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DESIGN AND CONSTRUCTION MANUAL FOR FLOATING TIRE BREAKWATERS

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BURLINGTON, ONTARIO, CANADA

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DESIGN AND CONSTRUCTION MANUAL
FOR
FLOATING TIRE BREAKWATERS

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Cover photos (clockwise from upper left corner): Goodyear FTB at Westfield, New York; PT-breakwater being tested at Coastal Engineering Research Center; 1/8-scale PT-breakwater; Assembly of a car tire Goodyear module.

PREFACE

This draft manual, which is based on current research and experience, was prepared to provide a sound procedure for the design and construction of floating tire breakwaters.

Users or interested readers of this unpublished manual are invited to comment on the contents and bring to my notice any corrections or perceived improvements.

Such comments will be considered and, where used, will be acknowledged in the published edition of the manual. Following the publication policy of Environment Canada, the published version will be in both French and English.

T. M. Dick, Chief
Hydraulics Division
July, 1980

Note: This draft manual is published to provide advance information. No endorsement of any product mentioned in this manual is intended. The National Water Research Institute assumes no responsibility for any use that is made of this information.

PRÉFACE

Ce projet de manuel, qui est fondé sur la recherche et l'expérience actuelles, a été rédigé afin d'offrir des lignes directrices appropriées en vue de la conception et de la construction de brise-lames flottants sur pneus.

Les usagers ou les lecteurs intéressés de ce manuel non publié sont invités à soumetire leurs observations à son propos et à me faire part de toute rectification ou amélioration possible.

Ces commentaires seront étudiés et, s'ils sont utilisés, on en fera part dans l'édition publiée du manuel. Conformément aux lignes directrices de publication d'Environnement Canada, la version publiée sera en français et en anglais.

T. M. Dick
Division de l'hydraulique
Juillet 1980

Remarque: Ce projet de manuel est publié afin de fournir des renseignements anticipés. Nous n'avons pas l'intention d'appuyer les produits mentionnés dans le présent manuel. L'Institut national de recherche sur l'eau n'assumera aucune responsabilité quant à l'utilisation de ces renseignements.

ABSTRACT

The purpose of this manual is to act as a guide to designers and builders of two types of floating-tire breakwaters (FTB): the Goodyear FTB and the PT-breakwater (also known as the Harms FTB). This manual is a compilation of worldwide research work and experience with FTB's. It contains information on the determination of design waves for exposed, short-fetch sites, but does not attempt to deal with design waves for more complicated situations. For known design wave conditions and required breakwater peformance, this manual serves as a guide in the design of an FTB, the choice of construction materials, and the assembly and installation of the breakwater. A detailed design example and cost estimates are provided. This manual should be useful for specialists, such as coastal or marine engineers, as well as for technically knowledgable non-specialists such as marina owners and other engineers.

SOMMAIRE

Le présent manuel a pour but de servir de guide aux concepteurs et constructeurs de deux types de brise-lames flottants sur pneus: le brise-lames Goodyear et le brise-lames PT (aussi connu sous le nom de brise-lames Harms). Dans ce manuel ont été rassemblés tous les travaux de recherche et l'expérience acquise avec ces brise-lames flottants, à l'expérience acquise avec des brise-lames flottants, à l'échelle mondiale. Il contient des renseignements sur la détermination des vagues de projet pour des fetchs courts et exposés, mais n'essaie pas de traiter des vagues de projet dans des situations plus compliquées. Dans le cas de conditions connues de vagues de projet et lorsque le brise-lames doit obtenir des résultats précis, le manuel servira de guide pour la conception d'un brise-lames flottant sur pneus, permettre de choisir les matériaux de construction et d'assembler et d'installer le brise-lames. Un exemple de plan détaillé et des estimations du coût sont fournis. Ce manuel devrait aider les spécialistes comme les ingénieurs pour les travaux maritimes et les ingénieurs de genie maritime, de même que des non-spécialistes ayant des connaissances techniques, comme les propriétaires de ports de plaisance et d'autres ingénieurs.

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CONVERSION OF SI UNITS TO ENGLISH UNITS

1 metre (m)	=	3.28 ft
1 kilometre (km)	=	0.621 mi
1 Newton (N)	=	0.225 lb f
1 kilogram (kg)	=	2.205 lb
1 N/m^2	=	0.0209 lb f/ft^2
1 N/m^3	=	0.00637 lb f/ft^3
1 litre (ℓ)	=	0.22 Imperial gallons
	=	0.264 U.S. gallons

1.0 INTRODUCTION

What is a Floating Tire Breakwater? It is a type of floating breakwater that is composed primarily of car or truck tires. Like other floating breakwaters, it floats at the surface, partially submerged, and is anchored to the bottom. The main purpose of a breakwater is to reduce wave agitation on its lee side. The Floating Tire Breakwater, commonly referred to as an FTB, achieves wave energy dissipation by transforming incoming wave energy into turbulence within and around the tires. The FTB's outstanding feature is that, in certain situations, it can cost substantially less than other forms of breakwater protection.

There are few natural harbours remaining undeveloped near areas of intense recreational boating activity. At the same time, the popularity of recreational boating is increasing rapidly, and with it, the need for more small craft harbours and marinas. Usually, these man-made harbours require protection from waves. The recently developed FTB presents a low cost, effective solution to wave problems at some of these harbours. However, to date, a comprehensive design and construction manual for FTB's has not been available.

Because of low construction costs, FTB's appeal to those seeking quick remedies to wave problems. All too frequently, an attempt is made to construct the FTB as cheaply as possible by taking shortcuts or by ignoring field-tested technology. Similarly, FTB's are attractive to volunteer groups whose do-it-yourself approach often lacks thoroughness and uniformity. In both cases, failures often result.

Another problem is that FTB's have been installed at sites where the wave conditions are far greater than the FTB design's capabilities. Furthermore, many FTB's are still being designed with out-of-date information, without full recognition that maintenance is a key factor in the success of an FTB.

This manual has been prepared to meet the need for guidance in the design and construction of FTB's. It has been written for specialists, such as coastal or marine engineers, as well as for technically knowledgable non-specialists such as marina owners and other engineers. It is not intended that this manual answer all questions concerning the location, length, and performance required of a breakwater; it is strongly recommended that the assistance of a specialist be obtained to evaluate these problems. Nevertheless, basic information is provided on situations in which an FTB is feasible, the determination of design waves for exposed short-fetch sites, and the required length of FTB. Given the location, length and required performance of an FTB, this manual enables the determination of required FTB beam width and mooring forces. Furthermore, it describes suitable construction materials, construction procedures and provides a detailed design example and cost estimates.

There are three main types of FTB's: Goodyear, PT, and Wave-Maze. Each type differs in structural design, effectiveness and cost.

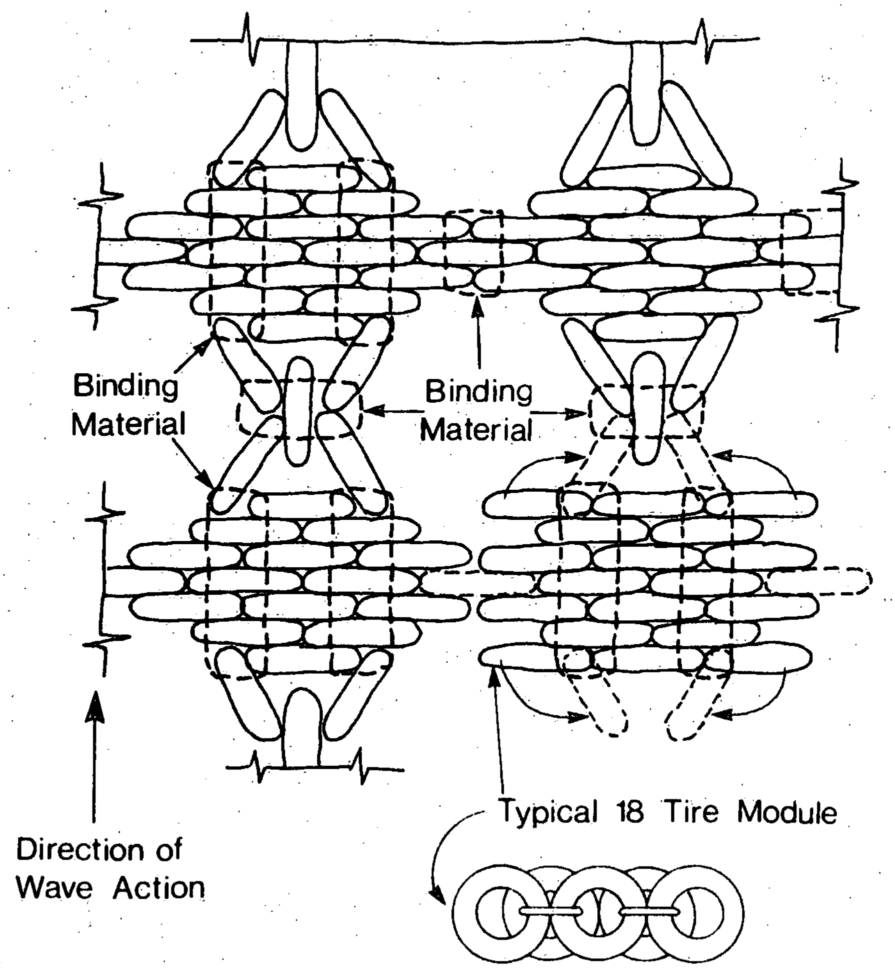
The Goodyear FTB design originated in 1974 (Candle and Piper, 1974). It consists of modules, each containing 18 tires, interconnected to form a flexible mat as shown in Figure 1. One of this design's most attractive features is that a Goodyear FTB can be assembled by unskilled labourers with virtually no heavy equipment. The Goodyear FTB has been flume-tested at prototype and model scales (Figures 2 and 3) and there have been numerous field installations in both salt and fresh water (Figure 4).

The PT-breakwater or Harms FTB design originated in 1978 (Harms and Bender, 1978). It consists of tire-encased pipes or poles and tire strings as shown in Figure 5. The PT-breakwater is a much more rigid structure than the Goodyear FTB and definitely requires the use of heavy equipment during assembly. It has been flume-tested at prototype and model scales as shown in Figures 6 and 7. The first field installation of a PT-breakwater was during the spring of 1980 at Mamaroneck, New York in Long Island Sound (Figure 8).

The pioneer floating tire breakwater, called the Wave-Maze, was designed by Stitt (1963). The Wave-Maze design consists of a vertically-oriented layer of tires sandwiched between two layers of horizontally-oriented tires (Figures 9 and 10). The Wave-Maze was tested at model scale by Kamel and Davidson (1968). Adee (1977) reports that the Wave-Maze has been used in California and Australia. This design has been patented and therefore a royalty fee must be paid for its use.

Although there have been model tests and field installations of the Wave-Maze, there still have not been any controlled prototype scale tests. Thus engineering design information for the Wave-Maze is quite limited. Furthermore, since equivalent protection using a Wave-Maze costs considerably more than either a Goodyear FTB or a PT-breakwater (Harms 1979a), the Wave-Maze is not considered further in this manual. Design and construction information for the Wave-Maze can be found in reports by Noble (1969, 1976) and Harms (1979a).

This manual is a compilation of the latest worldwide research and experience with FTB's. However, as more experience with FTB's is gained, and research continues, improved structural designs and construction techniques will evolve. Thus, this manual should be considered state of the art in the design and construction of Goodyear and PT type FTB's.



Plan View

Proposed Floating Tire Breakwater for Dunkirk Harbor, Dunkirk, N.Y. sheet 2 of 2

Figure 1 Typical arrangement of tires in a Goodyear FTB (DeYoung, 1978)

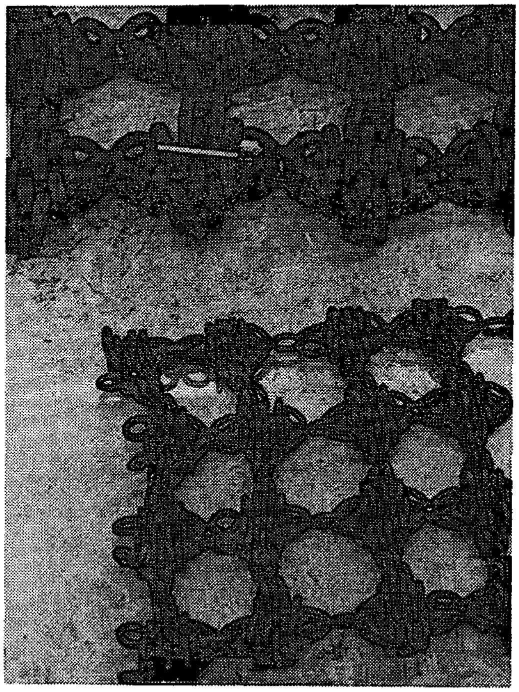


FIGURE 2 1/4 and 1/8 scale model Goodyear FTB's (Harms and Bender, 1978)

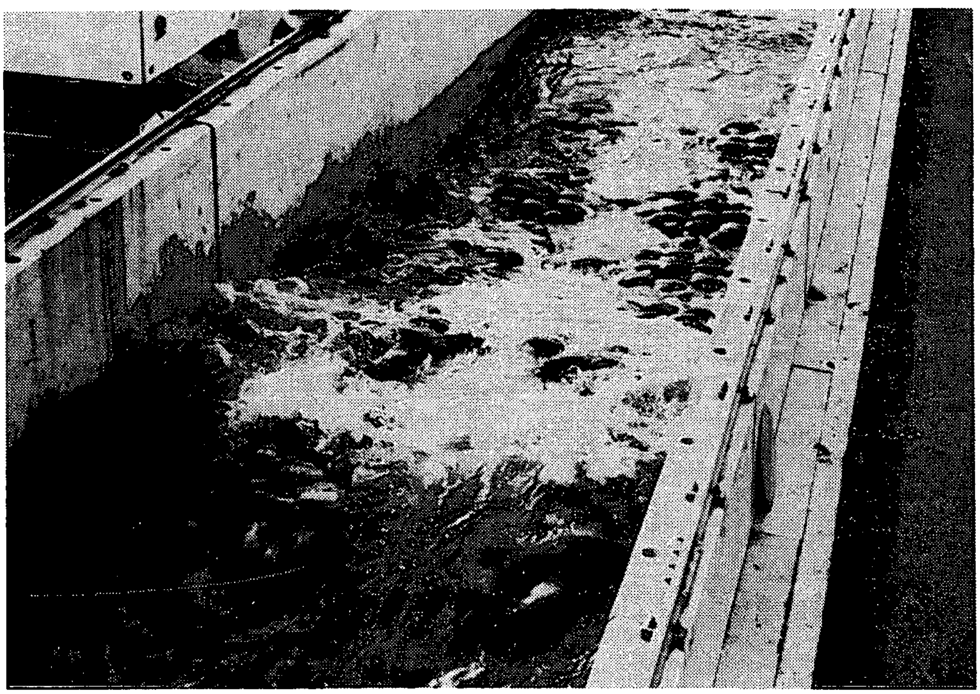


FIGURE 3 Prototype scale Goodyear FTB being tested in CERC flume (Courtesy R.E. Pierce)

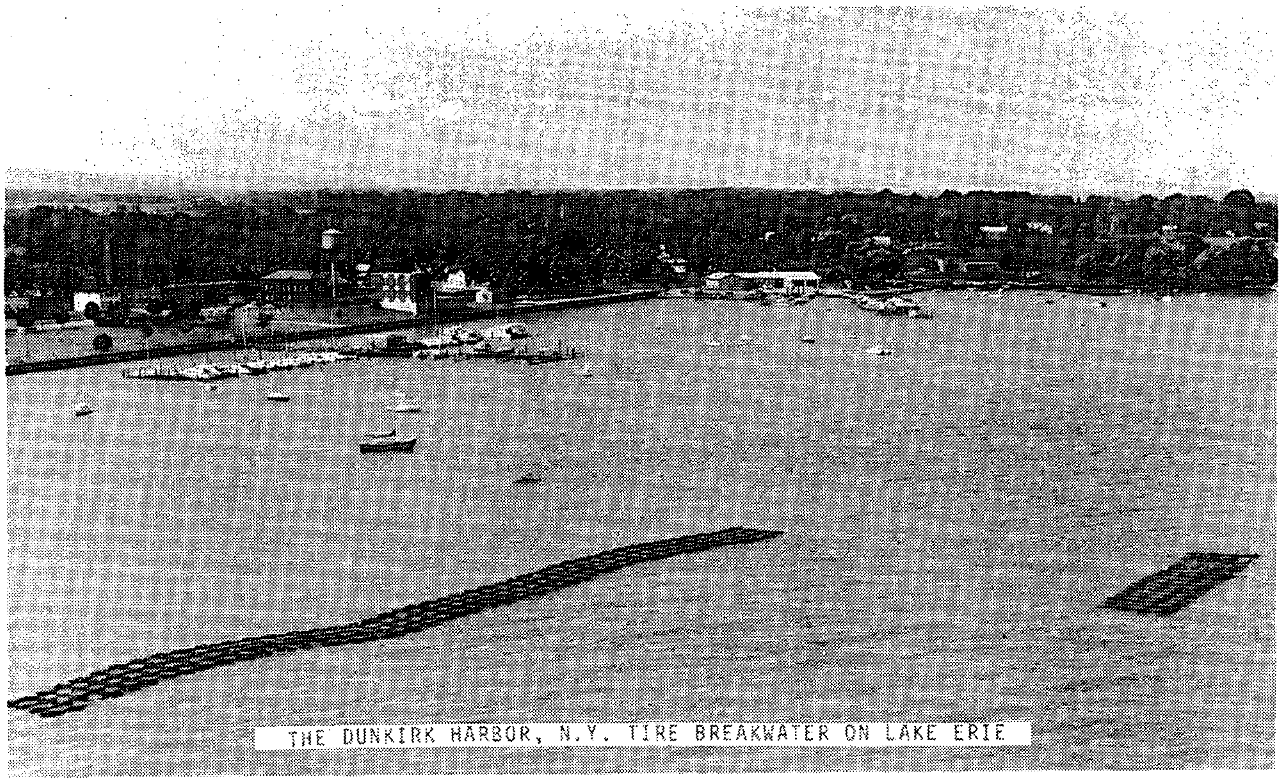
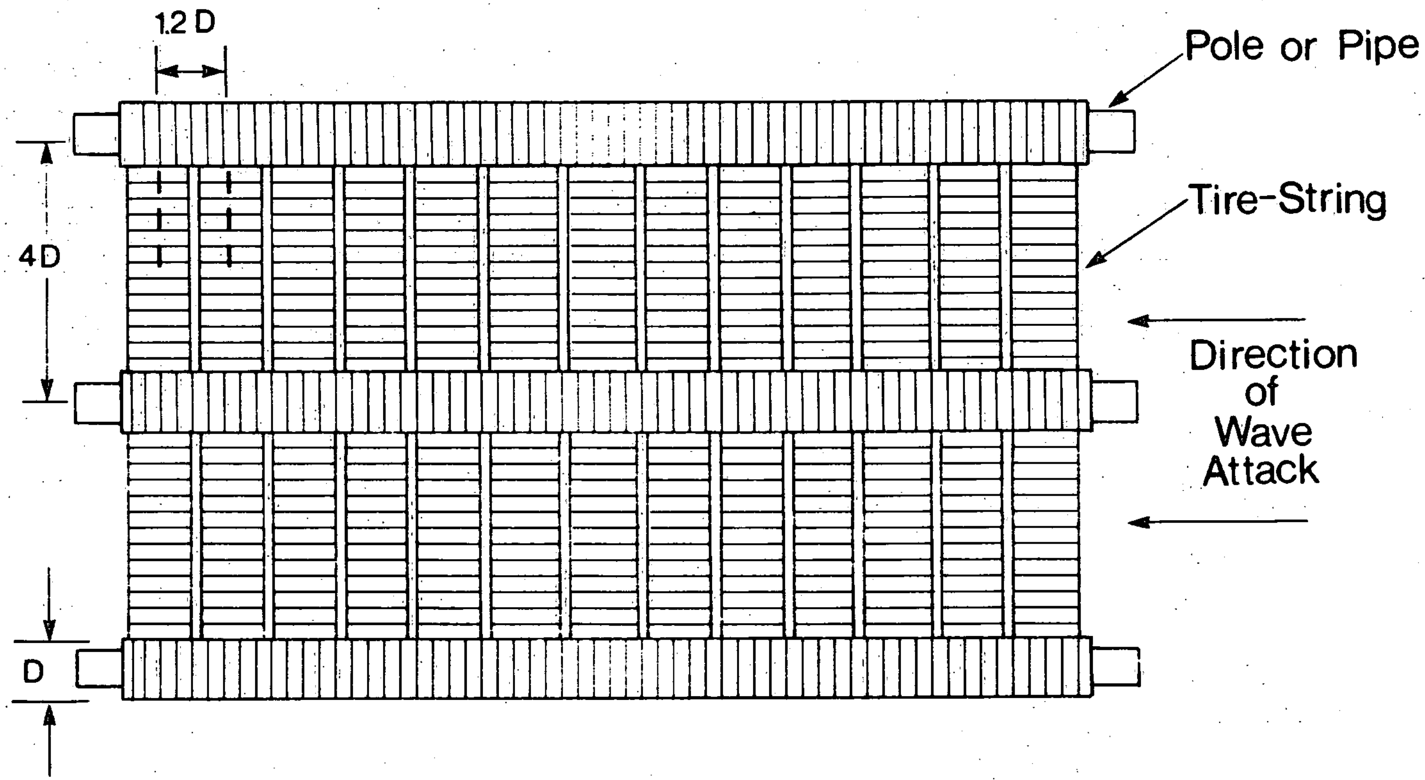
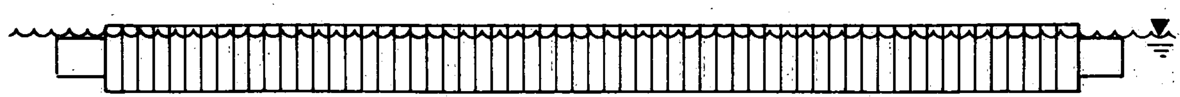


FIGURE 4 Goodyear FTB installation at Dunkirk, New York (Courtesy Goodyear Tire and Rubber Co.)



