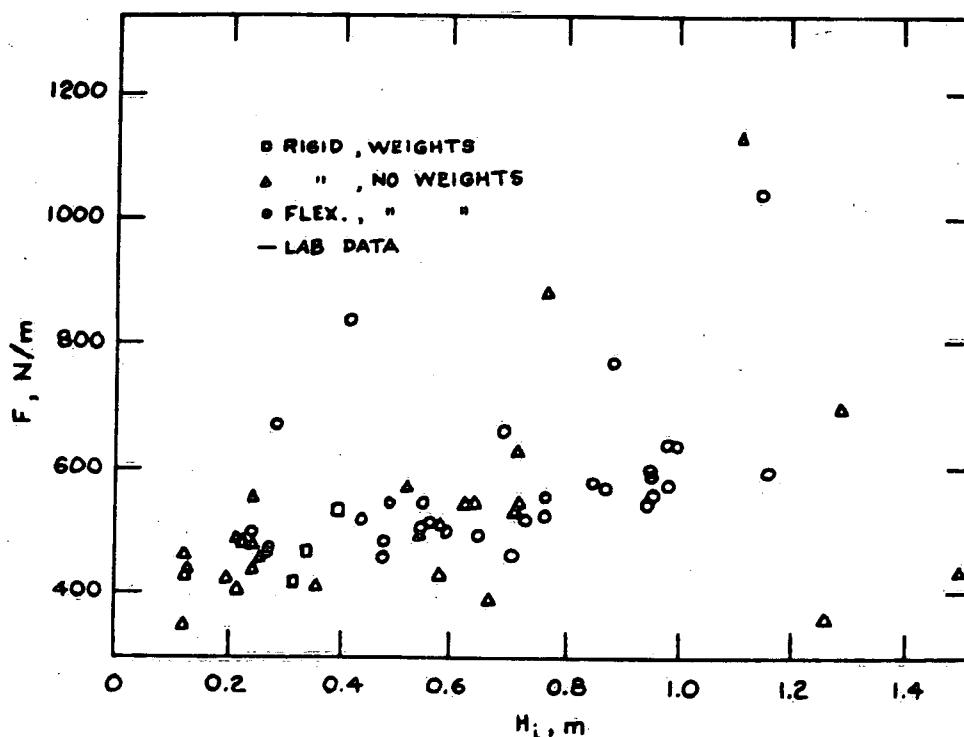


Fig.7. Peak anchor line forces from field monitoring study of concrete breakwater for Friday Harbor (ref.15).

27. The test breakwater was subjected to limited boat wave tests. Wave transmission data are given in dimensionless form in Figure 8 for waves generated at three speeds V_s shown by a 15-ton U.S. Coast Guard utility boat (ref.17). Maximum height of the boat waves was 0.6m; although not shown in Figure 8, incidence angles between wave crest and breakwater face varied between 5 and 35 degrees. Model data are for the same model shown in Figure 6. For longer wave lengths, C_t values are larger than in the model tests. When larger test waves (H_i to 0.9m maximum) from a 193 ton displacement marine tug acted on the breakwater there was significant overtopping and water on the breakwater deck.

28. The Friday Harbor breakwater was monitored closely in the period December, 1984 - June, 1986. Both winters were exceptionally calm, so the breakwater was not subjected to near-design wave conditions. The breakwater hosts large numbers of transient boats in the summer and is a popular fishing pier for the local population. Breakwater excursions were monitored. Maximum longitudinal motion was about 0.8m, most likely due to sail effects of transient boats moored to the floats during winds in excess of 18 m/s but which, because of orientation, did not generate large waves against the breakwater; maximum lateral motion was about 0.15m. All anchor

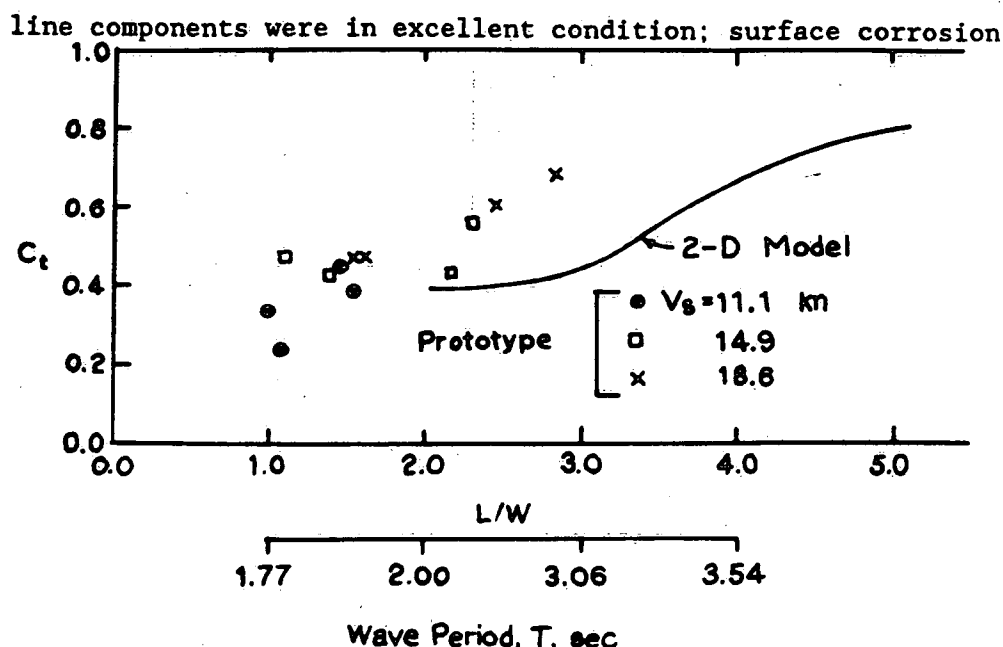


Fig.8. Boat wave transmission data from field monitoring study of concrete breakwater for Friday Harbor (ref.17).

of the anodes had begun. After 2.5 years of operation some maintenance problems persisted. Stanchions on the breakwater to provide electrical service to transient boats are vulnerable to collision with bowsprits of docking boats. Electric junction boxes mounted flush with the deck are subject to water damage, and hardware providing support for electrical wiring has corroded. There was little or no wear or damage to the fenders separating the floats (ref.13).

29. The 1984 cost of the breakwater, when installed, was \$4,020 U.S. per metre of length.

CONCLUSIONS

30. Field experience in North America with successful tire and concrete breakwaters has led to design and construction techniques which now exist to make these floating structures more economically and structurally viable and reasonably maintenance free, and they have become an attractive alternative in the design of harbours and marinas at limited-fetch locations. At some sites floating breakwaters are economically competitive with fixed structures although risks and costs associated with the still higher levels of maintenance must be recognised.

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