Top view of PT - Breakwater



Side view of PT - Breakwater

Figure 5 Typical arrangement of tires in a PT - Breakwater

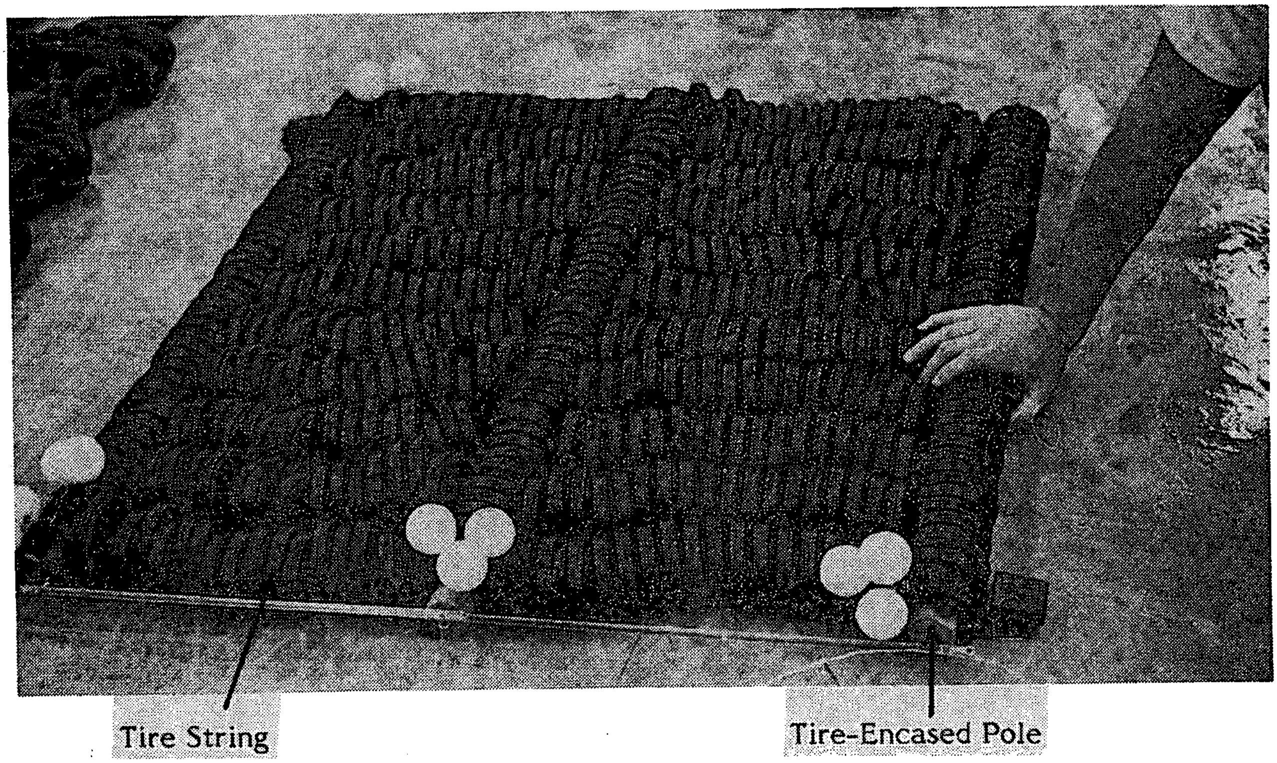


FIGURE 6 1/8 scale model PT - breakwater (Harms and Bender, 1978)

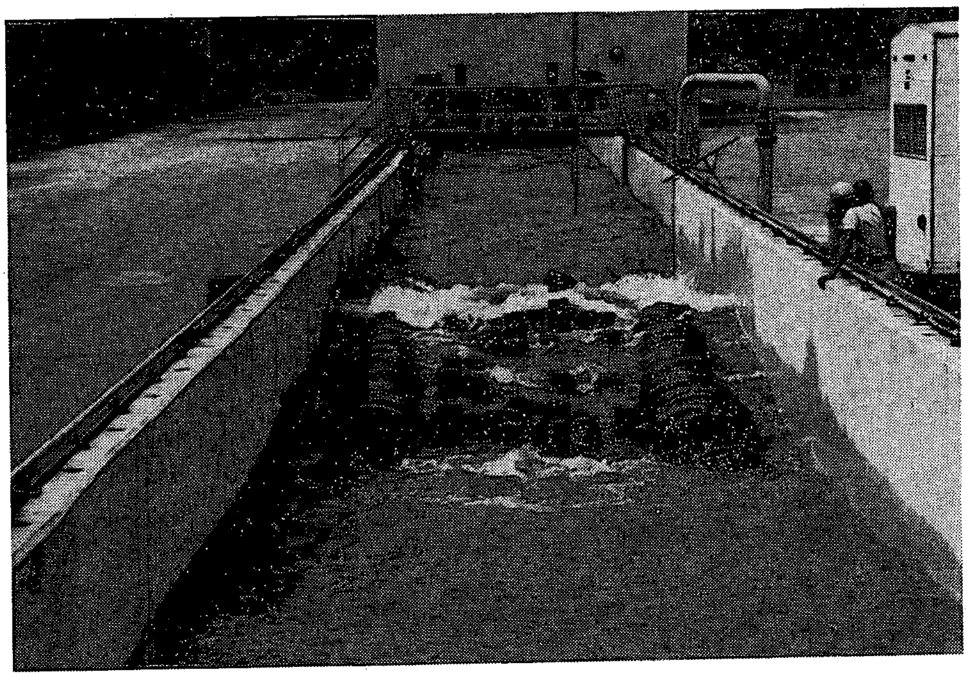
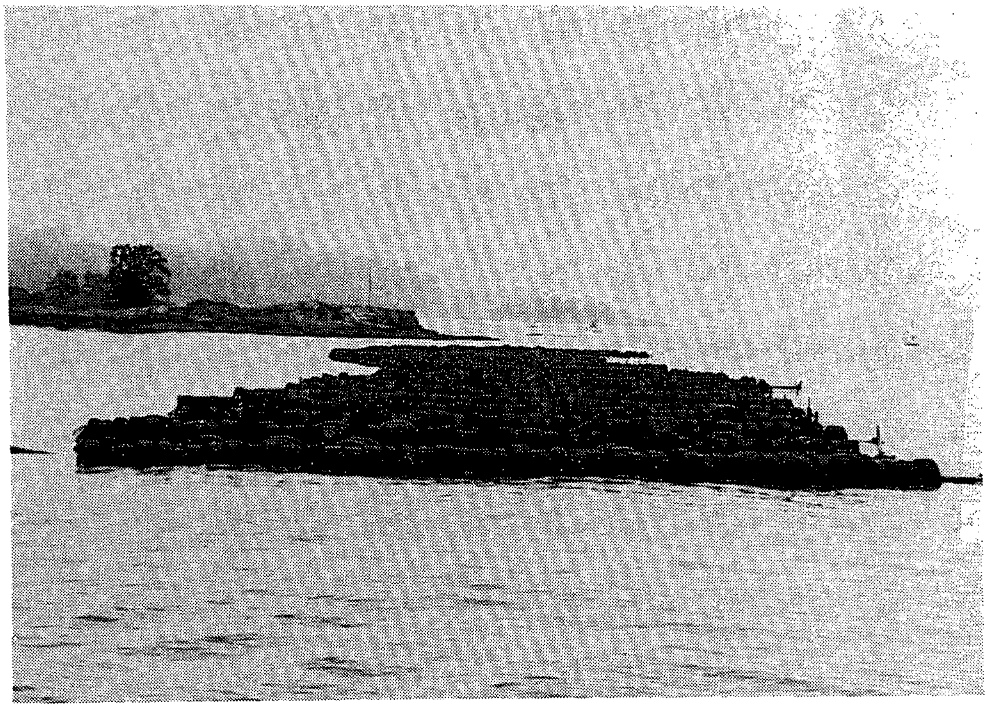


FIGURE 7 Prototype scale PT - breakwater being tested at CERC flume (courtesy V.W. Harms)



View across the length of the breakwater. (Uneveness of edges is due to temporary mooring)

View across the beam of the breakwater.

FIGURE 8 PT - Breakwater installation at Mamaroneck, New York

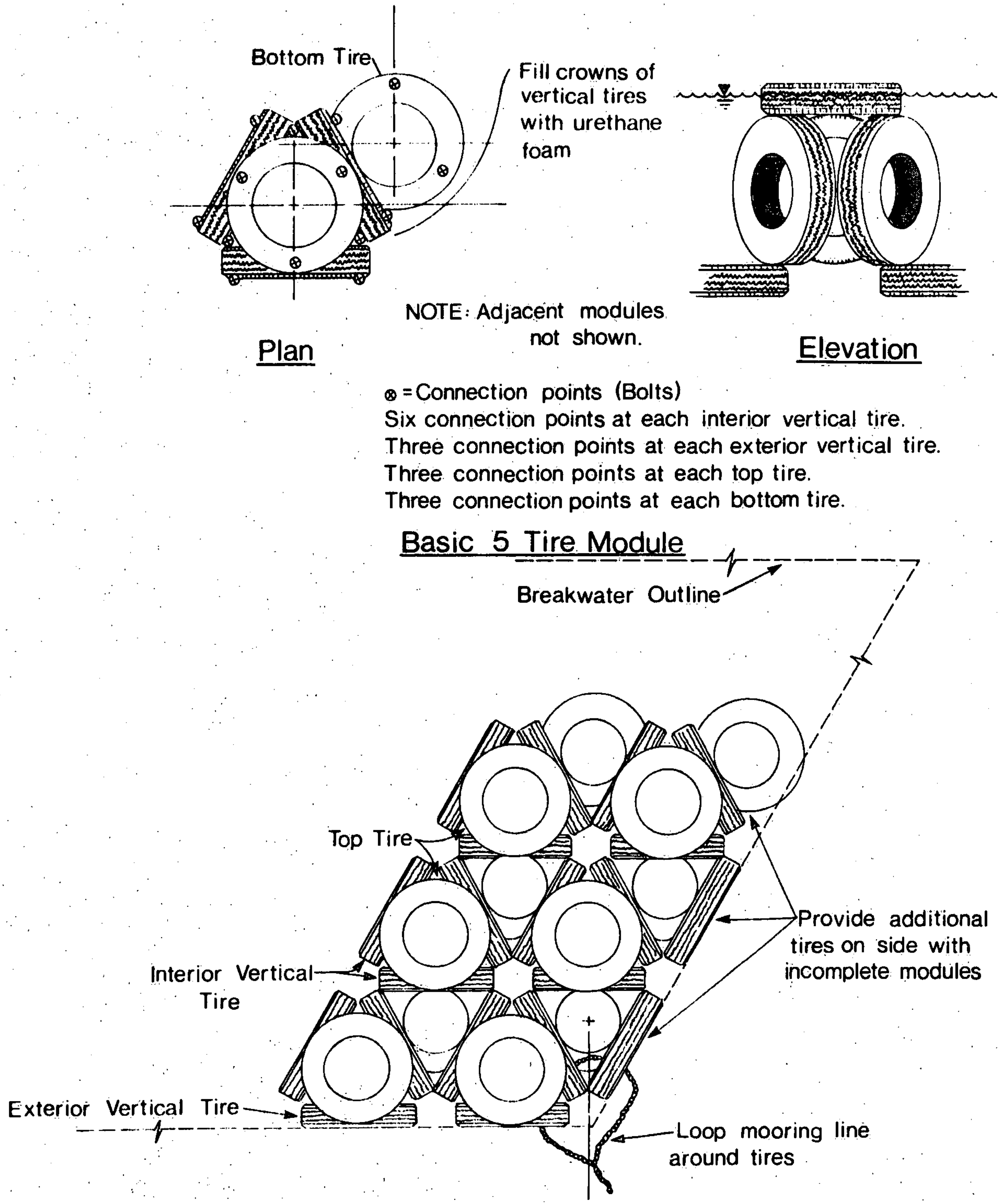


Figure 9 Typical arrangement of tires in a Wave-Maze
(courtesy U.S. Army Corps of Engineers, Philadelphia District)

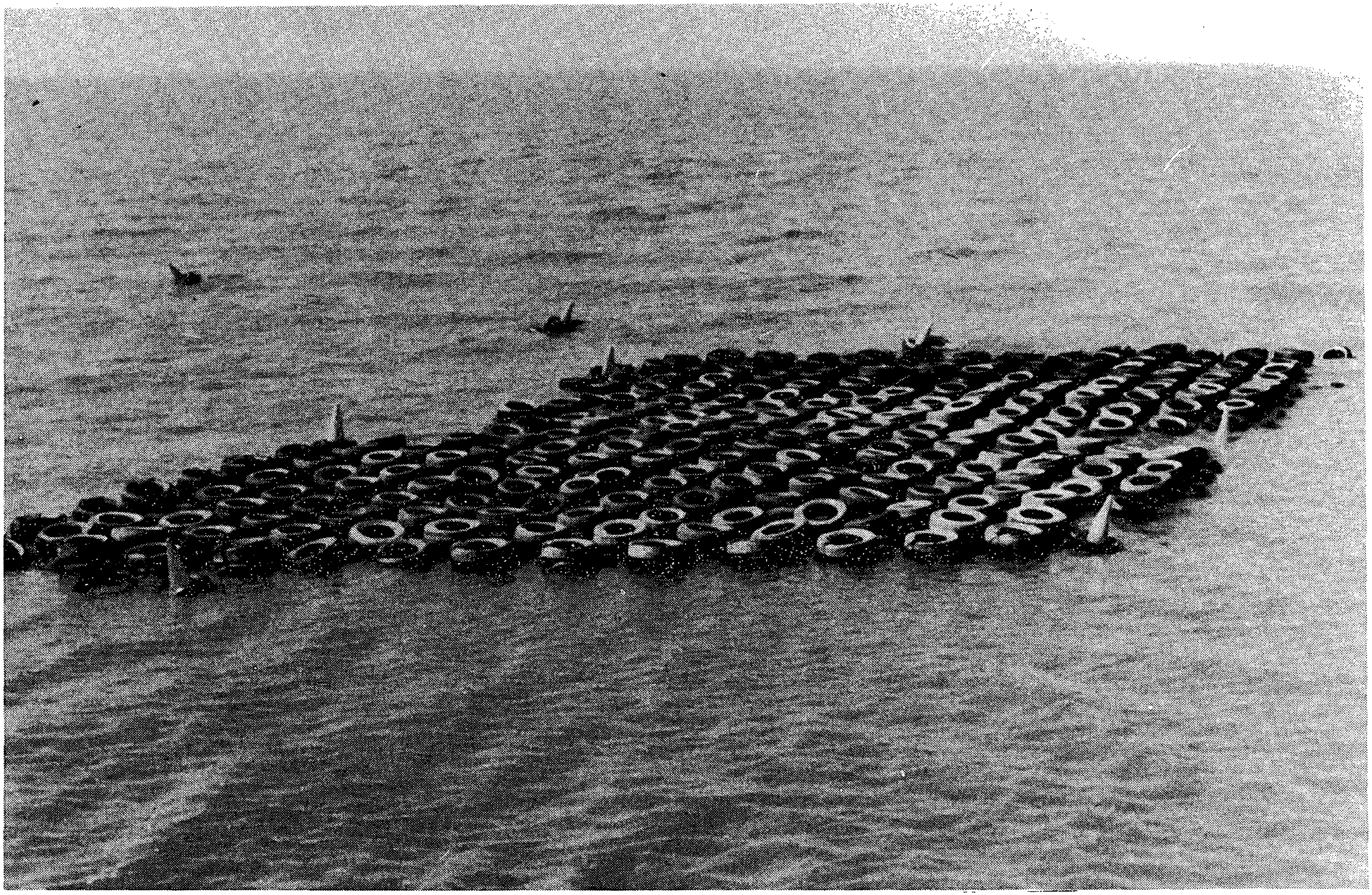


FIGURE 10 Wave-Maze test section at Delaware Bay, Delaware (courtesy U.S. Army Corps of Engineers, Philadelphia District)

2.0 WHEN TO CONSIDER AN FTB

2.1 Feasible Situations

An FTB is not the solution to everyone's wave problems. The effectiveness of FTB's in attenuating wave heights depends strongly on the ratio of wavelength to FTB beam width* (details in Section 4). In general, an FTB can be a practical alternative to other forms of breakwater when the significant period of the design waves is less than about 5 seconds.

The results of full scale testing of Goodyear FTB's at the U.S. Army Coastal Engineering Research Center large wave flume appear to indicate that structural breakdown may occur if a Goodyear FTB is repeatedly subjected to wave heights greater than about 1.4 m. Although failure did not occur during the tests, the FTB's windward edge was observed to undergo severe deformation when attacked by waves of this magnitude (Pierce and Lewis, 1977). This severe cyclic loading may lead to failure of the binding material (which holds the FTB together) or of the connecting tires between modules. Until further controlled prototype experience is gained, it is suggested that Goodyear FTB's should only be considered for use at sites where the significant wave height is not expected to exceed 1.4 m.

Although field experience with PT-breakwaters is just beginning, their survival characteristics can be predicted from the results of prototype scale tests conducted at the U.S. Army Coastal Engineering Research Center large wave flume (Harms et al, 1980). In those tests, a PT-breakwater constructed of steel pipes and truck tires successfully withstood attack by regular waves with a 1.8 m wave height (the limit of the flume's wave generating capabilities); also, a PT-breakwater constructed of telephone poles and car tires was successfully tested against 1.5 m regular waves. At these maximum wave heights, neither version of PT-breakwater appeared to be at its limit of structural survival (Harms, private communication). Therefore, the PT-breakwater appears to be capable of withstanding larger waves than the Goodyear FTB. Until further controlled prototype experience is gained, it is suggested that PT-breakwaters should only be considered for use at sites where the significant wave height (H) is not expected to exceed the following limits:

Steel pipe - truck tire PT-breakwater	$H < 1.8$ m
Wooden pole - car tire PT-breakwater	$H < 1.5$ m

---

* Definitions of technical terms are provided in Appendix A.

The preceding wave height and period restrictions limit the situations in which an FTB can be used successfully. In general, FTB's can be cost-effective alternatives in the following situations:

- As primary protection where the maximum fetch is less than 10 kilometres.
- As secondary protection where the FTB is installed on the lee side of a conventional bottom-resting breakwater.
- As temporary protection for military needs, marine construction, or other short term requirements (maximum fetch can exceed 10 km).

A Goodyear FTB used successfully at Dunkirk, New York from 1975 to 1979 is an example of an FTB used to provide secondary and temporary protection. A conventional breakwater protects the harbour from north and northwest waves (see Figure 11) but northeast waves used to enter the harbour unimpeded. Boats moored at the marinas were sustaining wave-induced damage from the northeast waves. As part of a harbour development scheme, another conventional breakwater was planned for the harbour's east side, but construction was not scheduled until 1979-1980. In order to provide temporary protection, the City of Dunkirk installed an FTB on the lee side of the existing offshore breakwater. The FTB experienced some difficulties, but, on the whole, performed satisfactorily. The FTB was removed and disposed of by a contractor in the autumn of 1979 (City of Dunkirk, private communication).

The determination of design waves for long-fetch or partially sheltered sites, such as Dunkirk Harbour, can be very complicated. This manual enables the determination of design waves for exposed, short-fetch locations but does not attempt to deal with more complicated situations. In those situations, the advice of a professional engineer specializing in coastal engineering should always be obtained.

2.2 Advantages and Disadvantages

Floating breakwaters have several advantages over conventional breakwaters, including the following:

- Lower capital cost.
- Suitability for deep water sites - can be installed in deep water where conventional breakwaters are prohibitively expensive.

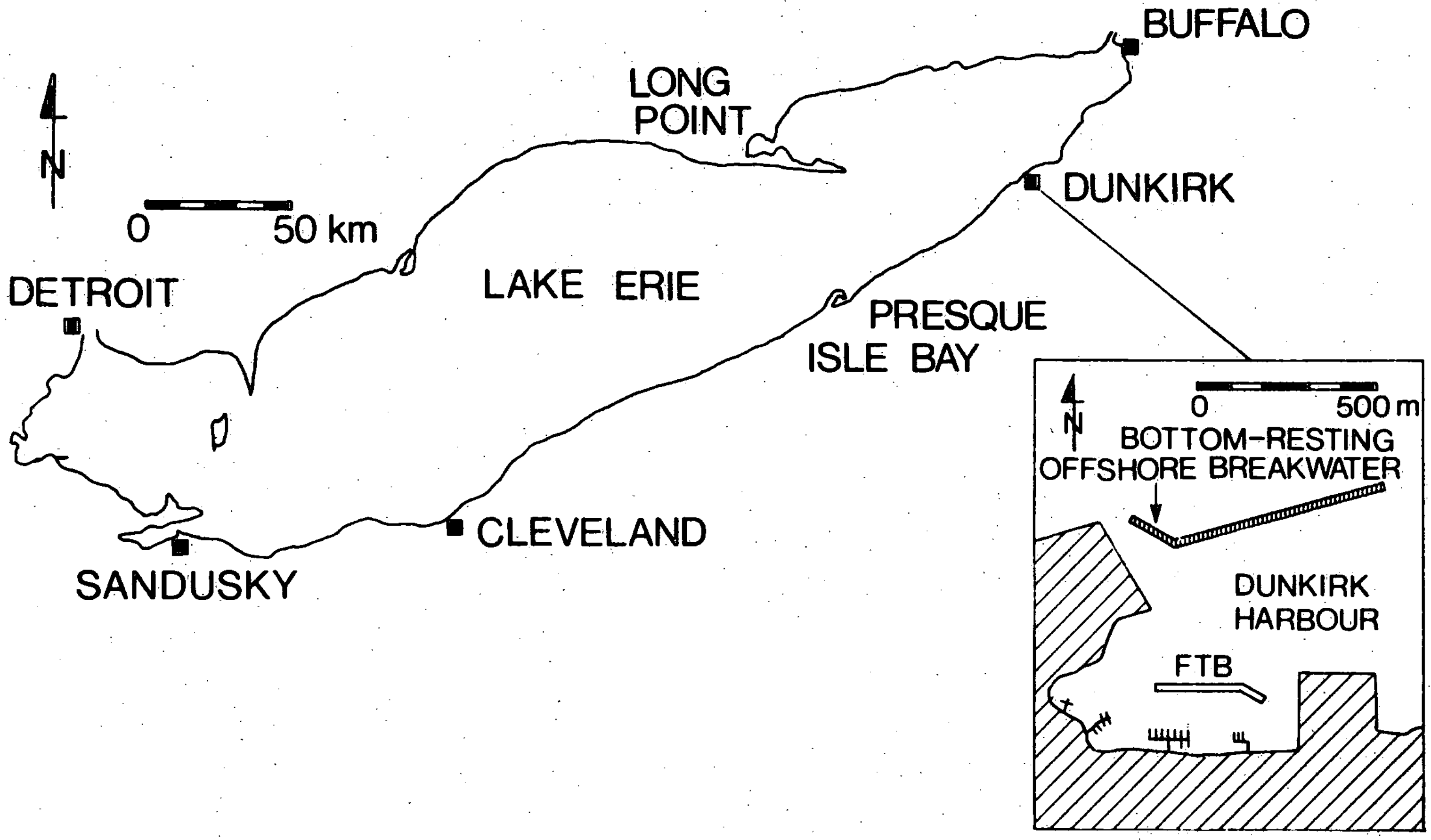


Figure 11 FTB used to provide secondary protection at Dunkirk, New York

- Suitability for sites with large seasonal water level fluctuations.
- Adaptability of location - can be moved relatively easily.
- Less disruption to water circulation.
- Shorter construction time.

Some disadvantages of floating breakwaters compared with conventional breakwaters include the following:

- Feasible only in short-fetch or semi-protected locations.
- Wave attenuation is partial. Unlike a well-designed conventional breakwater, which transmits virtually no wave energy, a floating breakwater always transmits part of the incident wave energy.
- Annual maintenance costs can be high.
- Service life is short.
- Ability to protect lee side from ice is poor.
- Space occupied by FTB and its mooring system can be large.

Compared with other floating breakwaters (concrete caissons, A-frame, tethered floats, etc.), the FTB has the following advantages:

- Lower cost - installed costs of \$350-\$720 per metre length have been estimated (see Section 10).
- Wave reflection is minimal (Kamel and Davidson, 1968).
- Construction can be carried out by non-skilled workers.
- Discarded tires, the primary construction material, are readily available at most locations.
- A favourable environment for fish is usually created (Stone et al, 1974).

The most common problem encountered with FTB's has been their tendency to sink. Continued flotation can be ensured by an adequate FTB design and annual maintenance. Another potential problem is that some people consider FTB's to be aesthetically unappealing.

2.3 Survival in Ice

In bodies of water that freeze over, the question arises as to whether or not the FTB has to be removed from the water during the winter.

Horizontal forces due to ice can be considered in two categories: dynamic forces caused by ice floes or wind-driven ice, and static or thermal forces caused by the expansion and contraction of stationary ice (Wortley, 1978). Dynamic ice forces can be very large and could easily exceed the restraining capacity of an FTB mooring system designed for wave forces. Therefore, at sites where dynamic ice forces are considered important, it is recommended that the FTB be moved to a sheltered location during the winter, or be removed completely from the water. Towing an FTB to an exposed location in shallow water or to a beach for winter safekeeping should be avoided. In such locations, the tires could be filled with sediment if subjected to wave attack.

A car tire Goodyear FTB at Plattsburgh, New York has survived four winters (Riley, private communication) at a location where the FTB is subjected to only thermal ice forces. Each winter the FTB is towed from its summer mooring to a more protected site at the entrance of the marina. Only minor damage to the FTB has occurred - primarily the crushing of plastic containers used to provide supplemental flotation.

A truck tire Goodyear FTB, with urethane foam providing supplemental flotation, has successfully survived the 1980 winter at Lake Charlevoix, Michigan with no damage to the breakwater (Biddick, private communication). The stationary ice was estimated to be 0.6 m thick. At this location the breakwater was not moved from its summer mooring; however, the FTB was not subjected to significant dynamic ice forces during that winter.

The two preceding examples indicate that an FTB designed correctly for wave forces can withstand thermal ice forces.

2.4 Approval for Installing an FTB

Under the Navigable Waters Protection Act, approval from the federal Ministry of Transport is required before installing an FTB in Canada. The Ministry may require that the following steps be taken:

a) Submit a description of the proposed FTB site and a plan of the proposed work to the Aids to Navigation Division of the Ministry of Transport and a duplicate to the office of the Registrar of Deeds for the district, county or province in which the work is proposed.

b) Provide the public with one month's notice of the application for approval by advertising in two local newspapers and in the Canada Gazette.

Correspondence in connection with an application under the Act should be addressed to:

Chief, Aids to Navigation
Canadian Coast Guard
Transport Canada Building
Tower A, Floor 6-G
Place de Ville
Ottawa, Ontario
K1A 0N7

The approval process can take from six months to a year.

3.0 DETERMINING DESIGN WAVES

3.1 General

This section serves as a guide in determining FTB design waves for short-fetch, exposed sites with fairly simple bathymetry. Non-specialist users of this information are advised to have their design wave calculations reviewed by a coastal engineer. Complicated design situations should always be referred to a specialist.

3.2 Measured Wave Data

The design of an FTB depends primarily on the site's wave climate. Some information on the size of waves at the FTB site and on their frequency of occurrence is required. Measured wave data is available for some locations in Canada. These locations are generally offshore on large bodies of water and provide only limited coverage. Listings of available data may be obtained from:

Marine Environmental Data Services Branch
Marine Information Directorate
Ocean and Aquatic Sciences
240 Sparks Street, 7th Floor West
Ottawa, Ontario
K1A 0E6
(613) 995-2007

In many cases, recorded wave data does not exist, or else it covers too short a period to adequately define the wave climate. Although the best description of a site's wave climate would be obtained by installing a wave recorder, there is frequently insufficient lead time or funds to do so. Therefore, waves are usually determined from the more readily obtainable wind information. Wind-wave forecasting charts enable the prediction of significant wave heights and peak periods from wind speeds.

3.3 Design Wave Concept

A complete wave climate, although useful, is not essential to the design of an FTB. For FTB design purposes, the wave characteristics corresponding to a certain direction can be represented by two waves: the beam-design wave and the anchor-design wave (Harms and Bender, 1978).

The beam-design wave is related to the performance of the FTB. It is the largest wave that the FTB is designed to reduce in height to a predetermined acceptable height. For example, a commonly imposed criterion for waves in marinas is that the significant wave height should not exceed 0.3 metres during an average boating season. The required beam width of an FTB is proportional to the size of the beam-design wave. Therefore, for economic reasons, an FTB cannot be designed to attenuate all waves to an acceptable height; a number of hours when wave heights exceed the allowable criterion must be accepted. Typical beam-design waves at sites where FTB's are feasible have significant heights of 0.6 to 0.9 metres and periods of 2 to 3 seconds.

The anchor-design wave is related to the FTB's survival. It is the largest wave that the FTB is designed to sustain without structural damage. The mooring forces are proportional to the size of the anchor-design wave. Therefore, in most cases, the FTB cannot be designed to sustain the maximum possible wave; instead, a risk of the anchor system failing must be accepted. Typically, the significant wave height of the anchor-design wave at sites where FTB's are feasible is 1.2 to 1.8 m.

3.4 Wind Information

Wind information can be obtained from the weather station nearest the FTB site. Monthly weather summaries, published for individual weather stations by Canada's Atmospheric Environment Service, are a convenient source of wind data. These summaries include mean hourly wind speeds and directions; an example is given in Appendix B. More useful tables called "Hourly Data Summaries" are also published by AES for some stations. Wind information may be obtained from:

Atmospheric Environment Service
Information Services
4905 Dufferin Street
Downsview, Ontario
M3H 5T4
(416) 667-4920

Over-water wind speeds can differ from those measured on land. However, for fetches less than 10 km and for land wind speeds greater than 35 km/hour, it is safe to assume that over-water wind speeds are the same as the measured over-land speeds (Phillips and Irbe, 1978; Resio and Vincent, 1977).

Wave generation depends, in part, on wind duration (see Figure C11 in Appendix C). For a given wind speed, on a fetch of less than 10 km, waves of interest in the design of FTB's can be considered independent of the wind duration if the duration exceeds 2 hours; for a fetch of 5 km the corresponding duration is one hour.

The choice of wind speeds appropriate for the forecasting of design waves depends on the frequencies of exceedance considered acceptable. For example, the designer of an FTB for a marina might consider five hours per average boating season to be an acceptable number of hours for the incident significant wave height to exceed that of the beam-design wave. Similarly, the designer might consider 50 percent to be an acceptable level of risk of encountering significant wave heights equal to or greater than the anchor-design wave height during the life of the FTB.

The probability P that a wind speed of return period RP (years) will be equalled or exceeded during a service life S (years) is given by

$$P = 1 - \left(1 - \frac{1}{RP}\right)^{S}$$

Thus, if a frequency analysis of hourly winds from a particular direction reveals that the one in 20 year SW wind speed is 90 km/hour, the probability of encountering an hourly SW speed of 90 km/hour or more during a ten-year period is

$$P = 1 - \left(1 - \frac{1}{20}\right)^{10}$$

$$= 0.40 \text{ or } 40 \text{ percent.}$$

It is beyond the scope of this manual to discuss acceptable frequencies of exceedance for wave heights in the lee of an FTB. The required performance of a breakwater varies from site to site and should normally be determined with the help of a specialist. However, for an FTB protecting a marina in southern Canada, the wind speed selected to forecast the beam-design wave would probably be representative of the highest hourly speeds from the direction of interest during the months of May to October (the active boating season). Similarly, for an FTB to be left in the water year round, the wind speed selected to forecast the anchor-design wave would probably be the maximum hourly wind speed measured from the direction of interest over a period of at least ten years. For most short fetch FTB locations in southern Canada, speeds of about 50 and 100 km/hour might be considered for forecasting beam and anchor-design waves respectively.

3.5 Fetch

For each direction being investigated, the designer must estimate the fetch to the FTB site. Wind and wave directions are usually specified by octants (N, NE, E, SE, S, SW, W, NW). Thus, the southwest (SW) fetch should be taken as the longest fetch in the 45 degree SW octant.

Based on comparisons of recorded and hindcasted wave data, an effective fetch calculation (U.S. Army, Coastal Engineering Research Center, 1977) which reduces the fetch in width-limited situations is not recommended (Baird, private communication).

3.6 Bathymetry

Before proceeding to forecast waves, the designer must estimate depths over each fetch of interest. For simple bathymetries, these depths can be estimated by drawing a depth profile of each fetch (see Section 9.3). For complicated bathymetries, a coastal engineer should be consulted to help determine design waves. The following two examples describe situations in which complicated bathymetry could not easily be represented by an average depth for determining design waves:

(i) A 2 km fetch where the first kilometre distance from the breakwater is an average 3 m deep, followed by a kilometre with an average depth of 20 m.

(ii) A uniformly deep fetch with the exception of a sizeable reef or shoal, at a depth of about 1 m, in the middle of the fetch.

In Canada, charts containing bathymetric data for many major water bodies can be obtained from the following address:

Chart Distribution Office
Canadian Hydrographic Service
P. O. Box 8080
1675 Russell Road
Ottawa, Ontario
K1G 3H6
(613) 998-4931

Additional bathymetric data, primarily for small lakes, is available from provincial Ministries of Natural Resources. If no recorded data exists, the FTB designer can obtain depths by taking some soundings. The designer must also allow for the variation in mean water level due to tides or seasonal fluctuations. Tide and water level data for most major water bodies in Canada can also be obtained from the Canadian Hydrographic Service at the address noted above.

3.7 Wave Forecasting

Simplified wave forecasting curves for the significant wave height (H) and peak period (T) are given in Figures 12, 13 and 14 as a function of wind speed and water depth for fetches of 2.5, 5 and 10 kilometres respectively. For known values of wind speed and water depth, the designer can estimate H and T from the figure whose fetch most closely approximates the fetch of interest, or by interpolating between two figures (as done in the example in Section 9.5). These curves have been derived from shallow and deep water forecasting curves which are provided in Appendix C. For most FTB sites, the deep water curves are valid when the mean water depth over the fetch is greater than about 15 m.

For known values of peak wave period and water depth, the designer can determine the significant wavelength (L) from Figure 15. Note that for a constant period the wavelength decreases as the wave propagates into shallower water.

3.8 Refraction and Shoaling

The forecast waves can be altered by the processes of refraction and shoaling as they propagate into shallower water. Shoaling can be considered unimportant when the water depth (d) is greater than the square of the wave period divided by twelve:

$$d > \frac{T^2}{12}$$

For most FTB design waves, shoaling is unimportant in water depths greater than about 2 m. A coastal engineer should be consulted when determining design waves for an FTB situated in water less than 2 m deep.

For FTB's situated in bays or on relatively straight shorelines, the effects of refraction can usually be considered to be of secondary importance. However, refraction can be important for an FTB situated at a headland or in the lee of, and close to a reef or shoal. In these cases, wave energy can be focused

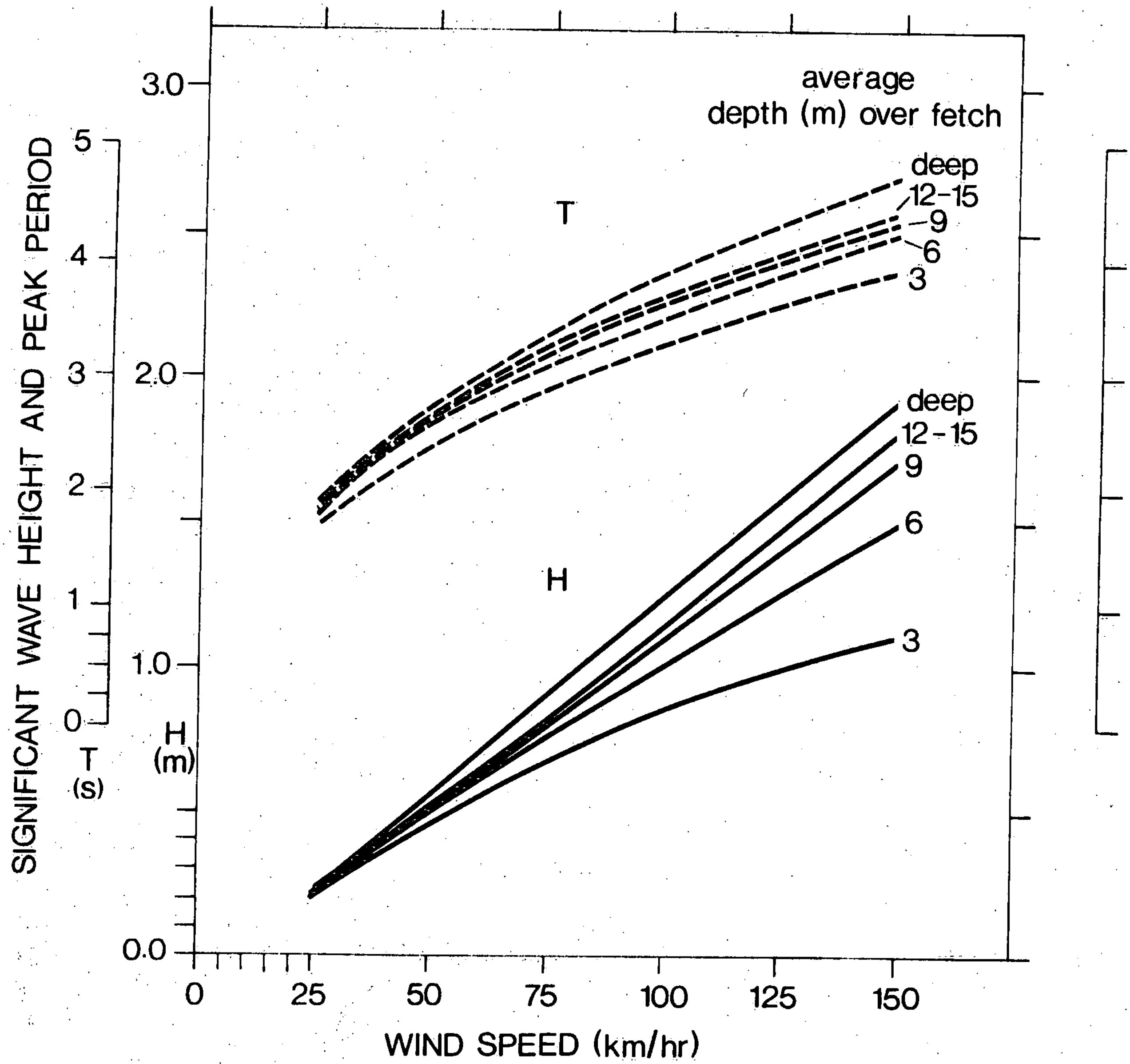


Figure 12 Wave forecasting curves for 2.5 km fetch

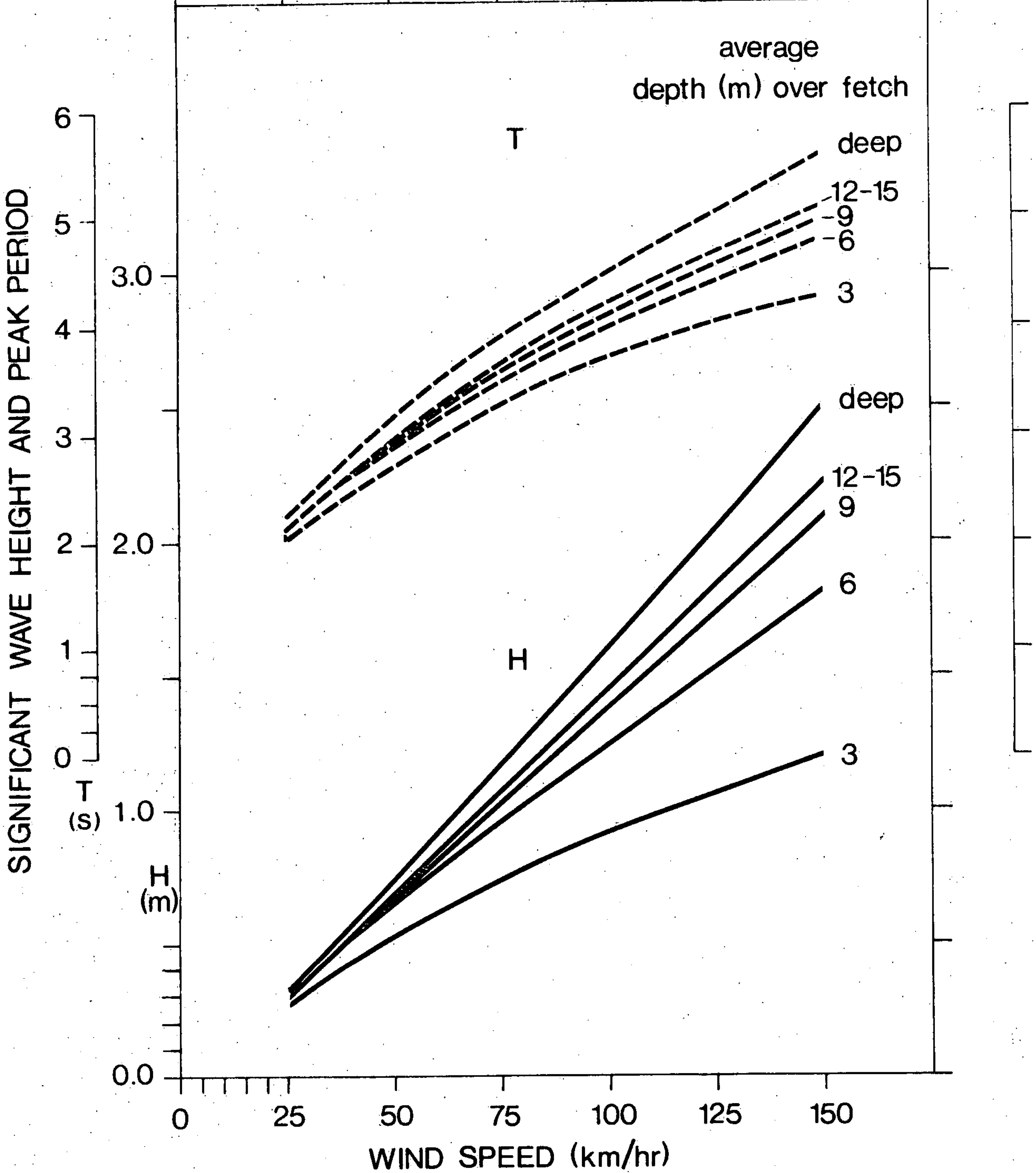


Figure 13 Wave forecasting curves for 5 km fetch

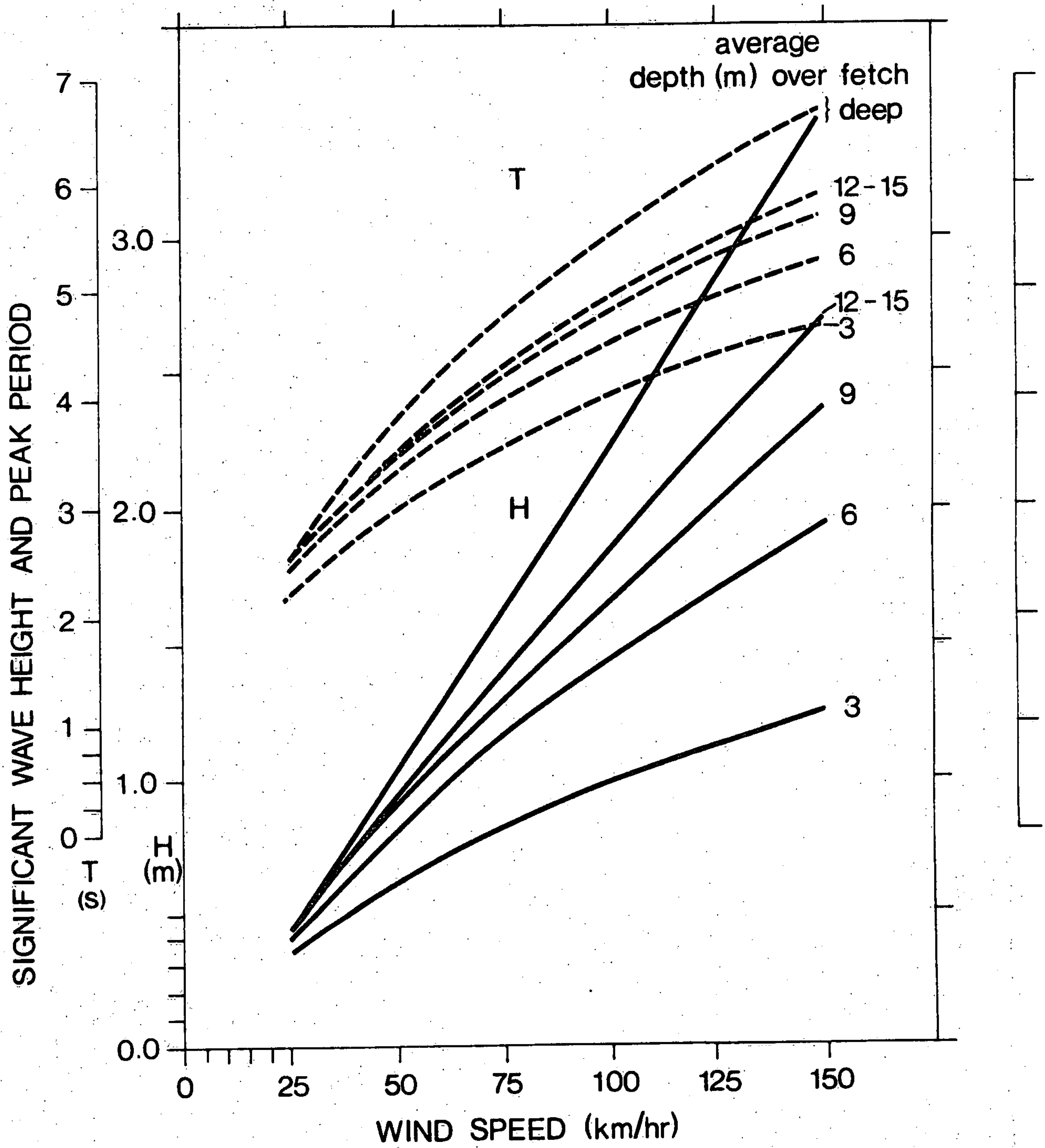


Figure 14 Wave forecasting curves for 10 km fetch

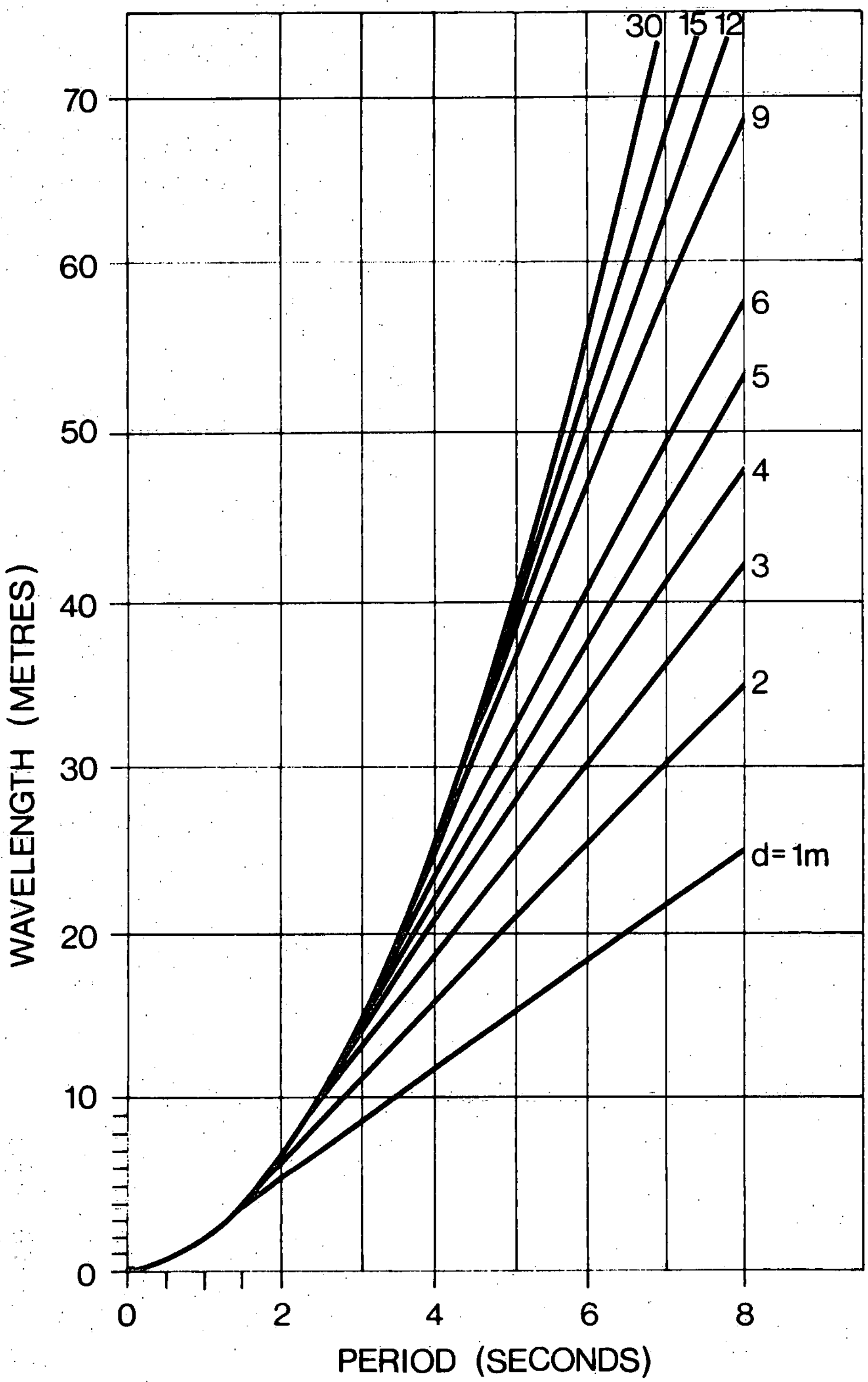


Figure 15 Relationship between wavelength, wave period and wave depth (linear theory)

on the FTB, substantially increasing the height of the design wave. In such situations, when the water depth at the FTB site is less than about one-fifth of the wavelength, $d<L/5$, refraction calculations should be done. Techniques for manual refraction estimates are described in the Coastal Engineering Research Center's "Shore Protection Manual". Also, a number of computer refraction programs are available from consulting engineers, universities and government agencies.

4.0 DESIGNING AN FTB

4.1 General

The overall size of an FTB can be characterized by its length, beam width and draft. A definition sketch is provided in Figure 16. For known design wave conditions and desired breakwater performance, this section provides design information which enables the determination of required beam width. Some basic information related to the length of the breakwater is also provided.

This section is not intended to provide comprehensive information for the design of marina breakwater protection. For a breakwater (not necessarily an FTB) protecting a marina, it is recommended that a specialist be consulted to consider the problems and to determine the location and length of the breakwater.

Aid in the design and construction of a Goodyear FTB can be obtained from the Goodyear Tire and Rubber Company at the following address:

Manager Community Relations
Goodyear Tire and Rubber Company
1144 Market Street
Akron, Ohio, U.S.A. 44316
Telephone (216) 794-3886

Aid in the design and construction of a PT-breakwater can be obtained from the following:

Dr. V. Harms
University of California
Lawrence Berkeley Laboratory
Marine Science Group - B77H
Berkeley, California 94720 U.S.A.
Telephone (416) 486-6461

Contributions to waves on the lee side of an FTB come from the following sources:

- Waves that are transmitted through the FTB
- Waves that diffract around the ends of the FTB
- Waves that are generated locally (between the FTB and the region being protected).
- Waves that are reflected from structures on the FTB's lee side.

H = incident wave height
H_t = transmitted wave height
L = wavelength
d = water depth
MWL = mean water level
D = tire diameter
B = beam size of FTB
C_t = H_t/H = ratio of transmitted to incident wave height

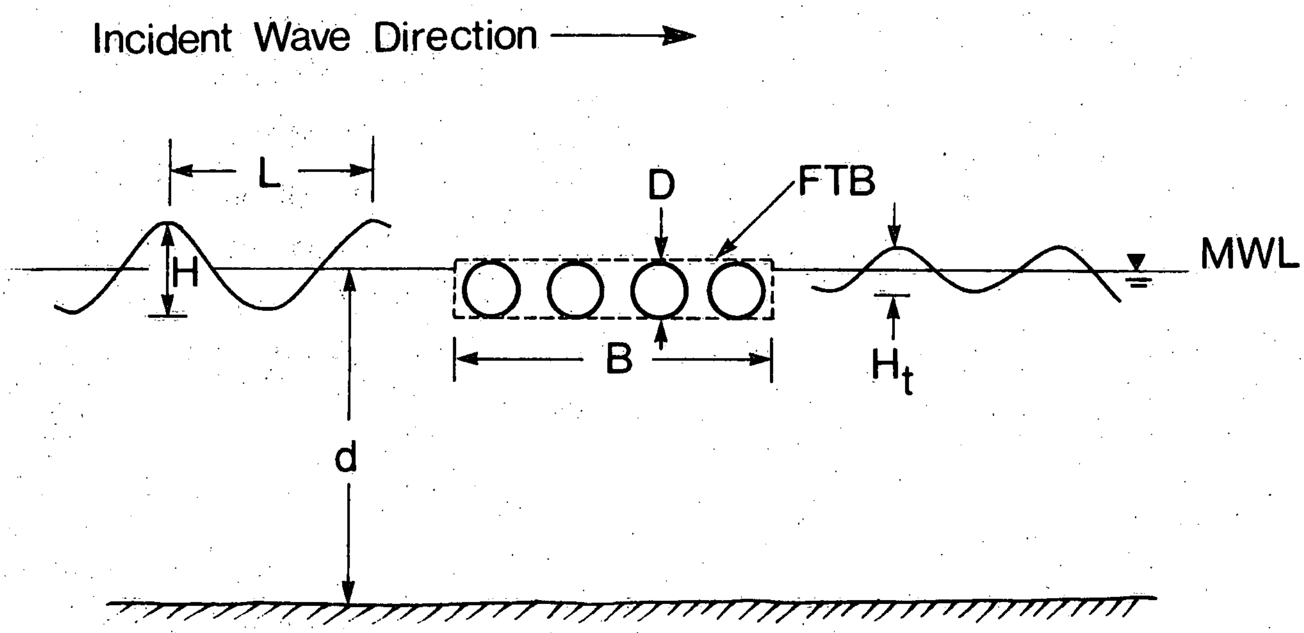


Figure 16 Definition Sketch of an FTB

The beam width of the FTB is sized to control the magnitude of the transmitted wave. The length and orientation of the FTB control the magnitude of the diffracted wave. Usually, the FTB is close enough to the region it is protecting that locally-generated waves can be considered unimportant. Reflected waves are generally not a problem unless there are some vertical, impermeable walls in the region being protected. Wave agitation problems in a marina, for example, can be aggravated by reflected waves from vertical walls.

4.2 Wave Transmission

Since a floating breakwater always transmits part of the incoming wave energy, it is necessary to be able to estimate the transmission characteristics of a given FTB for known incident wave conditions. For FTB design purposes, the ratio of transmitted to incident wave height can be considered to depend on the following variables:

- L/B, the ratio of wavelength to FTB beam width
- H/L, the wave steepness
- D/d, the ratio of tire diameter (a measure of the FTB draft) to water depth
- The type of FTB (Goodyear or PT)
- The direction of wave attack relative to the breakwater's orientation.

Furthermore, a PT-breakwater's wave attenuation depends on G/D, the ratio of pole spacing to tire diameter.

Prototype scale wave transmission tests of car tire Goodyear FTB's have been conducted by Giles and Sorenson (1978) in the U.S. Army Coastal Engineering Research Center's (CERC) large wave flume (6.1 m deep, 4.6 m wide, 194 m long). The tests were done on two different beam widths, four and six modules wide (8.5 and 12.8 m respectively), at two water depths, 2 and 4 m. Monoperiodic waves with heights up to 1.4 m were used in the tests.

Model scale transmission tests of Goodyear FTB's have been conducted by Harms and Bender (1978) using 1/4 and 1/8 scale tires and McGregor (1978) using 1/4 scale tires. The test results of Harms and Bender (1978) and the mathematical analysis of Isaacson and Fraser (1979) show clearly that wave transmission depends on incident wave steepness: for steeper waves, the FTB is a more effective wave attenuator. Unfortunately, McGregor does not report the values of wave steepness or water depth used in his tests. Until these points are clarified, the range of validity for his design curves cannot be established.

Transmission test results of the PT-breakwater (Harms et al, 1980) show that wave transmission is also dependent on the ratio of D/d. Based on these later findings, the transmission data of Giles and Sorenson (1978) has been re-plotted, paying particular attention to wave steepness and the ratio of D/d. Curves have been fit to the data points by eye for an approximately constant value of wave steepness of 0.04; the resulting curves are shown in Figure 17. These curves are almost the same as the single design curve of Giles and Eckert (1979), based on the same data, which does not explicitly recognize the importance of wave steepness or D/d. The Goodyear design curves in Figure 17 are also similar to the design curve of Harms (1979a, b), though slightly more conservative for values of C_t greater than 0.5.

The Goodyear FTB's dependence on D/d, at least for D/d=0.16 or 0.32, is less than the scatter of the data. This weak dependence is consistent with the results of Harms (1979 a, b) which show that a Goodyear FTB's wave transmission is virtually independent of D/d for $0.07 \leq D/d \leq 0.27$*. At present, design information for cases in which $D/d > 0.32$ is not available.

The design curves in Figure 17 are for FTB's that are one layer of tires thick. Research by McGregor (1978) and Harms (1979a) has revealed that a single layer Goodyear FTB provides more wave protection than a multi layer Goodyear FTB constructed of the same number of modules.

Prototype scale wave transmission tests of two types of PT-breakwater have been reported by Harms et al (1980). Their tests were done on a section with a beam width of 12.2 m at two water depths, 2 and 4.6 m, in the CERC large wave flume. The two types of breakwater tested are referred to as:

PT-1 constructed of steel pipes and truck tires, and
PT-2 constructed of wood poles and car tires.

Model scale transmission tests of PT-breakwaters have been conducted by Harms and Bender (1978) using 1/4 and 1/8 scale tires. The model tests were done with different values of G/D and D/d than were used in the prototype tests. Consequently, a rigorous comparison of prototype and model test transmission results is impossible. However, in general, the results compare favourably.

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* Harms (1979a, b) claims that a Goodyear FTB's wave transmission is virtually independent of D/d for $0.07 \leq D/d \leq 0.52$. However, the vast majority of his data is for $0.07 \leq D/d \leq 0.27$ (see Figure I.15, p. 61, Harms 1979a).

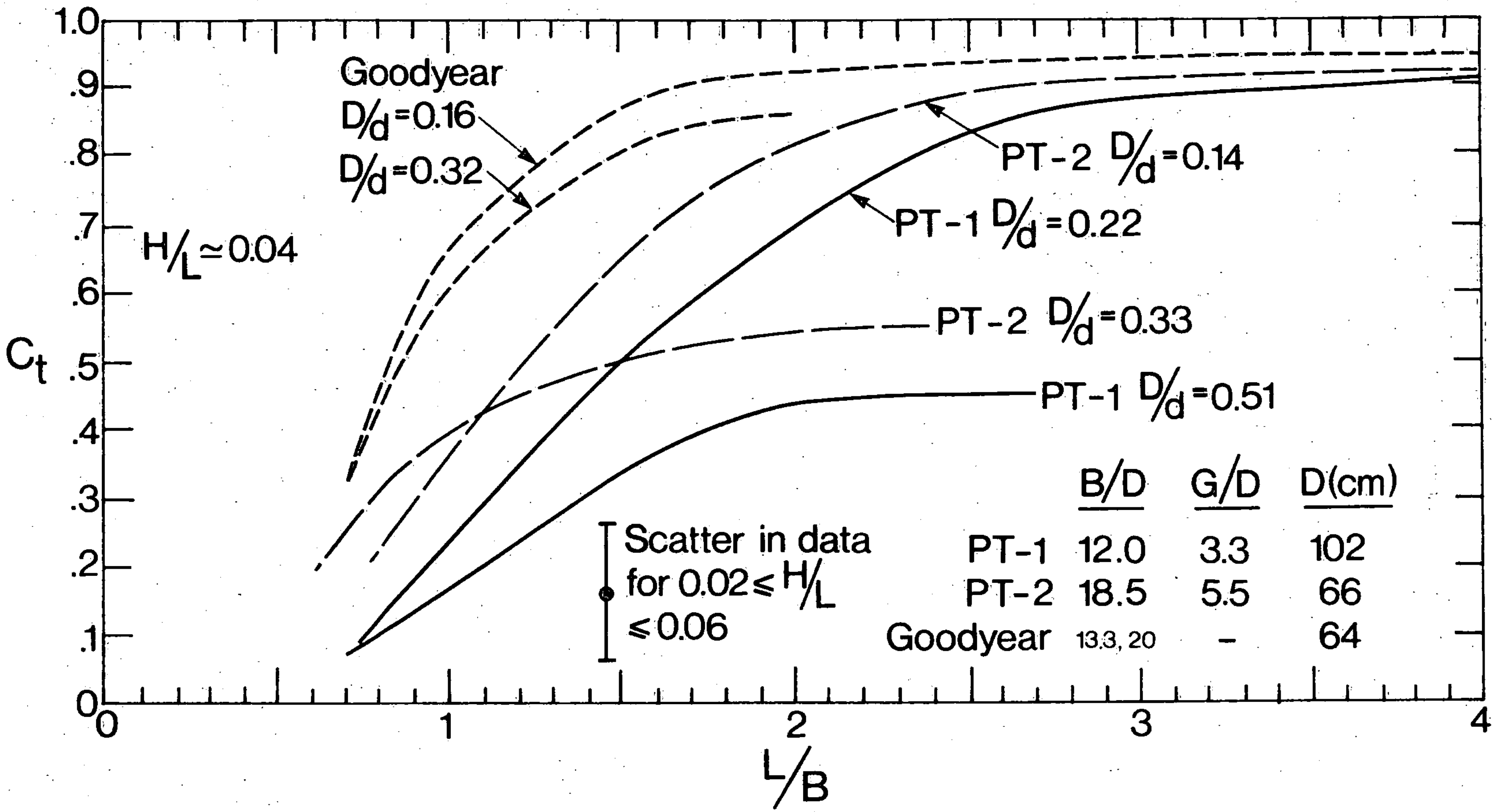


Figure 17 FTB WAVE TRANSMISSION DESIGN CURVES (after Giles and Sorenson, 1978, Harms et al, 1980)

The PT design curves shown in Figure 17 are those resulting from the prototype scale tests of Harms et al (1980). They are drawn for a wave steepness of 0.04. The anomalous crossover of the PT-2 curves is believed to be due to a lack of data for L/B<1.

4.3 Use of Transmission Design Curves

To date, all FTB transmission tests have been two-dimensional, i.e. the incident wave crests approach parallel to the breakwater. In practice, with wind-generated waves, this condition rarely occurs. It has been found that the effectiveness of floating breakwaters in attenuating waves improves slightly for oblique wave attack (Carver 1979, Adee et al, 1976, Kowalski 1976); however, this improvement has not been quantified for FTB's. Therefore, the design curves in Figure 17 can be considered adequate for predicting wave transmission for the "worst case" of wave crests approaching parallel to the breakwater.

Prototype tests and the majority of model tests have been conducted with monoperiodic (regular) waves. In nature, waves are highly irregular and are commonly described by a significant wave height and peak period. It is not yet known which wave height parameter (e.g. root mean square, significant or maximum wave height, etc.) of an irregular sea state is appropriate for use as "H" in the design curves derived from regular wave tests. Until further research in this area is completed, it is suggested that the significant wave height and wavelength corresponding to the peak period be used in the transmission design curves (as done by Giles and Eckert, 1979). This implies that some waves in the lee of the FTB will exceed the transmitted beam-design significant wave height.

The design curves in Figure 17 are for an incident wave steepness of about 0.04. This is a typical design wave steepness at sites where the fetch is less than 10 km. To date, the quantity and quality of wave transmission data does not enable the determination of design curves for other values of wave steepness. It is suggested that the design curves in Figure 17 be used for values of beam-design wave steepness greater than 0.03. For lower values of steepness, the designer is advised to inspect the data plots in Harms (1979a) and Harms et al (1980) and, subsequently, to use engineering judgement in arriving at a final design.

The value of relative draft, D/d, is an important variable influencing wave transmission. It appears that the wave transmission of a Goodyear FTB is only weakly dependent on D/d for values of D/d less than 0.32. However, the transmission of PT-breakwaters seems to be much more sensitive to D/d (Figure 17). It is suggested that the PT-1 design curve for D/d=0.22 be used to predict wave attenuation for $0<D/d\leq 0.22$; similarly, the PT-2 design curve for D/d=0.14 is recommended for $0<D/d\leq 0.14$, and the Goodyear curve for D/d=0.16 is recommended for $0<D/d\leq 0.16$. For values of D/d intermediate to those of the two design curves for each type of FTB, it is suggested that interpolation be undertaken in a very conservative manner.

The pole spacing in a PT-breakwater affects the breakwater's rigidity, cost and transmission characteristics. The majority of model tests by Harms and Bender (1978) were conducted with G/D values of 6.4, but some larger ratios were also tested. They found that increasing the G/D ratio lead to increased wave transmission and oscillatory motion of the tire strings (Bender, private communication). Later, the prototype scale tests (Harms et al, 1980) were conducted with G/D=3.3 and 5.5 for the PT-1 and PT-2 respectively. Thus our knowledge on PT transmission characteristics is essentially limited to values of G/D from 3.3 to 6.4.

The mooring system can affect the transmission characteristics of a floating breakwater. In general, a given floating breakwater will attenuate waves more effectively if the mooring lines are taut, at the expense of higher mooring forces (Isaacson and Fraser, 1979). None of the FTB flume tests to date have simulated realistic mooring systems. Instead, a small but constant seaward restoring force acted on the test breakwaters. This type of mooring system is neither taut nor slack but, for wave transmission characteristics, can be considered representative of slack moorings.

When the natural period of a moored body is about the same as that of the incident waves, resonance affects can lead to larger wave transmission. The natural period of a moored body depends on the mooring system as well as on the body's dimensions, weight and components. Tests to date have not revealed any significant wave transmission resonance in FTB's (Giles and Sorenson, 1978; McGregor, 1978; Harms and Bender, 1978; Harms et al, 1980).

For known values of beam-design wave height and wavelength, as well as D/d, G/D (for a PT-breakwater) and acceptable transmitted wave height, the required FTB beam width can be estimated from Figure 17. Conversely, for known values of beam width, D/d, G/d, and incident wave height and wavelength, the transmitted wave height can be estimated from Figure 17.

Some typical wave conditions and the beam sizes necessary to attenuate the wave height to 0.3 m are given in Table 1, assuming 0.64 m diameter tires are used in the Goodyear and PT-2 breakwaters, and 1.0 m diameter tires in the PT-1. Clearly, the PT-breakwaters require a considerably smaller beam size than the Goodyear FTB. It is interesting to note that the ratio of transmitted to incident wave height for a Goodyear beam size equal to half the wavelength is 0.93 for D/d=0.16. Nevertheless, several Goodyear FTB's have been designed using the "rule of thumb" that the beam size should be greater than or equal to half the wavelength of the design wave (Shaw and Ross, 1977).

TABLE 1 BEAM SIZES NECESSARY TO ATTENUATE GIVEN WAVE CONDITIONS TO 0.3 m IN HEIGHT

Required Beam Size (m)							
Beam-Design Waves		Deep Water			Water Depth=3 m		
H(m)	T(s)	Goodyear	PT-1	PT-2	Goodyear	PT-1	PT-2
1.2	4.5	-	31	38	-	21	27
0.9	3.5	27	16	20	23	14	17
0.6	2.5	11	6.5	8	11	6	8

4.4 Length

The determination of required FTB length should usually be done with the help of a coastal engineer. Some basic considerations are outlined in this section.

The required length of FTB depends on several factors including:

- The geometry of the region to be protected.
- The distance between the region to be protected and the FTB.
- The incident wave climate.

Incident waves diffract around the ends of the FTB, propagating into the region requiring wave protection. In order to protect the lee side from diffracted waves, the length of the FTB can be increased by a length proportional to the beam-design wavelength at each end. Using design charts for semi-infinite rigid impermeable breakwaters (U.S. Army, CERC, 1977) as a first approximation to diffraction around an FTB, increasing the FTB length by one beam-design wavelength at each end should result in the ratio of diffracted to incident wave height being less than 0.33, for waves approaching within 30 degrees of normal to the FTB.

Depending on the possible directions of wave attack, the required length of FTB increases with increasing distance from the region it is protecting. This can be seen in Figure 18 in which an FTB is required to protect an area from waves from the predominant wave sector. The required length of FTB can be conservatively estimated as follows:

1. Draw a line parallel to the predominant wave direction from each side of the region to be protected.
2. Draw a line outward at 22½ degrees (half the octant) from each of the lines from step 1, and extend it to the desired FTB location.
3. Increase the FTB length from step 2 by one beam-design wavelength at each end.

In situations where an FTB must provide protection against wave attack from more than one octant, the FTB can be bent to face each direction or else more than one FTB section can be used.

4.5 Tire Size

The Goodyear FTB design is based on a module, constructed of 18 tires, which serves as a building block for any size of breakwater (Figure 19). It is reported that the dimensions of a tightly-bound Goodyear module assembled using small car tires (outer diameter approximately 0.58 m) is 1.8 m x 1.5 m (Lyttelton Harbour Board, private communication). This is somewhat smaller than the typically reported dimensions of 2.1 m x 2.0 m shown in Figure 19 (Kowalski and Ross, 1975) and is believed to be due to the differences in tire size and the tautness of the module binding material.

Typical weights in air for 0.64 m diameter car tires and 1.0 m diameter truck tires are 7.5 and 40 kg respectively. The size and weight of truck tires make assembly of truck tire modules more difficult. Therefore, for most Goodyear FTB installations, car tires are used. Truck tires could be considered if attempting to increase the breakwater's draft (see section 4.2) or if smaller tires were unavailable.

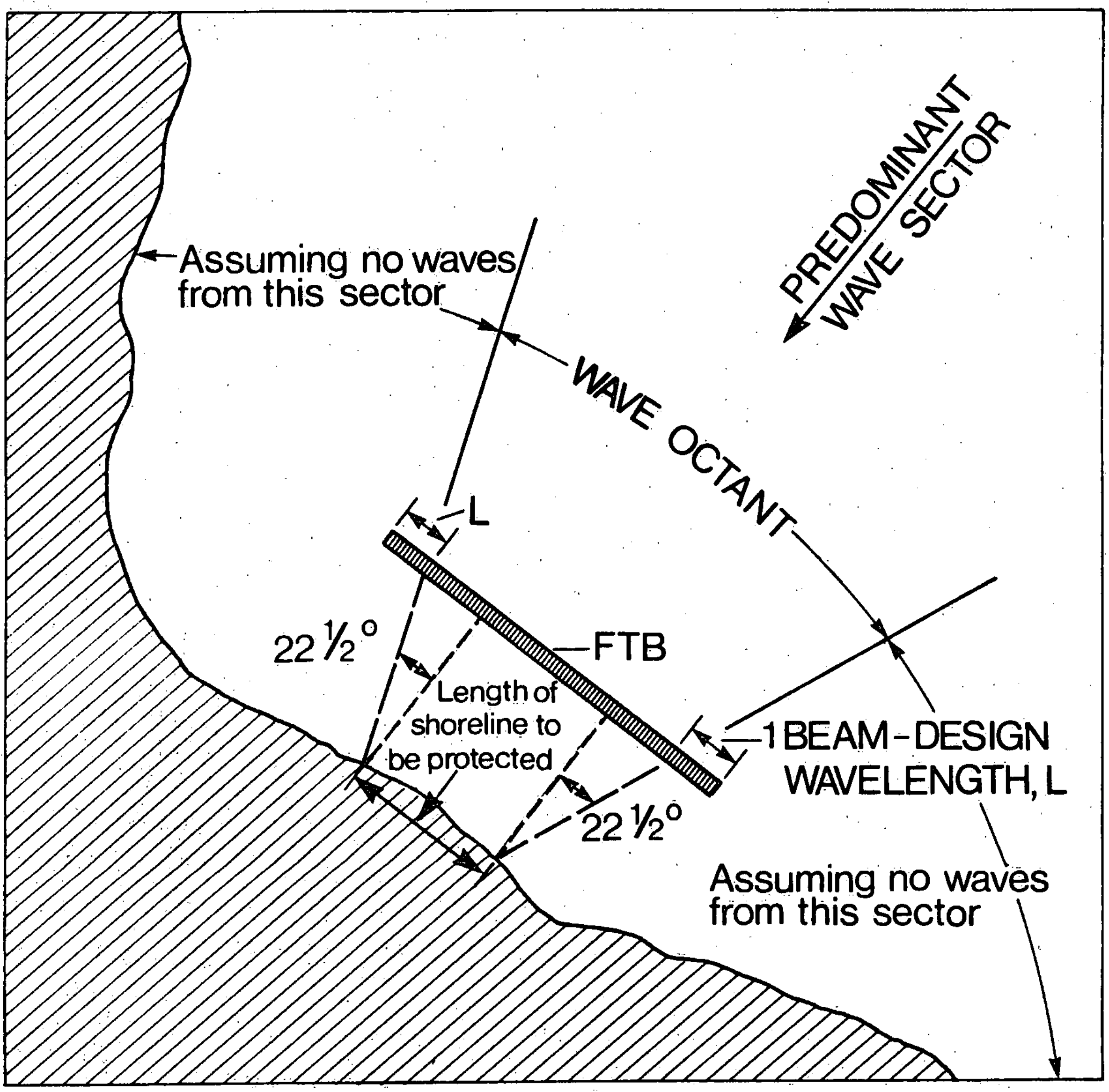
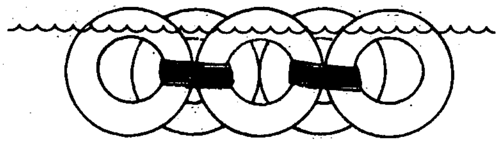
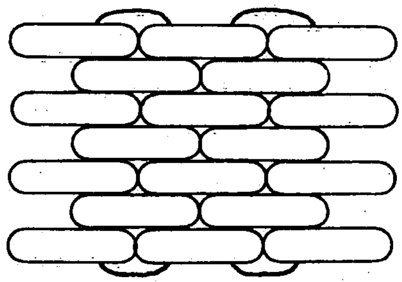


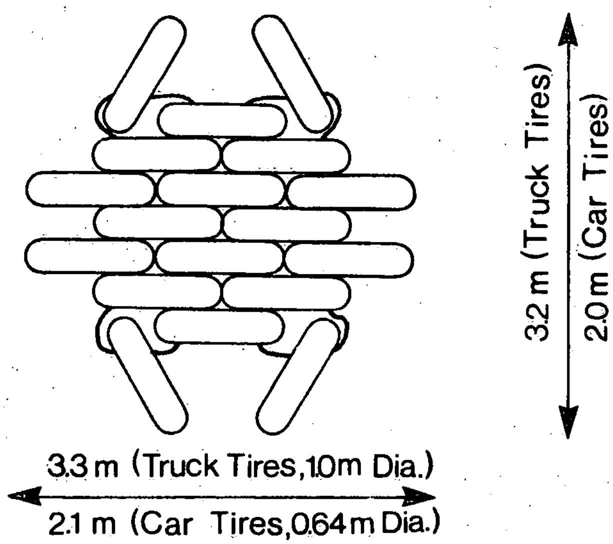
Figure 18 Determination of required FTB length



Side view of Goodyear module in the water.



Top view of the same module as it is constructed on land.



Top view of the same module preparatory to attachment to other modules.

Figure 19 Views of a Goodyear module. (Kowalski and Ross, 1975)

The PT-breakwater design is based on tire-encased pipes or poles, and tire strings, arranged as shown in Figure 20. The pole spacing should be about four times the tire diameter (see section 4.3). Thus, for tire diameters of 0.64 or 1.0 m, the pole spacing would be about 2.5 or 4.0 m respectively.

The choice of PT-1 or PT-2 is a design consideration related to the availability of materials, the required wave attenuation, the site's wave climate, and estimated costs of maintenance. The PT-1 is believed to be a sturdier breakwater than the PT-2, able to withstand larger waves, and perhaps capable of a longer service life.

4.6 Flotation

The most frequently encountered problem with Goodyear FTB's has been their tendency to sink. Where this has occurred the FTB's were not equipped with adequate supplemental flotation (e.g. Port Colborne, Ontario and Westfield, New York). A field test of a Goodyear FTB in New Zealand had some tires equipped with supplemental flotation and other tires with none. It was found that the tires without supplemental flotation had sunk after approximately six months, while the tires with supplemental flotation continued to float at the end of a documented 10-month period (Lyttelton Harbour Board, private communication).

A naturally buoyant force is exerted on an FTB by the air trapped in the crowns of the tires. This trapped air is recharged periodically when parts of the FTB briefly move above the water surface when the FTB is subjected to waves. The air trapped in the crown of one newly vertically-installed car tire provides an excess buoyant force of about 5 kg (Harms 1979a). Consequently, a newly installed tire will float. However, this naturally buoyant force tends to decrease with time for the following reasons:

- Trapped air dissolving in the water.
- Trapped air leaking out through holes in the tire crowns.
- Lack of air recharge due to prolonged calm periods or ice cover.

Furthermore, the weight of an FTB tends to increase with time for the following reasons:

- Growth of aquatic plants and organisms (more pronounced in salt water FTB installations)
- Accumulation of sediment in the bottoms of the tires.
- Accumulation of snow, ice or debris on the surface of the FTB.

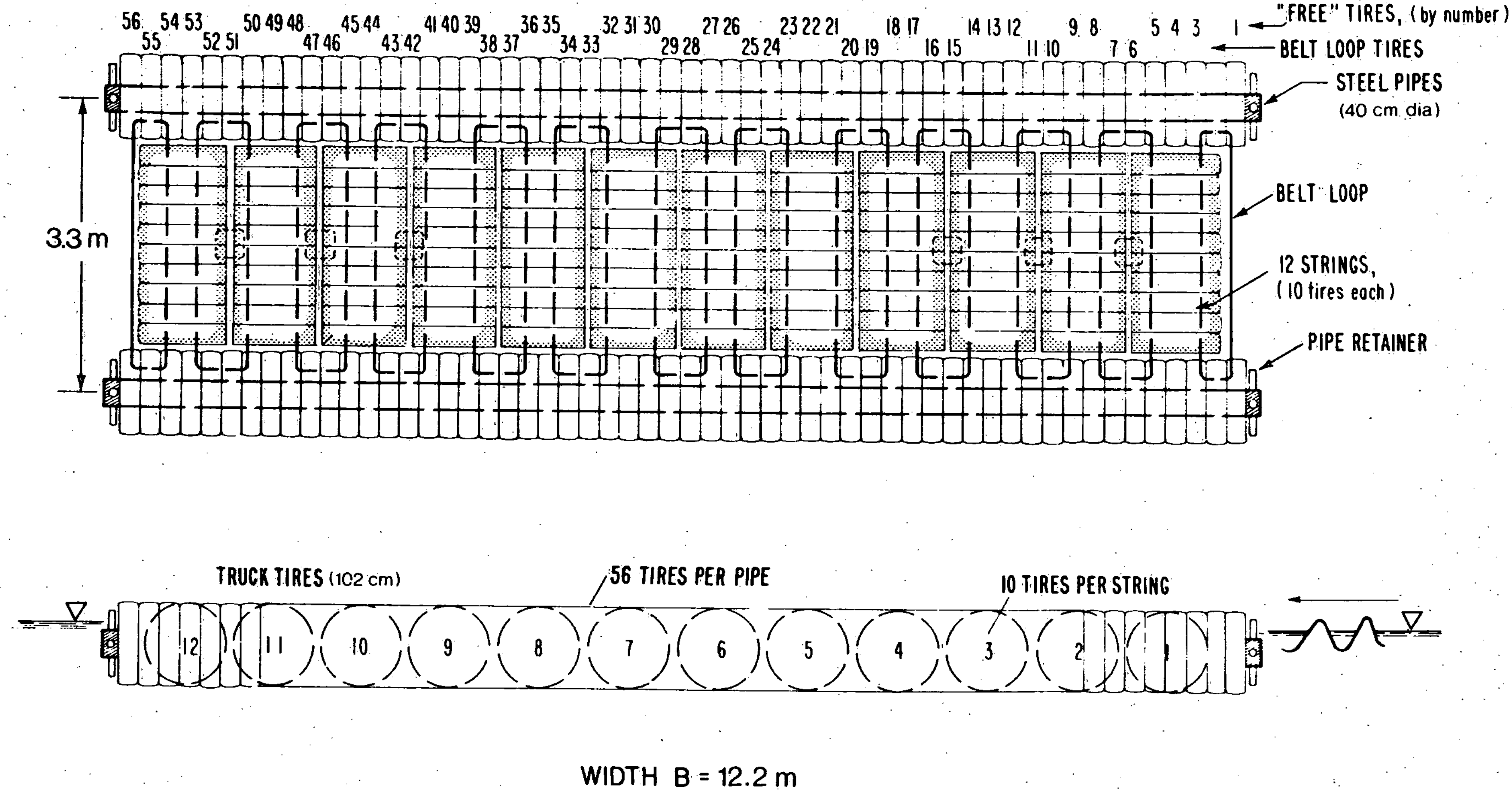


Figure 20 Views of a PT-breakwater section (Harms et al, 1980)

After 10 months of use in salt water, the Goodyear FTB test section in New Zealand was moved to a dry dock. The combined weight of marine growth and sediment resulted in an approximate doubling of a typical tire's weight in air, although the submerged tires were still buoyant (Lyttelton Harbour Board, private communication). In some tires the sediment filled two-thirds of the height up to the bead.

To ensure continued FTB flotation, a supplemental buoyant force should be provided. Some FTB flotation calculations, which illustrate the need for supplemental flotation are presented in Appendix D. Supplemental flotation agents and methods of implementation are described in Sections 6.6 and 7.4 respectively. If in doubt about the necessity of supplemental flotation, consider the expense and difficulty of refloating an FTB that has sunk to the bottom and whose tires are full of mud or gravel.

5.0 DESIGNING THE ANCHORS FOR AN FTB

5.1 FTB Mooring Force Research

Since an FTB is a floating structure, it must be anchored in position. Inadequate estimation of the peak mooring force can result in shifting of the FTB's position with accompanying loss of wave protection. This section deals with the estimation of mooring forces caused by waves. For a discussion of ice forces, refer to section 2.3.

It has been found that the force exerted on an FTB by waves is an impulse type function, attaining a peak value and then almost complete relaxation in each wave period (Pierce and Lewis, 1977; Galvin and Giles, 1979).

For FTB design purposes, the peak mooring forces exerted by waves can be considered to depend on the following variables:

- H, the incident wave height
- The type of FTB (Goodyear or PT)
- D/d, the ratio of tire diameter to water depth
- H/L, the wave steepness
- L/B, the ratio of wavelength to FTB beam width
- The type of mooring system

Forces exerted by breaking waves are much greater than those of non-breaking waves. Waves can be considered non-breaking when the water depth is greater than 1.3 times the wave height. The following design information is for non-breaking wave conditions.

Prototype scale tests (Giles and Sorenson, 1978) and model scale tests (Harms and Bender, 1978; McGregor, 1978) of Goodyear FTB's included measurements of mooring forces. All mooring systems in the tests were essentially slack moored. The prototype scale tests were conducted with monoperiodic waves and the peak mooring force was taken as the maximum force recorded during a five-minute test. The model scale tests of Harms and Bender (1978) were conducted mainly with monoperiodic waves, but some tests were performed with irregular (spectral) waves. In both cases, mooring lines were connected directly to the FTB's, and the peak mooring force was taken as the maximum force recorded during the test, excluding start or stop transients. For the irregular wave tests, the wavelength was taken as that corresponding to the peak period, while the wave height was taken as the average wave height obtained from time series analysis. McGregor (1978) tested with irregular waves and recorded the force time series for all tests. He found that, to a first approximation, a Raleigh distribution fitted the force data. Unfortunately, his report does not enable a designer to estimate mooring forces for a given FTB size and known wave conditions.

The ongoing field test of a 45 m x 15 m Goodyear FTB test section in New Zealand is investigating mooring forces in an innovative manner. Weaker sections of polyester rope (8 and 12 mm diameter) have been spliced into the main anchor lines, in order to establish the mooring forces based on the different breaking strengths of the varying diameters of rope (Lyttelton Harbour Board, private communication). Test results to date are incomplete. However, preliminary results indicate that the mooring force design curves of Harms and Bender (1978) provide estimates of peak mooring forces which are of the correct magnitude though somewhat conservative.

The one year field test of a 30 m x 7 m Goodyear FTB section (Kowalski and Candle, 1976) provided another opportunity to investigate a realistic mooring system. However, the published test results provide very little useful design information.

The results of Harms and Bender (1978) and Giles and Sorenson (1978) are in good agreement (Harms and Bender, 1978; Harms, 1979a; Harms, 1979b). Since the model tests cover a wider range of relevant variables than the prototype tests, the force design curves of Harms and Bender (1978) are presented in Figure 21. At present, force design information is not available for Goodyear FTB's when D/d exceeds 0.32 or H/L exceeds 0.06.

Prototype scale tests (Harms et al, 1980) and model scale tests of PT-breakwaters (Harms and Bender, 1978) included measurements of peak mooring forces. Test procedures were essentially the same as those for the Goodyear tests. It was found that the modelled forces considerably underestimate the prototype forces. This is believed to be due to the scale effects of not correctly modelling the elastic properties of the PT-breakwater. (These scale effects were not important for the much more flexible Goodyear design.) Thus the PT force design curves in Harms and Bender (1978) and Harms (1979a, b) <u>should not be used.</u> Instead, the following results of the prototype tests should be used:

PT-1 with B = 12.2 m, G/D = 3.3, <u>and a five-tire mooring damper on each line</u> (See Figure 31)

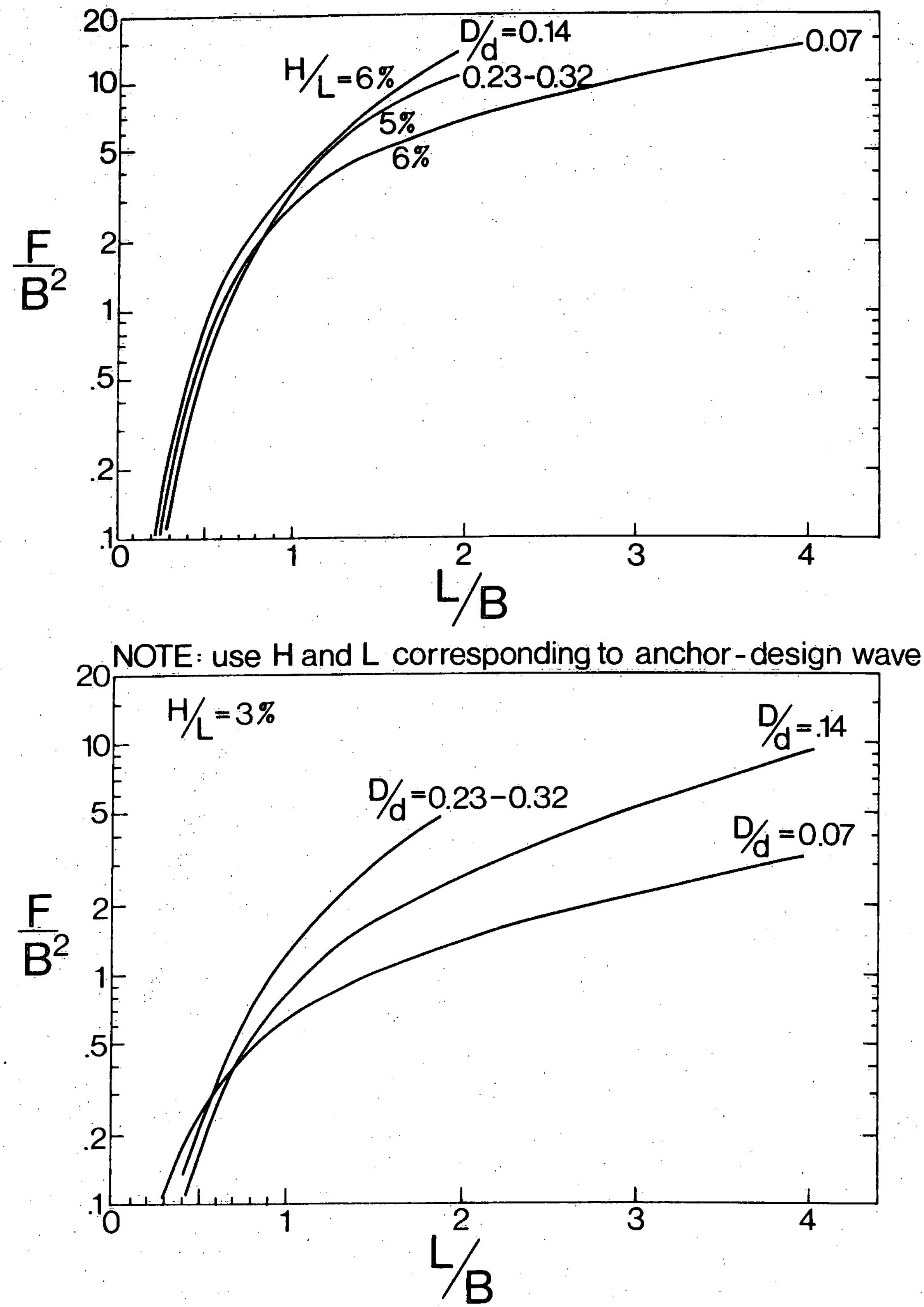


Figure 21 GOODYEAR FTB PEAK MOORING FORCE DESIGN CURVES (after Harms and Bender, 1978) (Note that F is in Newtons, B in metres

$$F = kH^{1.5} \qquad (1)$$

where F is the peak mooring force in N/m

H is the wave height in m, $H \leq 1.8$ m

k = 2750 for $D/d = 0.22$, $1.0 \leq L/B \leq 3.7$

k = 4500 for $D/d = 0.51$, $1.0 \leq L/B \leq 3.3$

For PT-breakwaters, Harms and Bender (1978) found that a tire damper incorporated into each mooring line significantly reduced peak mooring forces.

PT-2 with B = 12.2 m, G/D = 5.5, and mooring lines connected directly to the poles (i.e. no mooring dampers)

$$F = kH^2 \qquad (2)$$

where F is the peak mooring force in N/m

H is the wave height in m, $H \leq 1.5$ m

k = 2650 for $D/d = 0.14$, $1.0 \leq L/B \leq 4.3$

k = 4200 for $D/d = 0.33$, $1.0 \leq L/B \leq 2.9$

The peak mooring forces of a PT-breakwater are considerably greater than those of a Goodyear FTB providing comparable wave attenuation. As seen in the design example (Section 9.7), the PT mooring forces are two to three times greater than the Goodyear's.

Tests for other combinations of B, G/D, D/d and mooring dampers were not conducted. Use of these results for values of B other than 12.2 m should be done with care; as seen by the Goodyear FTB results of Galvin and Giles (1979), a 50 percent increase in the beam width can lead to much more than a 50 percent increase in peak mooring force.

5.2 Use of Mooring Force Design Information

Since prototype tests and the majority of model tests have been conducted with monoperiodic waves, the designer is again faced with the problem of selecting an appropriate wave height parameter for application of the mooring force information to irregular waves. Using H_{MAX}, the largest wave height expected to strike the FTB, might be too conservative because it seems unlikely that a single wave of height H_{MAX} would exert the same force as a train of regular waves of height H_{MAX}. However, the effect of wave grouping (Johnson et al, 1978) on FTB mooring forces is unknown. Until further research in this area is reported, it is suggested that the significant wave height and wavelength corresponding to the peak period be used in the determination of mooring forces.

Tests to date have been two-dimensional, i.e. wave crests approach parallel to the FTB length. Under these conditions, the entire length of the FTB test section is hit by the wave at the same instant. In nature, the crest lengths of waves are finite. Therefore, it is unlikely that the entire FTB length would be hit by a wave at the same instant. For short-crested waves approaching normal to a breakwater, it has been shown (Traetteberg, 1968) that mooring forces per unit length decrease as the ratio of breakwater length to wavelength increases. Thus one might be tempted to reduce the calculated mooring force obtained from the results of two-dimentional tests. However, the following three-dimensional occurrence produces a compensating effect.

In nature, wave crests do not always approach parallel to a breakwater. Oblique wave attack can exert localized forces which exceed those determined from two-dimensional tests. For instance, the force from a wave obliquely striking the corner of an FTB might be resisted mainly by the corner anchor, rather than being uniformly distributed over the length of the FTB and many anchors. Under such conditions, the mooring force exerted on the corner anchor might exceed the force determined from two-dimensional tests; this could lead to "walking" the anchors, a process whereby one anchor at a time shifts its position.

Until further research on the three-dimensional affects of waves on mooring forces is conducted, it is suggested that the two-dimensional results (Figure 21, Equations 1 and 2) be used to estimate FTB mooring requirements.

The peak mooring force estimated from Figure 21 or Equations 1 and 2 is for the FTB's windward side. Limited data has been obtained for the leeward mooring forces (Giles and Sorenson, 1978); it was found that the peak leeward forces are of the order of 5 to 10 percent of the peak mooring forces on the windward side. It is recommended that the leeward anchors be designed for the larger of the forces resulting from a leeward anchor-design wave or 20 percent of the windward requirement.

5.3 Designing the Anchors for an FTB

For FTB sites with sand, silt or clay bottoms, gravity anchors are generally used to moor the FTB. Piles or embedment anchors can also be used but their high cost of installation favours the use of gravity anchors whenever possible. Thus, only the design of gravity anchors is covered here.

For a known value of peak mooring force, the required size and spacing of a gravity anchor can be determined by the following equation:

$$S = \frac{(\gamma - \gamma_w)\, V\, \mu}{F\; F_s} \tag{3}$$

where
S = Spacing of anchors (distance between adjacent anchors)
γ_w = Specific weight of water
γ = Specific weight of anchor in air
V = Volume of anchor
μ = Coefficient of static friction
F = Peak mooring force per unit length
F_s = Factor of safety

The specific weights of fresh and salt water are 9810 and 10,060 N/m^3 respectively, while the specific weight of normal weight concrete and steel in air are about 20,900 and 75,600 N/m^3 respectively. The submerged anchor weight $(\gamma - \gamma_w)$ V, times μ represents the value of the horizontal force at which the anchor will start to slide (or drag). For sand, silt or clay bottoms, a value of $\mu = 0.5$ can be used for design (Myers et al, 1966). This should result in a conservative design, especially if the anchors become partially embedded. The factor of safety, F_s, allows for uncertainty in the design value of the peak mooring force. From the upper limit of force data points (Harms et al, 1980; Giles and Sorenson, 1978) it appears that a values of $F_s \simeq 1.5$ should be used in design.

For concrete anchors 1 m^3 in size, the allowable spacing in fresh water is

$$S(m) = \frac{5550}{F \times F_s} \tag{4}$$

where F is the peak mooring force in N/m.

In practice, anchor spacing is determined, in part, by the strength of the mooring line. The working strength of the mooring line should be greater than or equal to $F \times F_s \times S$. To fully utilize the working strength of the mooring line (see Section 6.8 for mooring line materials and working strengths) the anchor spacing determined from Equation 4 might have to be increased. This can be done by placing more than one 1 m^3 size anchor on each mooring line. The number of anchors on each line, and the spacing, should be increased by the ratio of the mooring line's working strength to the numerator of Equation 3 (i.e. 5550N if using 1 m^3 size concrete anchors and μ=0.5). This procedure is demonstrated in the design example (Section 9.8).

6.0 CONSTRUCTION MATERIALS

6.1 General

The success of an FTB depends in large part on the type and quality of materials used in its construction. Only proven materials should be used.

6.2 Tires

In most urban areas, scrap tires are available from tire manufacturers, tire retail outlets, trucking firms and others. Usually, the only costs associated with obtaining scrap tires are for labour and transportation.

Since the local availability of scrap tires can vary, it is advisable to make arrangements to acquire the necessary number of tires well in advance of the planned construction date. A lead time of six months to a year should be adequate.

The number of tires needed to construct a unit area of FTB has been estimated using information from Section 10 as:

4.8 car tires per m^2 Goodyear FTB

1.9 truck tires per m^2 Goodyear FTB

7.8 car tires per m^2 PT-2

3.8 truck tires per m^2 PT-1

To allow for substandard scrap tires (those with ripped casings or large holes), the number of tires ordered should be greater than the number needed to construct the FTB.

6.3 Poles/Pipes

An important component of a PT-breakwater is the pole. The "pole" can be a wooden pole or a steel pipe. If using wood, marine piling should be used for the poles. Marine piling is a chemically treated wood piling that resists deterioration in a marine environment. It is available in standard lengths from 7.6 m to 15.2 m in 1.5 m increments, at a cost of about $16 per metre length. The diameter of a pile tapers from 30-40 cm at the base to 23-30 cm at the other end, depending on the length of the pile.

For PT beam widths greater than about 12 m, steel pipes and truck tires should be used. Steel pipe with a 40 cm diameter and 6 mm thick walls is available in standard lengths of 6.1 and 12.2 m at a cost of approximately $50 per metre length. Steel pipe-pipe connections can be accomplished by welding.

6.4 Binding Materials

The binding material is used to interconnect components of an FTB and is essential to the success of an FTB. Several pioneer FTB's failed because of unsatisfactory binding materials. Some of these unsatisfactory binding materials which are not recommended for FTB use (Davis, 1977) are:

- Nylon lines because of poor abrasion resistance, knot loosening and ultra-violet degradation.
- Kevlar lines because of poor strength characteristics in flexure.
- Any metallic wire rope or banding because of problems with corrosion and metal fatigue.

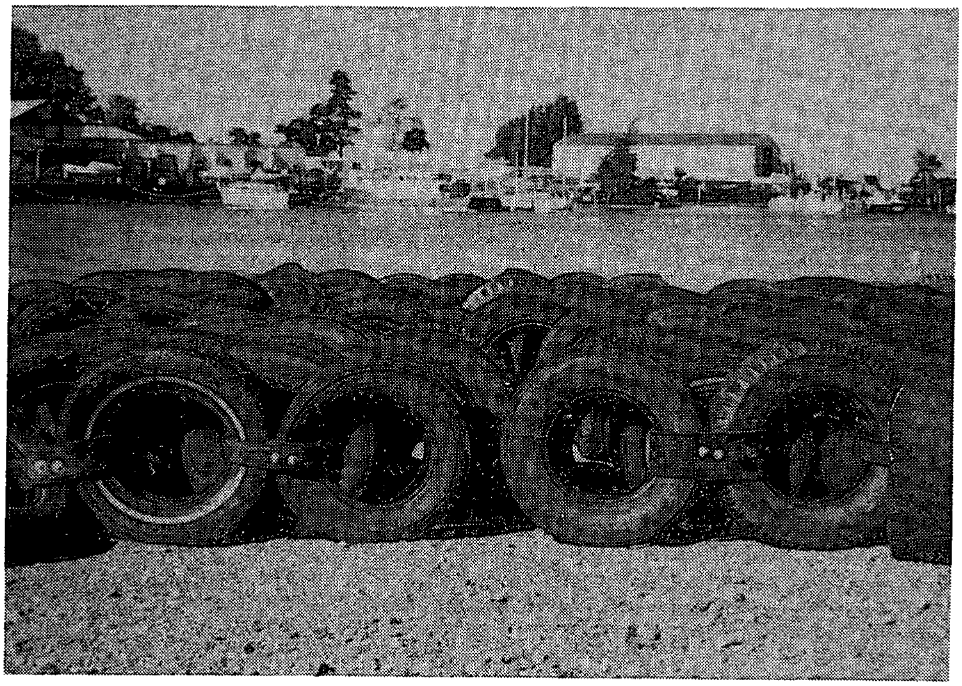
Field testing of binding materials (Davis, 1977) has lead to the recommendation that conveyor belt edging be used as the binding material for FTB's. Conveyor belt edging is a scrap rubber product with nylon plies which results from the trimming of new conveyor belts (Figure 22). The edging is available from tire manufacturers and is non-corrosive, non-abrasive and lightweight.

Since the edging is a scrap product, its dimensions, quality and availability vary. The minimum recommended dimensions are 10 cm wide by 12 mm thick, with three or more nylon plies. To ensure uniform strength characteristics, it is important that the nylon plies extend completely through the edging. A lead time of six months to a year is advised when ordering conveyor belt edging. The price of 10 cm wide by 12 mm thick conveyor belt edging is about $0.72 per metre length (Goodyear Tire and Rubber Co., Bowmanville, Ontario).

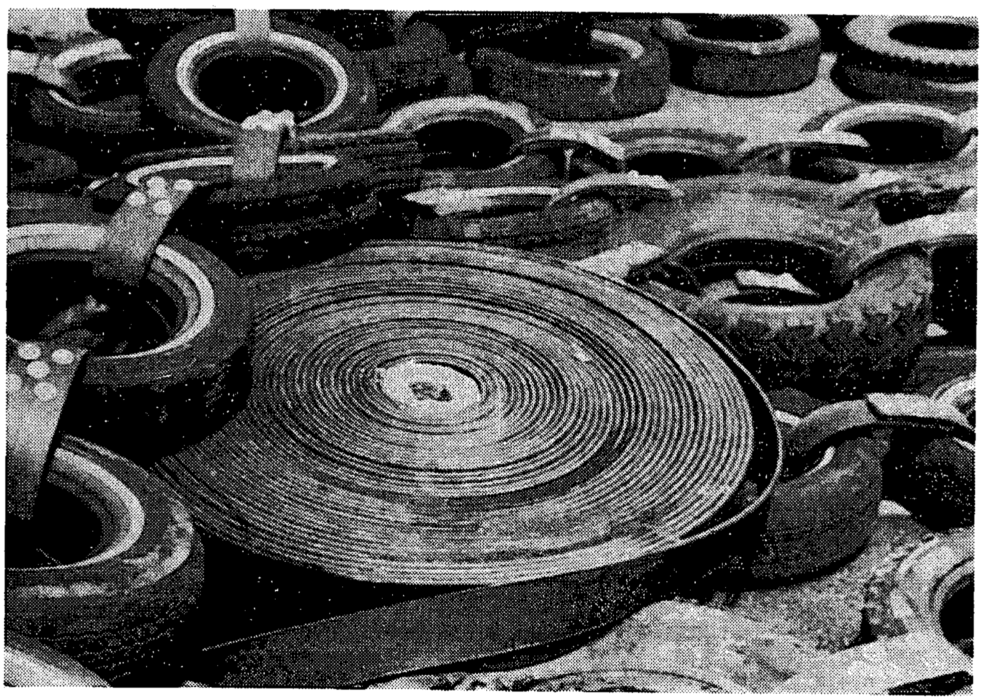
If conveyor belt edging is not available, steel chain can be used as the binding material. The disadvantages of chain are its abrasion and corrosion characteristics, and its weight of about 3.7 kg/m. Regular 12.5 mm steel chain costs about $4.80 per metre length, $6.30/m when galvanized. A light weight, open-link, ungalvanized chain has been used in several FTB's in the United States (DeYoung, 1978). This 12.5 mm steel chain, developed by the Campbell Chain Co. (York, Pennsylvania), costs about $3 per metre length, and weighs 2.8 kg/m.

The length of binding material needed to construct a unit area of FTB has been estimated using information from Section 10 as:

1.7 m per m^2 Goodyear FTB constructed of car tires
0.94 m per m^2 Goodyear FTB constructed of truck tires



Conveyor belt edging used to bind car tire Goodyear modules at Westfield New York. Note that 4, not 2, bolts per connection are recommended.



Conveyor belt edging used in tire mooring dampers, and as shipped from supplier, at Mamaroneck, New York.

FIGURE 22 Views of conveyor belt edging used as binding material.

3.1 m per m^2 PT-2

2.0 m per m^2 PT-1

To allow for substandard conveyor belt edging, the length of edging ordered should be greater than the length needed to construct the FTB.

6.5 Connectors

For freshwater FTB installations using conveyor belt edging as the binding material, steel nuts, washers and bolts are adequate connectors. The bolts should be about 12 mm in diameter. The cost of a 12 mm diameter by 50 mm long steel bolt, 12 mm nut, and two flat washers is about $0.25. Since metal corrosion rates are faster in salt water, nylon nuts, washers and bolts are recommended for connectors in salt water FTB installations (Davis, 1977). The cost of a 12 mm diameter by 50 mm long nylon bolt, 12 mm nut, and two flat washers is about $0.35. To prevent ultra-violet degradation of the nylon, the nylon connectors should be dyed black. This can be accomplished by immersing the nylon parts in a boiling mixture of household dye and water for several minutes.

If regular steel chain is used as the binding material, the ends of the chain can be connected with shackles. If light weight, open-link chain is used, the links can be opened or closed with special hand tools (available through Goodyear Tire and Rubber Co.); thus no other connectors are needed.

6.6 Flotation Agents

The most common supplemental flotation agent used in FTB's is urethane foam. Part of the inside of each tire is filled with foam. Urethane foam for marine uses costs about $3.25 per kilogram (June 1980, Witco Chemical Ltd., Toronto, Ontario). Unfortunately, the life expectancy of urethane foam used in FTB's is unknown. A potential problem with foam is that muskrats and other marine animals sometimes use pieces of the foam to build nests.

Sealed plastic containers can also be used to provide supplemental flotation by jamming one or more containers in the crown of each tire. Milk and soft drink containers have been used. One-gallon size (approximately 4 ℓ) milk containers have been obtained for $0.22 each at Plattsburgh, New York (Riley, private communication). However, due to the tendency of the containers to crack or be crushed (especially in ice), and the risk of water entering the containers, this method of providing supplemental flotation requires more maintenance than the method using foam.

Polystyrene and styrofoam should not be used to provide supplemental flotation for FTB's in salt water. Marine organisms have been found to cause severe deterioration of these materials.

6.7 Anchors

Gravity anchors for FTB's can be made from any readily available material. Typical anchor materials are mass concrete and steel. Leftover concrete poured in 1 m^3 blocks is usually available from concrete manufacturers for about $45/$m^3$. Concrete anchors poured on site, near an urban area, would cost about $65/$m^3$. Steel is available from scrap metal dealers for about $0.06/kg.

Conventional anchors (Navy stockless, mushroom, stock admiralty) or lightweight anchors (Danforth) can also be used. Their costs vary with size.

6.8 Mooring Lines

Mooring lines are used to attach the FTB to its anchors. The allowable spacing of the anchors depends on the strength of the mooring lines. The standard mooring line, consisting of regular 12.5 mm steel chain, can support a working load of about 18 000 N. The 12.5 mm open link steel chain developed by Campbell Chain Co. has an average ultimate strength of 9800 N; adopting a factor of safety of two, one can say that it can support a working load of about 4900 N.

Conveyor belt edging can also be used as the material for the mooring lines. Edging 10 cm wide by 12 mm thick with adequate connections (discussed in Section 7.5) can support an ultimate load of about 13 000 N (Harms, 1979a). Adopting a factor of safety of two, one can say that conveyor belt edging 10 cm wide by 12 mm thick with adequate connections can support a working load of 6500 N. Advantages of edging include its cheaper price and its superior resistance to abrasion and corrosion. A disadvantage of edging is that, because it is almost neutrally buoyant, it might tend to float near the water surface, thereby obstructing boat traffic. This can be overcome by attaching a few weights to each mooring line.

7.0 CONSTRUCTION METHODS

7.1 Site

FTB's should be constructed near the water's edge to facilitate launching. It is advisable to choose a construction site that is above the high water level. The construction of a Goodyear FTB at Westfield, New York was set back considerably when assembled modules left on a wharf were inundated during a storm and the tires became filled with sediment (D. Eno, private communication). The modules had been bound with conveyor belt edging and the ends of the bolts had been distorted to prevent the nuts backing off. Consequently, the only way to effectively remove the sediment from the tires was to cut the conveyor belt edging, empty each tire separately, and then reconstruct the modules.

FTB's can also be constructed on the ice cover of the body of water. FTB's have been assembled and launched successfully from the winter ice covers of Lake Champlain, New York (DeYoung, 1978) and Lake Charlevoix, Michigan (C. Biddick, private communication). Anchors were positioned through holes cut in the ice, and later the FTB's eased into position as the ice melted.

7.2 Heavy Equipment

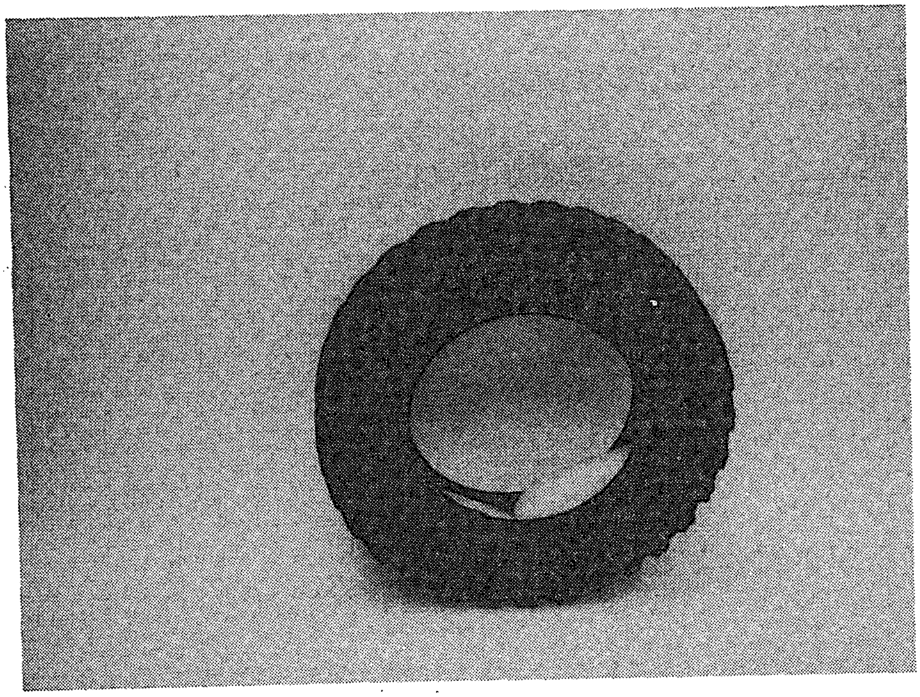
The land-based construction of most car tire Goodyear FTB's can be accomplished with the aid of one high-lift tractor. The tractor is needed for moving assembled modules and for launching sections of the FTB. A crane would be required to construct a truck tire Goodyear FTB or a PT-breakwater.

If the FTB can be launched into water deeper than its draft, it can be towed to position by small boats. The required size of boat engine depends on the size of the FTB section being towed. At Plattsburgh, New York, a 3.7 m long aluminum outboard motor boat with a 7000 Watt (9.5 horsepower) engine is used to move Goodyear FTB sections 27 m long by 8 m wide (Riley, private communication). If the FTB is launched from a beach, a tugboat would probably be required to pull the FTB off the bottom.

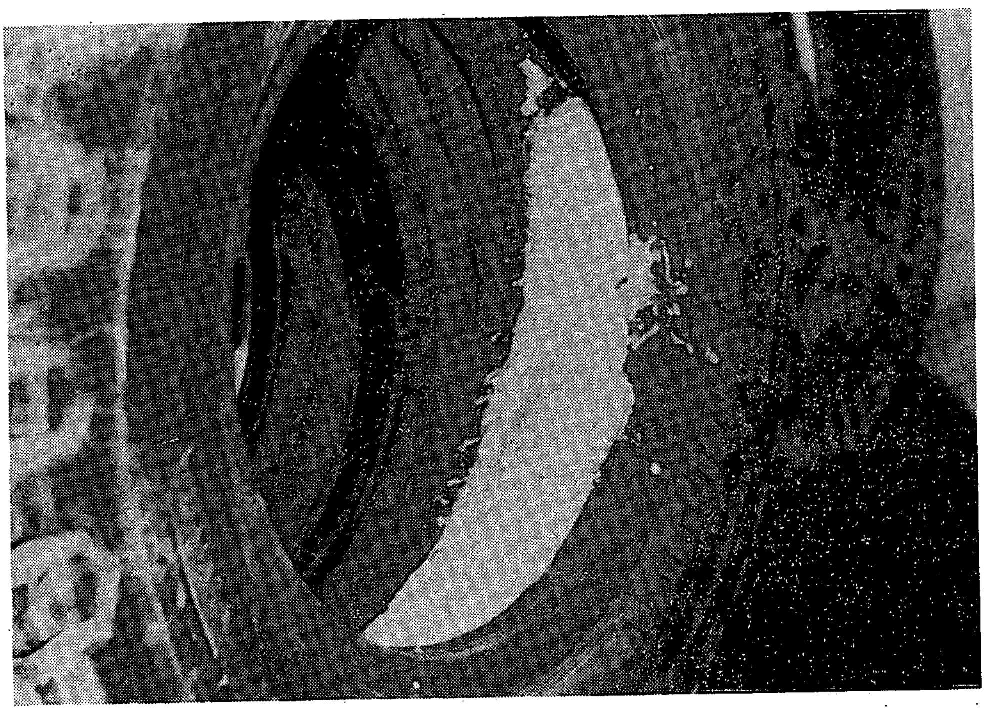
Mooring an FTB is best accomplished with a barge-mounted crane.

7.3 Labour

A construction crew of 6 to 12 workers is needed to assemble an FTB. A foreman experienced in FTB construction would be a valuable asset (see



Foamed car tire. Uneven rise is due to two separate pours by hand.



Foamed truck tire, sprayed with foaming equipment.

FIGURE 23 Views of foamed tires.

Section 4.1). Several FTB's have been constructed as community projects using volunteer labour. At face value, this would seem to be a cost-saving measure. However, experience has shown that close supervision of volunteer labourers is required in order to ensure good quality of construction. It is recommended that FTB fundamentals and construction details be carefully explained to all labourers before they start working.

7.4 Tire Preparation

After the construction materials have been delivered to the construction site, one of the first tasks usually carried out is to provide the tires with supplemental flotation. But before that, some builders choose to cut a couple of 5 cm diameter holes in the bottom of each tire to allow sediment to escape and to make removal of the FTB from the water easier. However, experience has shown that it is very difficult and time-consuming to cut holes in steel-belted tires. Furthermore, since individual tires in an FTB are known to rotate (Pierce and Lewis, 1977), any holes in the perimeter of a tire will, at some time, allow trapped air to escape. Therefore, unless an FTB is used at a site where the suspended sediment load is appreciable, it is recommended that holes not be cut in the tires.

For Goodyear FTB's and the wood pole PT-breakwater, it is recommended that each tire be provided with supplemental flotation (see Appendix D).

If using urethane foam to provide supplemental flotation, the crown of each tire should be filled with foam (Figure 23). This can be accomplished by using foaming equipment and spraying the foam into the tire crowns, or by manually pouring liquid urethane foam into the tire crowns. At some installations, a plastic bag was inserted in each tire crown, and then the bags were filled with foam (Goodyear Tire and Rubber Co.). A standard car tire crown holds about 225 grams of a 32 kg/m^3 density foam.

If using plastic containers to provide supplemental flotation, one or more containers should be jammed in the crown of each tire. The one-gallon size (approximately 4 ℓ) milk container with screw-on tops has been used effectively in each car tire of a Goodyear FTB at Plattsburgh, New York (Riley, private communication). However, the use of a 2ℓ plastic container in each car tire of a Goodyear FTB in New Zealand was found to be unsatisfactory because some of the containers cracked (Lyttelton Harbour Board, private communication).

For a steel pipe PT-breakwater, most of the required buoyancy is provided by the steel pipes. They should be filled with foam and then sealed by welding a circular steel plate at each end. To prevent the pipes rusting from the inside, some used engine oil should be poured into the pipes before they are sealed. The outer surface of the pipes should be coated with a rust retardant. In order to ensure that the tire strings keep floating, it is recommended that about every third tire in a string be provided with supplemental flotation.

7.5 Goodyear FTB

Each module can be constructed by two labourers using hand tools in about twenty minutes. The tires can be stacked free-standing, or with the help of a home-made tire rack, in a 3-2-3-2-3-2-3 vertical arrangement (Figure 24). All the tires in an individual module should be the same diameter.

The binding material is pulled through the tires as the module is constructed. The length of binding material needed is about 3.5 m per car tire module and 5.0 m per truck tire module. These lengths can be precut to facilitate module construction. Each module should be bound as tightly as possible in order to minimize chafing between tires and binding material.

If using conveyor belt edging as the binding material, the ends should be fastened together with four-12 mm bolts, nuts and washers (one on each side) as shown in Figure 25. Bolt holes can be made in advance with a hammer and metal punch or an electric drill. Bolts should be long enough to permit a minimum of 6 mm of the threaded portion to protrude through the nut; thus, normally, bolts 5 cm long should be used. After tightening each nut, the

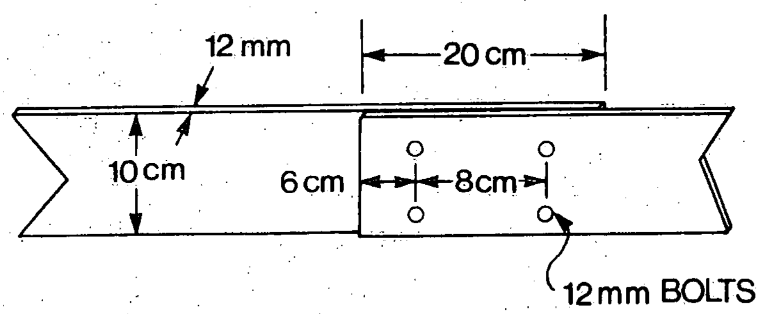


Figure 25 Recommended connection for conveyor belt edging

FIGURE 24 Assembly of a car tire Goodyear module using a tire rack. (Courtesy Goodyear Tire and Rubber Co.)

protruding threads of the bolt should be distorted to prevent the nut backing off. For steel bolts, this can be accomplished by hammering the protruding end of the bolt. For nylon bolts, the threads can be distorted with heat. Alternatives to distorting the threads include the use of an impact wrench with lock washers or lock nuts.

The interconnection of modules to form a breakwater requires a slight alteration of tire position and the addition of two tires per module. First, the four corner tires of each bundle are rotated 100 degrees as shown in Figure 26. Then, additional tires are inserted at each end of the module to serve as connectors. One module is attached to the next by using the same binding material as was used in the module construction. Again, modules should be interconnected as tightly as possible to reduce chafing. To make a sturdier connection, especially near the FTB's windward edge, it is suggested that themodule to module connection be duplicated (i.e. use 2 loops of binding material). Each single loop connection requires about 1.5 m of binding material in car tire FTB's and 2.5 m in truck tire FTB's.

The FTB can be assembled in sections on land, then launched into the water where the sections can be connected to form the final FTB. The size of section usually depends on the launching method.

To prevent the possibility of any individual modules separating and drifting away, a bridle line should be threaded through the outside tires around the FTB perimeter (Figure 26). The bridle line can be made from the binding material.

7.6 PT-Breakwater

The construction of a PT-breakwater starts with the armouring of poles (or pipes) with tires. This can be accomplished by placing tires on a pole which is balanced on a pivot, or by threading a pole through a set of pre-arranged tires (Figure 27). Tires should be as densely as possible on the poles.

If using wood poles, the tires can be locked on the poles by inserting two steel bars through the end tires and wood at both ends of the poles (Figure 28). The steel bars should have holes pre-drilled in each end; the bars can then be held in position by washers and hitch pins.

If using steel pipes, steel bars or pipes should be inserted through holes in the ends of each pipe (Figure 29). Steel bars of 20 mm diameter should be adequate for a PT-2, while 50 mm diameter pipe could be considered for a PT-1.

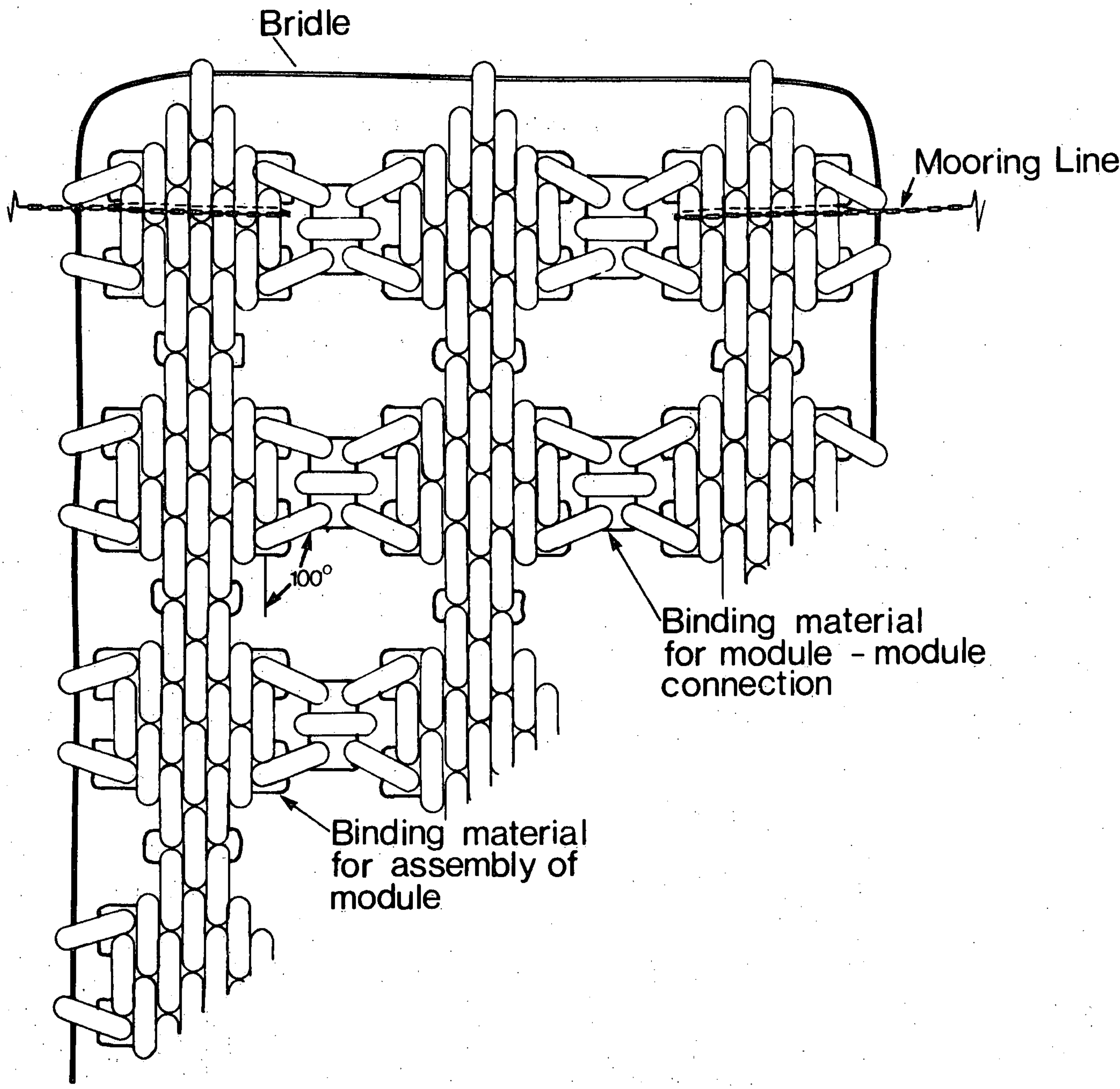
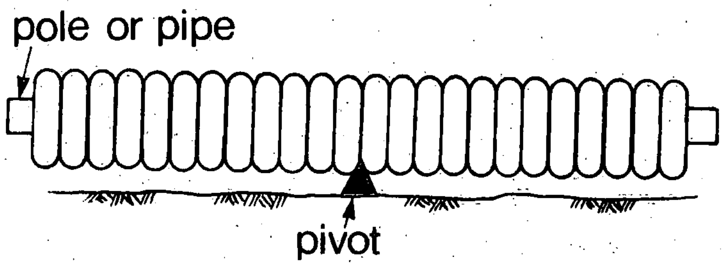


Figure 26 Interconnection of Goodyear modules.
(Shaw and Ross, 1977)



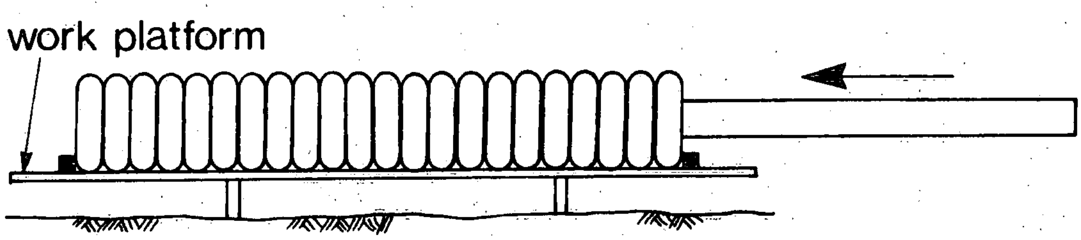


Figure 27 METHODS OF ARMOURING PIPES OR POLES WITH TIRES

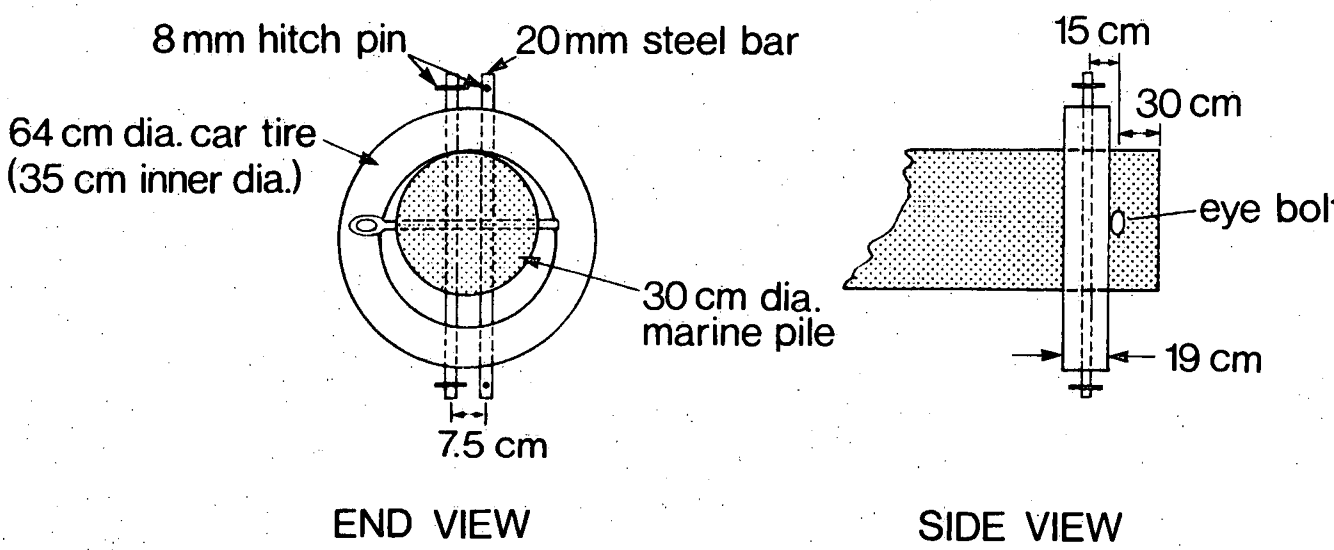


Figure 28 TIRE RETAINERS AT ENDS OF PT-2 POLES

Tire strings should be attached on land to an armoured pole, using binding material as shown in Figure 20. In this way, each tire string is attached to the poles by two loops of binding material. The loops of the binding material should be fastened with temporary connections. Then a PT unit consisting of one pole and attached tire strings should be lifted into the water. After assembling another unit on land, it should be placed into the water beside the first unit. One at a time, the temporary connections of the tire string loops on the first unit should be disconnected, the binding material threaded through the appropriate tires on the second unit's armoured pole, and the tire string loops connected permanently. In this manner, the difficulty of launching a large PT section can be avoided.

7.7 Anchoring

Concrete anchors can be cast in formwork on site. At several installations, anchors have been made by pouring concrete into large used tractor tires.

The FTB is connected to the anchors by mooring lines. Following standard marine practice, the scope of the mooring lines should be at least 6. To reduce impact loads on the mooring lines, five tires should be incorporated in each line of a PT-breakwater (Figure 30). For PT-1 breakwaters, the mooring lines can be connected by shackles to the ends of the steel pipes (Figure 31). It is recommended that the holes for these connections in the pipes be heavily reinforced (e.g. by welding an extra piece of steel to the pipe at the connection). For PT-2 breakwaters, it is suggested that mooring lines be connected with 18 mm shackles to 25 mm diameter eye bolts which have been inserted in the ends of the poles (Figure 31). Note that eye bolts should be utilized to resist shear rather than tension forces. For Goodyear FTB's, it is suggested that each mooring line be threaded through the centre tires of a complete module (Figure 26), i.e. through seven tires. The best way to attach a mooring line to a concrete anchor is by threading the line through the loop of a steel bar that has been embedded in the concrete.

Anchor positions are important because they determine the FTB's orientation and potential range of surface position. Most FTB's are slack-moored; in this way, the dragging and lifting of the steel chain mooring lines can help reduce the peak mooring force. On a calm day, the anchors should be

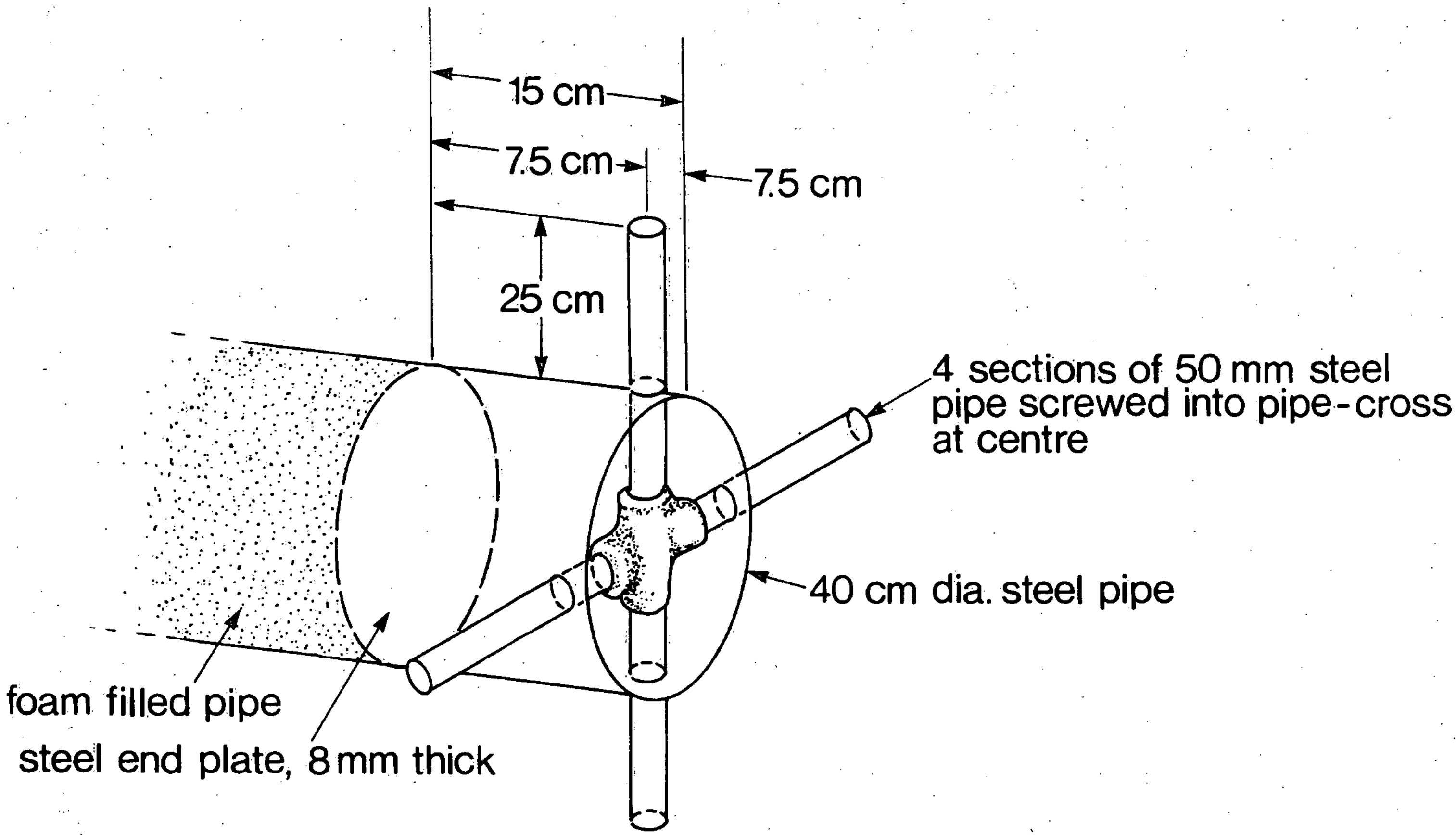


Figure 29 TIRE RETAINERS AT ENDS OF PT-1 PIPES
(after Harms et al 1980)

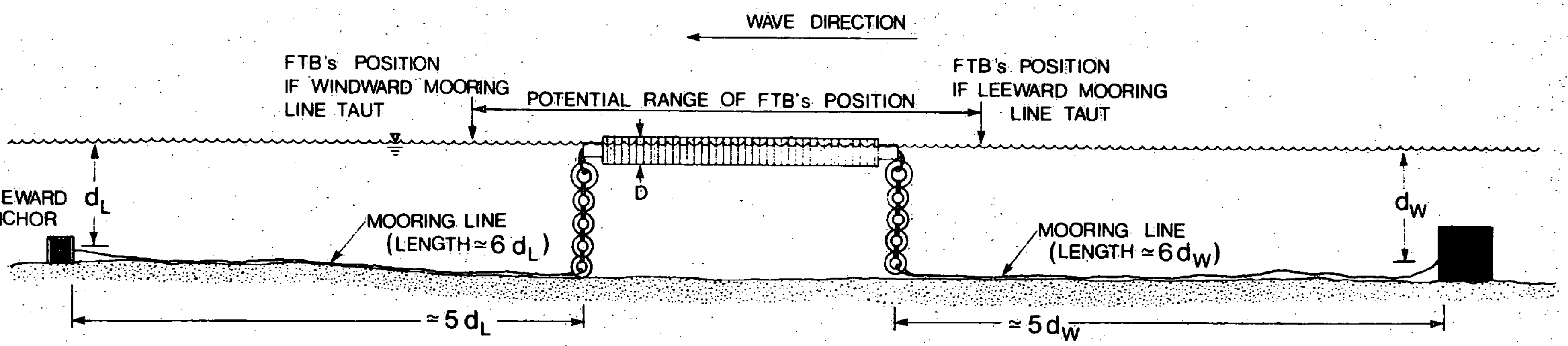


Figure 30 Schematic view of mooring lines and anchors for a FTB

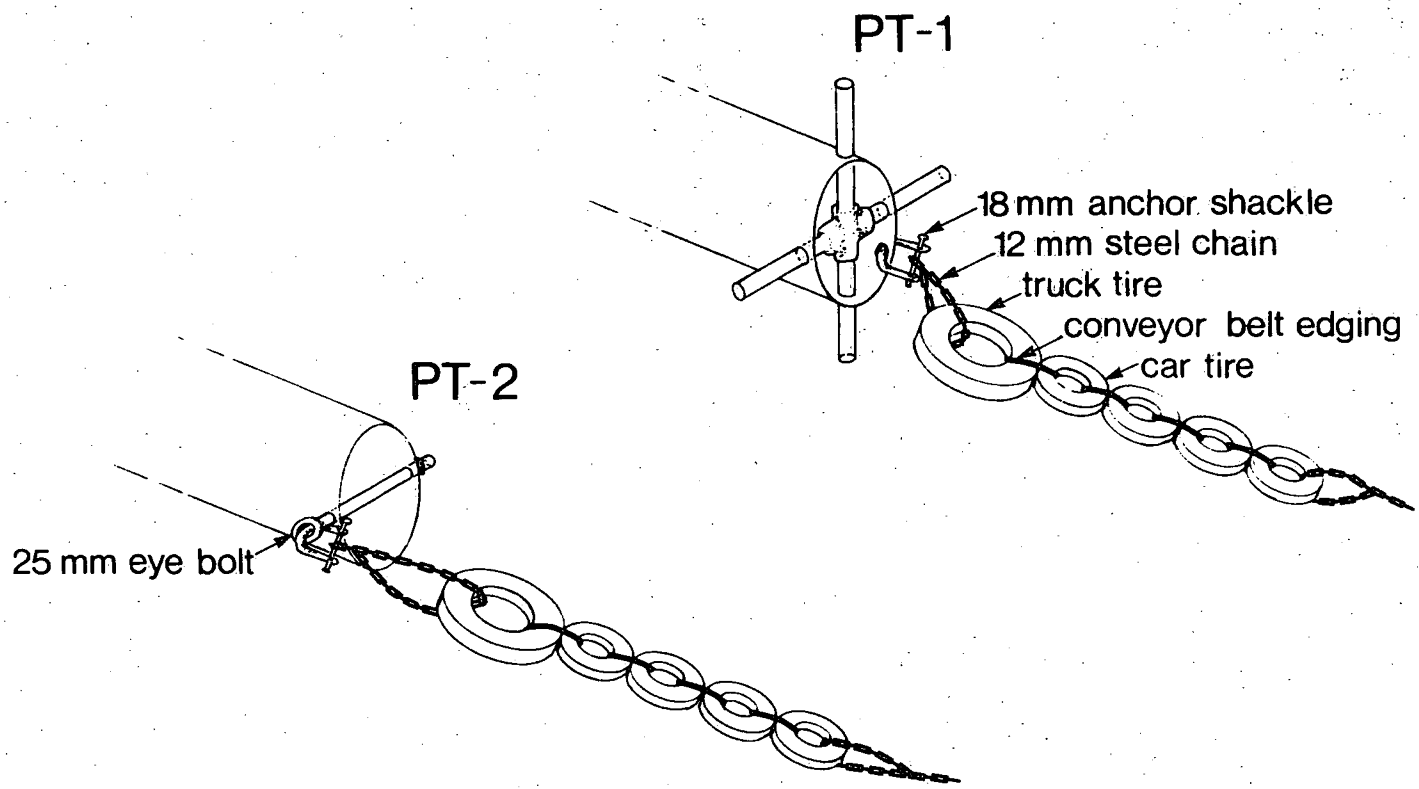


Figure 31 CONNECTION OF MOORING LINE WITH A 5-TIRE DAMPER TO PT-BREAKWATERS (after Harms et al, 1980)

positioned a distance about five* times the water depth from the FTB as shown in Figure 30. The best way to place anchors is by using a mechanical boat-mounted hoist. However, anchors can also be positioned by pushing them off a flat-topped barge.

Anchoring a Goodyear FTB is sometimes accomplished in sections of about 30 m length. One anchoring method depicted in Figure 32 is outlined as follows:

- Attach a windward anchor to the windward corner of the first FTB section, and tow the section to the mooring site using the anchor line as a towline.
- Drop the anchor when the FTB is in position.
- Attach additional windward anchors as required and drop into position.
- Attach leeward anchors as required and drop into position.
- Tow the next FTB section to the mooring site.
- Connect the two sections with the help of swimmers.
- Attach anchors and drop into position.
- Repeat this procedure until all sections are anchored.

Anchors at the ends of the FTB should be placed at angles of about 45 degrees to the FTB's beam. These anchors will help to restrain the lateral movement of the FTB.

7.8 Marking an FTB

In navigable waters, navigation lights must be installed at each end of the FTB. Local requirements can be determined from the Ministry of Transport.

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* The multiple of the water depth should equal the scope minus one.

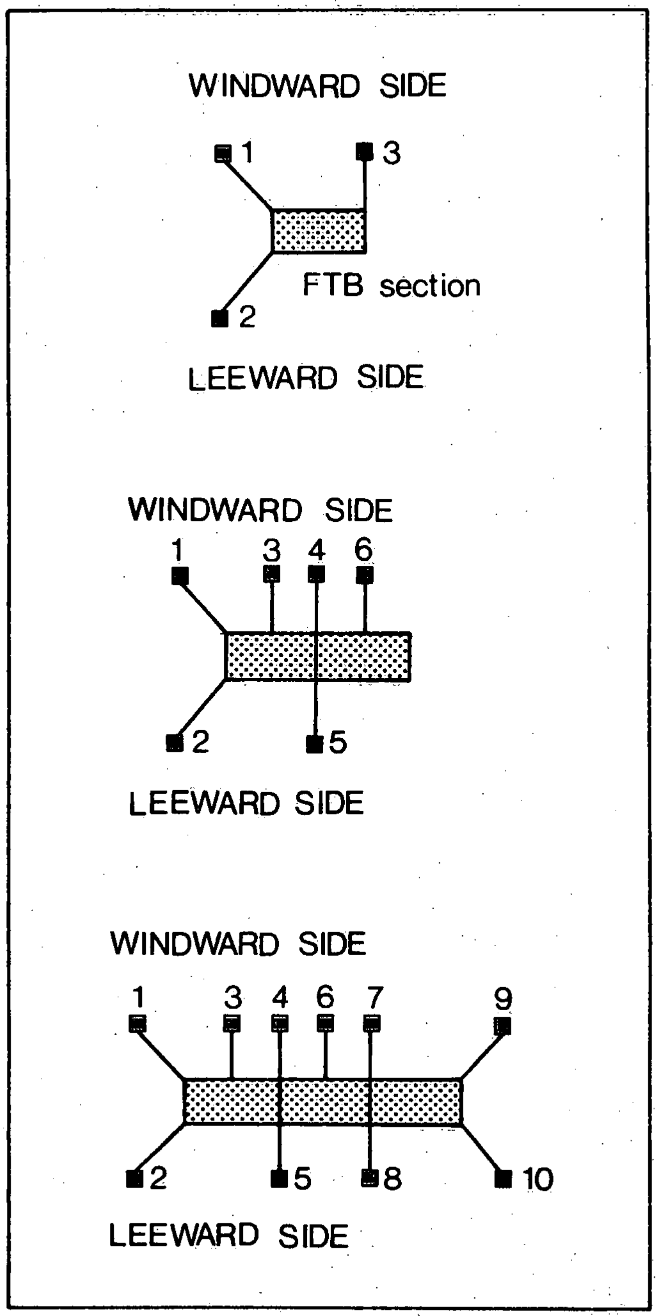

Figure 32 Goodyear FTB anchoring procedure (De Young, 1978)

8.0 LIFE EXPECTANCY OF AN FTB

The FTB is a relatively new type of breakwater and therefore long-term experience with FTB's is limited. The first FTB installations were in short fetch salt-water locations in California in 1964 using the Wave-Maze design; one of them is still in use in 1980 after 16 years (Noble, private communication). Operational experience with Goodyear FTB's started in 1974 at Wingfoot Lake, Ohio; that one has already been used for six years. As mentioned earlier, the first field installation of a PT-breakwater was completed in June 1980 and thus field experience is just beginning.

The life expectancy of an FTB is difficult to predict. It is in large part dependent on the choice of construction materials and on the degree of maintenance. The tires themselves can outlast the other construction materials such as fasteners, mooring lines and binding materials. Thus, the life of an FTB can be extended by replacing its less durable components as required. A properly designed, constructed and maintained FTB should provide useful protection from waves for up to ten years (before requiring a major overhaul).

Regular FTB maintenance should include the following:

- Removal of marine growth such as weeds.
- Removal of debris collected on the surface of the FTB.
- Removal of sediment deposited inside the tires.
- Checking the supplemental flotation. Plastic containers sometimes pop out, crack, or are crushed, and foam can deteriorate. Replace supplemental floatation in tires where necessary.
- Inspection of the binding material and mooring lines for abrasion and/or corrosion. Replace parts if necessary.
- Inspection of the connectors for corrosion and wear. Replace when necessary.
- Inspection of anchors.

9.0 FTB DESIGN EXAMPLE

9.1 Introduction

To demonstrate the procedures described in this manual, designs for a PT-1, a PT-2 and a Goodyear FTB are discussed in this section. The FTB's have been designed for LaSalle Park Wharf, Burlington, Ontario (Figure 33).

The northeast side of the wharf is the proposed site for a marina. This site is exposed to waves from the SW, S, SE and E octants. An FTB is well suited for providing wave protection at this site because the maximum fetch is less than 5 km and the water at the breakwater site is deep (about 10 m).

A suggested marina layout and the bathymetry in the vicinity of the wharf are shown in Figure 34. The proposed walkway and docks would be floating structures and boats would be moored between finger piers extending from the docks. Marina plans include an overnight/transient docking area at the end of the wharf and along the main walkway.

There is no measured wave data for Hamilton Harbour. Therefore, design waves have been forecast from wind information.

9.2 Fetch

Fetches have been measured and are shown on Figure 33. The longest fetches are 4.4 km from the SW and ESE directions.

9.3 Depth

From the bathymetric chart of Hamilton Harbour, the depth profiles for the SW and ESE fetches have been drawn as shown in Figure 35. The average depths below datum over the SW and ESE fetches have been estimated to be 11 and 17 m respectively.

9.4 Wind Information

Hourly wind measurements from Hamilton Airport, 14 km to the south have been used to predict waves. The monthly weather summaries reveal that winds from the W and SW prevail, and also produce the highest speeds. A summary of peak hourly wind speeds and directions recorded by month at Hamilton Airport from 1974 to 1979 is given in Table 2. From this summary, it can be seen that a SW wind speed of about 50 km/hour can be expected almost every month. The maximum hourly speed recorded in 20 years was 89 km/hour, once from the W and once from the SSW.

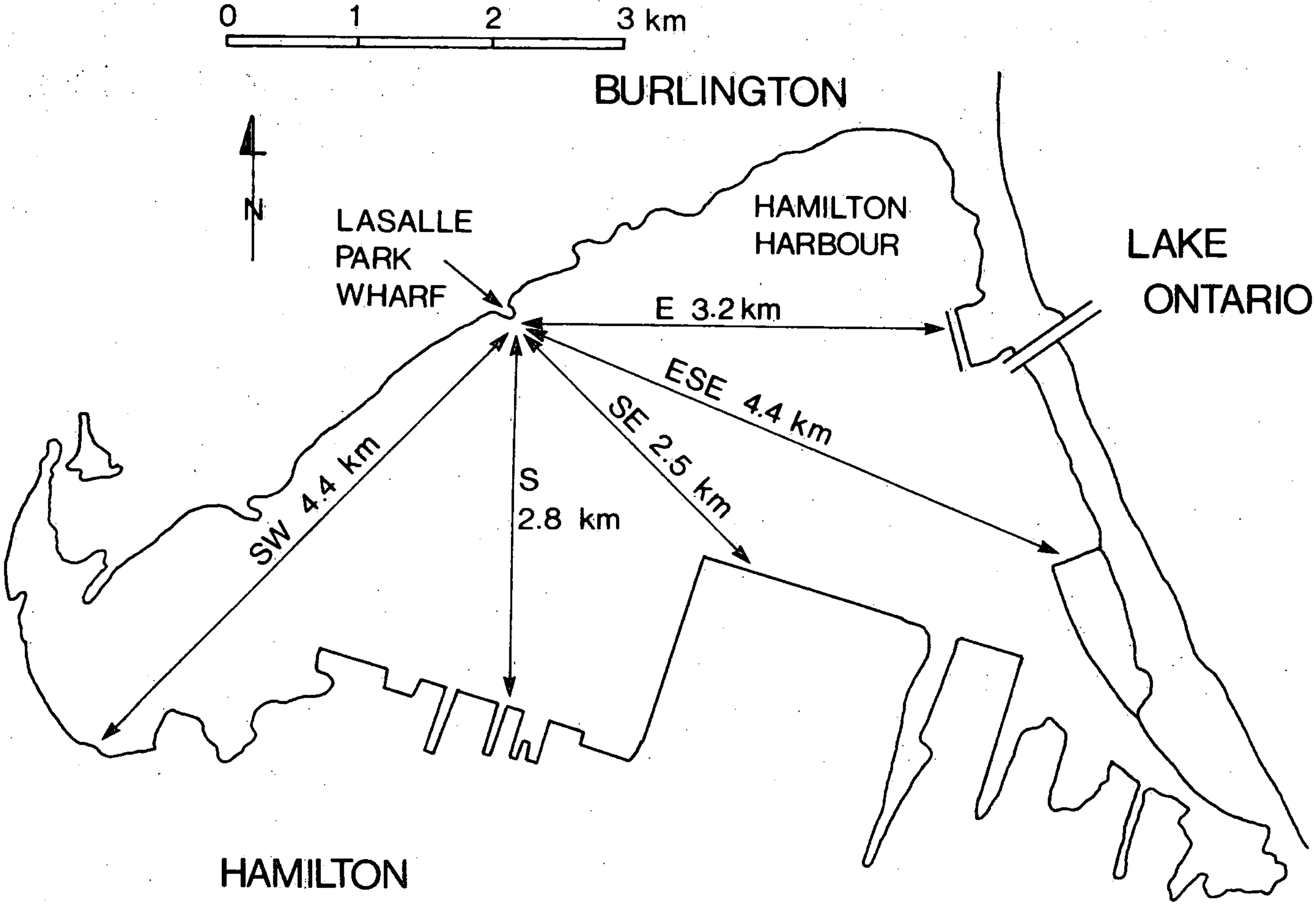

Figure 33 Location of LaSalle Park Wharf

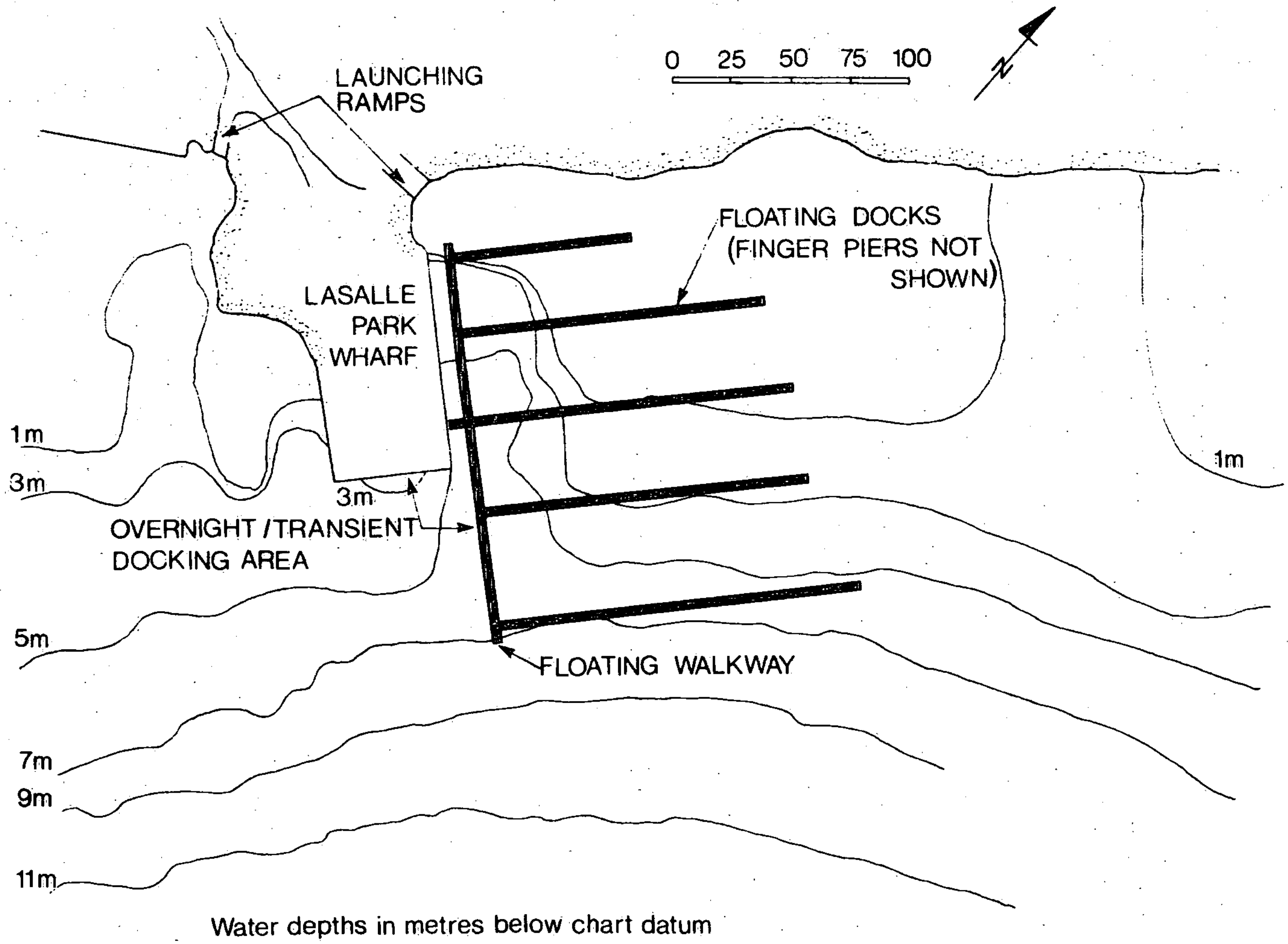

Figure 34 Bathymetry near LaSalle Park Wharf, and a suggested marina layout

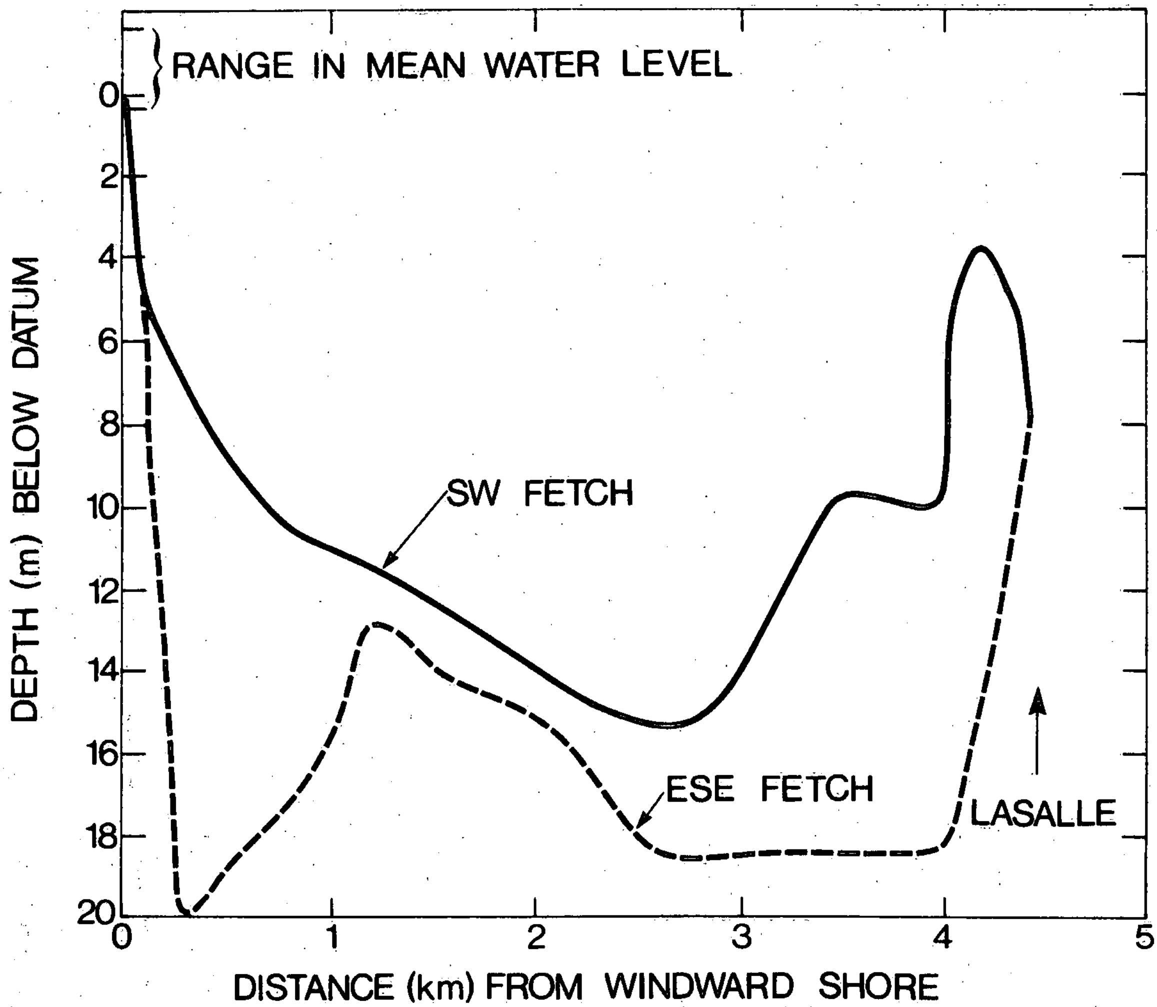

Figure 35 Depth profiles along SW and ESE fetches of LaSalle Park Wharf

TABLE 2 MAXIMUM HOURLY WIND SPEEDS (KM/HOUR) AND DIRECTIONS, 1974-1979, HAMILTON AIRPORT, ONTARIO

					Active Boating Season							
Month:	J	F	M	A	M	J	J	A	S	O	N	D
Year												
79	52WSW	52SW	48SW	89W	44NE	44SSW	37SSW	46W	44SW	52SW	65WSW	52WSW, SSW
78	89SSW	35W	52SW	52WNW	61WSW	43SW	37SW	48SW,S	37SSW, ENE	44WSW	61WSW	52WSW
77	59W	52WSW	63NE	61SW	50WNW	48SW	56SW	37W	37W	46NE, SW	48WSW	78NE
76	53WSW	64WSW	62SSW	61NE	63SW	56SW	43SW	41WSW	46W	46WSW	56WSW	61WSW
75	70SW	58W	50E	74W	45NE	40SW	35SW	37SW	46NE	51NE	72WSW	59WSW
74	80SW	58W	54W	58W	59W	45SW	38SW	40W	45SW	35SW	35SW	59NE

Source: Monthly meteorological summaries, Environment Canada

The monthly summaries also show that E winds with hourly speeds of 25 to 40 km/hour occur almost every month. The maximum hourly wind speed from the E recorded in ten years was about 75 km/hour. Strong winds from the S or SE are less frequent and weaker than those from the E, W or SW.

Since this manual does not attempt to provide comprehensive design information for complete marina breakwater protection, only one FTB section is designed here. The beam width and anchor requirements for an FTB facing the SW sector are considered, but the FTB's length, location and required performance are not dealt with in detail. For complete marina protection, other FTB sections facing the south and east sectors would probably be required.

The wind speeds selected to forecast the beam and anchor design waves are 50 and 90 km/hour respectively. Wind speeds of 50 km/hour or more from the SW fetch in the months of May to October can be expected during at least one storm per year (Table 2). This limited information does not allow the designer to estimate the number of hours when the incident wave height could be expected to exceed the beam-design wave height. To do so would require a complete incident wave climate. Therefore, the designer in this situation cannot rigorously quantify the number of hours when the transmitted wave height can be expected to exceed the acceptable wave height criterion.

By using the maximum hourly wind speed from the SW sector in 20 years, the designer implicitly assumes a risk of 40 percent (Section 3.4) of encountering incident waves greater than or equal to the anchor-design wave during a 10 year period (actually, this is an upper limit to the risk since the harbour is ice covered during part of each year).

9.5 Design Waves

Beam-design waves

SW fetch = 4.4 km
Wind speed = 50 km/hour
Average water depth over fetch = 11 m

From Figure 13 for a fetch of 5 km,

$H = 0.67$ m
$T = 2.9$ s

From Figure 12 for a fetch of 2.5 km,

$H = 0.52$ m
$T = 2.7$ s

Interpolating to get H and T for a 4.4 km fetch,

$$H = \left(\frac{4.4 - 2.5}{5 - 2.5}\right) \times (0.67 - 0.52) + 0.52 = 0.64 \text{ m}$$

$$T = \left(\frac{4.4 - 2.5}{5 - 2.5}\right) \times (2.9 - 2.7) + 2.7 = 2.85 \text{ s}$$

Rounding off the period to the nearest half-second, to be conservative, one obtains T=3 s. The wavelength from Figure 15, for an average water depth of about 9 m at the FTB sites, is 14 m. Thus, the beam-design wave characteristics for the SW fetch are:

H = 0.64 m

T = 3 s

L = 14 m

Anchor-design wave

SW fetch = 4.4 km

Wind speed = 90 km/hour

Average water depth over fetch = 11 m

The resulting anchor-design wave characteristics for the SW fetch are:

H = 1.2 m

T = 4 s

L = 25 m

Because the FTB site is located on a relatively straight shoreline in water deeper than 2 m, the effects of refraction and shoaling can be considered of secondary importance. The anchor-design wave height is less than 1.4 m, and thus the PT-1, PT-2 and Goodyear designs are all feasible at the LaSalle site (see Section 2.1). Therefore, designs for these three types of FTB are provided in this section.

9.6 Sizing the FTB

9.6.1 Length and orientation

The length and orientation of the breakwater are assumed to have been given as shown in Figure 36. In this position the breakwater faces the SSW direction. As discussed in section 4.3, waves approaching the FTB obliquely (e.g. from the SW) should be attenuated as much or slightly more than waves approaching normal to the breakwater.

9.6.2 Beam

From Figure 36 it can be seen that the water depths below datum vary from 1 to 12 m over the breakwater length. The mean monthly water level varies from +1.6 to -0.3 m relative to chart datum (Figure 35). Therefore, water depths at the FTB site can vary from 0.7 to 13.6 m.

An FTB's wave transmission increases with increasing water depth. However, as seen in Figure 17, wave transmission design curves are only available for certain tire diameter to water depth ratios. For water deeper than 5 or 6 tire diameters, the same design curve applies. For standard car and truck tires, most of the breakwater section is situated in water deeper than 6 tire diameters.

The steepness of the beam-design wave is 0.64/14=0.046. Since this is greater than 0.03, the wave transmission design curve in Figure 17 can be used for sizing the FTB. It is assumed that the incident beam-design significant wave height must be attenuated to a 0.3 m significant wave height.

From Figure 17, for a ratio of transmitted to incident wave height of 0.3/0.64=0.47, one obtains L/B=0.80 for a Goodyear FTB (curve for D/d=0.16). Consequently, for a beam-design wavelength of 14 m, the required Goodyear beam width is 14/0.80=17.5 m. Since the average width of a car tire module is about 2.0 m, the number of modules required is 17.5/2.0=8.75, which would be rounded off to nine nodules.

For a PT-2 breakwater one obtains L/B=1.15 using the curve for D/d=0.14. Thus the required PT-2 beam width is 14/1.15=12.2 m. For a PT-1 breakwater, using the curve for D/d=0.22, one obtains L/B=1.43 and thus B=9.8 m.

9.7 Mooring Forces

For given wave conditions, FTB mooring forces increase with decreasing water depth. The ratio of anchor-design wavelength to 9-module Goodyear FTB beam width is 25/18=1.39. At this value of L/B, the mooring forces can be seen to vary considerably with the value of D/d (Figure 21). The steepness of the anchor-design wave is 1.2/25=0.048. The calculation of peak mooring forces for three ranges of water depths, interpolating to a wave steepness of 0.048, is given in Table 3. The Goodyear design curve for D/d=0.06 has been used for values of $D/d \leq 0.06$.

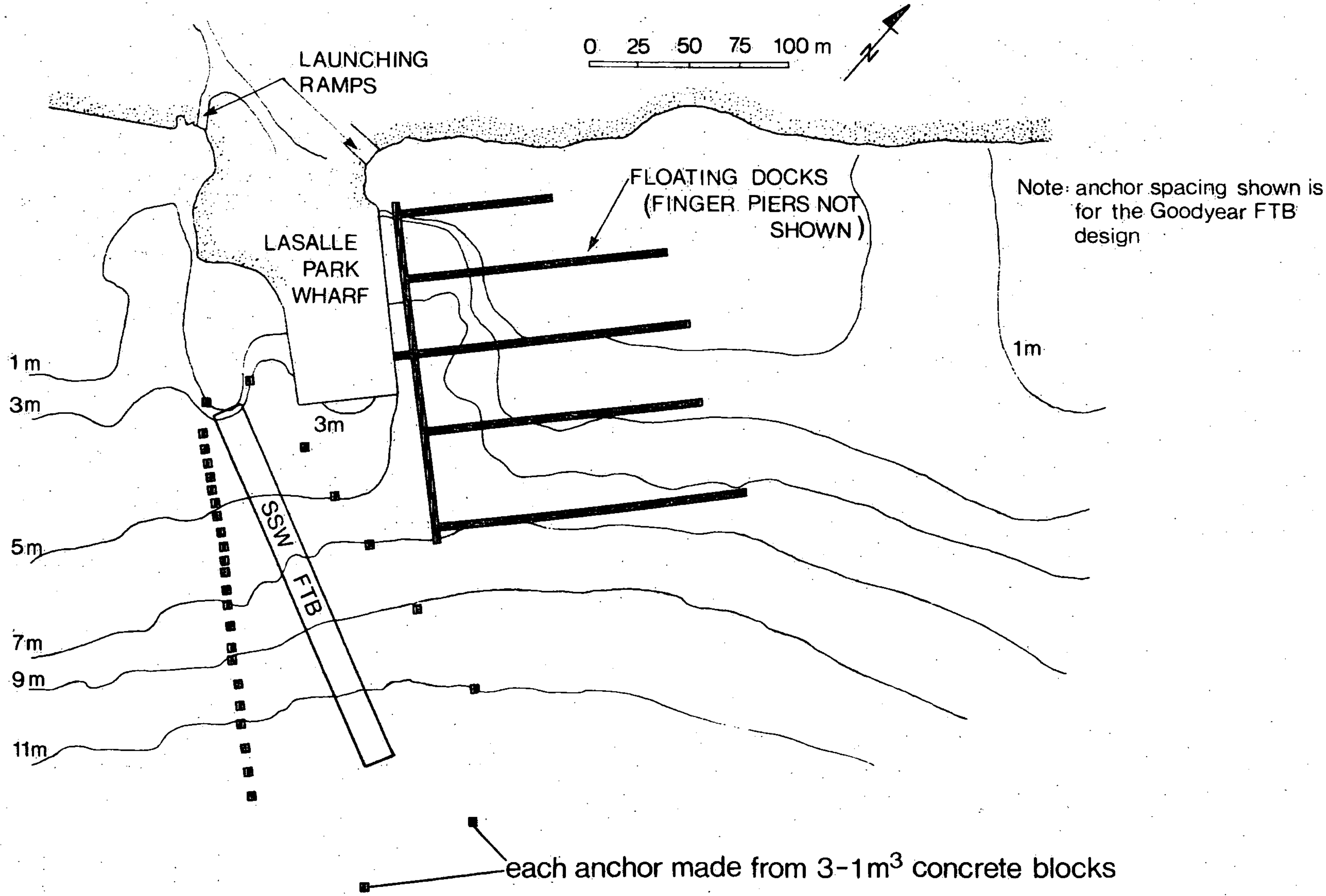

Figure 36 Length, orientation and anchors for the FTB at Lasalle Park Wharf

TABLE 3 Peak Mooring Forces for the Goodyear FTB Shown in Figure 36 (Anchor-design wavelength=25 m, anchor-design wave height=1.2 m, FTB beam width=18 m, 0.64 m diameter car tires)

Water Depth (m)	Peak Mooring Force (N/m)		
	Wave Steepness (%)		
	0.03*	0.05 - 0.06*	0.048+
≥9	300	1460	1080
4.5	490	2270	1720
1.5 to 2.7	810	2110	1920

* Peak mooring force from Figure 21

\+ By linear interpolation of the base 10 logarithms of the peak mooring forces

For a PT-2 without tire dampers, the peak mooring force for a 12.2 m beam width breakwater can be estimated from Equation 2 (section 5.1). The ratio of L/B=25/12.2=1.05 is within the range of data from which Equation 2 was derived. Assuming that the breakwater is constructed from 0.64 m diameter car tires, with a pole spacing of 5.5 tire diameters, the peak mooring forces are:

$$F = 3820 \text{ N/m} \quad \text{for } d = 4.6 \text{ m}$$
$$\text{and} \quad F = 6050 \text{ N/m} \quad \text{for } d = 2.0 \text{ m}$$

As an added safety precaution, it would be advisable to incorporate 5-tire mooring dampers in each mooring line.

For a PT-1 breakwater with tire dampers on the mooring lines, the peak mooring forces for a 12.2 m beam width breakwater can be estimated from Equation 1. To be conservative, it is assumed that the mooring forces for a 9.8 m beam width are the same as those predicted by Equation 1. Assuming that the breakwater is constructed of 1.0 m diameter car tires, with a pole spacing of 3.3 tire diameters, the peak mooring forces are:

$$F = 3610 \text{ N/m} \quad \text{for } d = 4.6 \text{ m}$$
$$\text{and} \quad F = 5920 \text{ N/m} \quad \text{for } d = 2.0 \text{ m}$$

9.8 Anchor Design

The silty bottom of Hamilton Harbour at LaSalle Park Wharf is suitable for the use of gravity anchors to moor the FTB. It is decided to use 1 m^3 size concrete anchors.

Since the PT-1 mooring forces are only slightly less than those of the PT-2, PT-breakwater anchor spacings have been calculated for the PT-2 forces only. Assuming that leeward anchors are to be sized for 20 percent of the windward requirements, the allowable spacings for 1 m^3 size anchors are calculated by Equation 4 (section 5.3) with a factor of safety of 1.5, and are presented in Table 4. These spacings will exert a peak force of about 5550N on each mooring line.

Since the working strength of regular 12.5 mm steel chain is about 18,000 N, the number and spacing of anchors can be increased to more fully utilize the chain's strength. The spacings for 3-1 m^3 size concrete anchors are given in Table 5.

Assuming that steel chain is used for the mooring lines, approximate positions for anchors consisting of 3-1 m^3 concrete blocks are shown in Figure 36 for the Goodyear design. Each mooring line should be connected to the closest module or pole/pipe. If two mooring lines are attached to the same pole in a PT-2, or pipe in a PT-1, each one should be attached to a separate anchor bolt for a PT-2, or separate reinforced hole in the pipe's wall for a PT-1.

TABLE 4 Anchor Spacings for FTB's at LaSalle Park Wharf (peak force in each mooring line $\simeq$ 5550 N)

Water Depth (m)	Spacing (m) of 1 m^3 Size Concrete Anchors			
	Goodyear		PT-2	
	Windward	Leeward	Windward	Leeward
$\geq$9	3.4	17	-	-
4.5	2.2	10.8	1.0	4.8
2	1.9	9.6	0.6	3.1

TABLE 5 Anchor Spacings for FTB's at LaSalle Park Wharf (peak force in each mooring line $\simeq$18000 N, which is the working strength of regular 12.5 mm steel chain)

Water Depth (m)	Spacing (m) of 3-1 m^3 Size Concrete Anchors			
	Goodyear		PT-2	
	Windward	Leeward	Windward	Leeward
$\geq$9	10.3	51.4	-	-
4.5	6.5	32.3	2.9	14.5
2	5.8	28.9	1.8	9.2

10.0 COST ESTIMATES

In Sections 10.1, 10.2 and 10.3, estimates are provided for the costs of materials needed to construct 30 m long sections of the FTB's designed in Section 9. These cost estimates are for breakwaters which provide equal wave attentuation. Other costs, including labour and transportation of materials, are discussed in Section 10.4.

10.1 Goodyear FTB, Material Costs for 30 m Long Section

- beam width = 17.5 m = 9 car tire modules
- anchors = 3 - 1 m^3 size concrete anchors; spacing given in Table 5 and shown in Figure 36.
- tires = 0.64 m diameter car tires

Tires

14 modules long x 9 modules wide x 20 tires/module = 2,520 tires

Total number of tires = 2,520 tires x 1.1 (safety factor*) = 2,770

Cost = 2,770 tires x $0.00 = nil

Binding material

(i) 126 modules x 6.5 m binding material/module = 819 m

(ii) Bridle line around peripheral tires, 30 m long section's share of 190 m long FTB's bridle = 66 m

Total length = 885 m x 1.2 (safety factor) = 1,060 m

Cost, using conveyor belt edging = 1,060 m x $0.72/m = $765

Flotation

(i) 225 g urethane foam/tire x 2,520 tires = 567 kg foam

Cost = 567 kg x 1.1 (safety factor) x $3.25/kg = $2,000

or

(ii) 1 plastic container/tire x 2,520 tires = $2,520 containers

Cost = 2,520 x 1.1 (safety factor) x $0.20/container = $550

Anchors

31 - 3 m^3 anchors for the 190 m long FTB

30 m long section's share = 14.7 m^3 concrete

Cost = 14.7 m^3 concrete x $65/$m^3$ = $955

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* The safety factor allows for an unsuitable portion of a scrap material order.

Mooring Lines

From Figure 36 the average length of the mooring lines for the entire 190 m long FTB has been estimated to be 42 m.

The 30 m long section's share of the mooring lines

is 4.9 anchors x 42 m = 206 m

Cost, using 12.5 mm steel chain = 206 m x $4.80/m = $990

Connectors

126 modules/30 m long FTB section x 16 connections/module

x $0.25/bolt-nut-washer connection = $500

Total materials cost

(i) The recommended choice of materials would include using urethane foam to provide supplemental flotation, conveyor belt edging for the binding material, steel chain for the mooring lines, and concrete gravity anchors.

Cost = $5,395/30 m long by 17.5 m wide FTB section

= $180/m length of 17.5 m wide FTB

= $10.30/m^2 Goodyear FTB

= $34,000 for the 190 m long FTB in Figure 36.

(ii) A cheaper alternative, which might result in higher maintenance costs, would include using plastic containers to provide supplemental flotation, conveyor belt edging for the binding material, steel chain for the mooring lines, and concrete gravity anchors.

Cost = $3,760/30 m long by 17.5 m wide FTB section

= $125/m length of 17.5 m wide FTB section

= $7.15/m^2 Goodyear FTB

= $24,000 for the 190 m long FTB in Figure 36.

10.2 PT-2, Material Costs for 30 m Long Section

- beam width = 12.2 m
- anchors = 3 - 1 m^3 concrete anchors; spacing given in Table 5
- pole spacing = 5.5 tire diameters
- tires = 0.64 m diameter car tires

Poles

30 m long FTB section @ pole spacing of (5.5 x 0.64) = 3.5 m

8.6 poles/30 m long FTB section

Cost, using marine piling = 8.6 poles x 12.2 m long x \$16/m

= \$1,680

Tires

Number of tires per pole = 12.2 m long pole/0.19 m width of tire = 64

Total number of tires on poles per 30 m long FTB section = 8.6 x 64 = 550

Number of tire strings = 12.2 m long pole/0.64 m diameter tires = 18

Number of tires per string = (3.5 m pole spacing - 0.64 m tire diameter) / 0.19 m width of tire = 15

Total number of tires on tire strings per 30 m long FTB section = 18 x 15 x 8.6 = 2,320

Total number of tires = 2,870 x 1.1 (safety factor) = 3,160

Cost = 3,160 tires x \$0.00 = nil

Binding Material

Number of loops of binding material needed to fasten tire strings to poles=number of tire strings + 1

= 18 + 1

= 19

Length of binding material per loop

2 x pole spacing

= 2 x 3.5 m

= 7 m

Total length of binding material per 30 m long FTB section

= 19 x 7 x 8.6 = 1,140 m

Cost, using conveyor belt edging = 1,140 m x 1.2 (safety factor) x \$0.72/m = \$990

Flotation

225 g urethane foam per tire x 2,870 tires = 646 kg foam

Cost = 646 kg x 1.1 (safety factor) x \$3.25/kg = \$2,300

Anchors

79 - 3 m^3 concrete anchors for the 190 m long FTB
30 m long section's share = 37 m^3 concrete
Cost = 37 m^3 concrete x $65/$m^3$ = $2,400

Mooring Lines

12.5 anchors x 42 m average length of mooring line = 525 m
Cost, using 12.5 mm steel chain = 525 m x $4.80/m = $2,520

Connectors

4 connections/loop x 19 loops binding material x 8.6 pole sections per 30 m long FTB section=654 connections
Cost = 654 bolt-nut-washer connections x $0.25/connection = $165

Anchor Bolts

12.5 anchor bolts per 30 m long FTB section
Cost = 12.5 anchor bolts x $18 = $225

Total Materials Costs

Using urethane foam to provide supplemental flotation, marine piles for the poles, steel chain for the mooring lines, conveyor belt edging for the binding material, and concrete gravity anchors

Cost = $10,280/30 m long x 12.2 m wide PT-2 section
= $340/m length of 12.2 m wide PT-2 section
= $28/$m^2$ PT-2 section
= $65,000 for the 190 m long FTB in Figure 36

10.3 PT-1, Material Costs for 30 m Long Section

- beam width = 9.8 m
- anchors = 3 - 1 m^3 concrete anchors; spacing given in Table 5
- pipe spacing = 3.5 tire diameters
- tires = 1.0 m diameter truck tires

Pipes

30 m long FTB section @ pole spacing of (3.5 x 1.0) = 3.5 m
8.6 poles/30 m long FTB section
Costs, using 40 cm diameter steel pipe = 8.6 x 9.8 m long x $50/m = $4,200

Tires

Number of tires per pipe = 9.8 m long pipe/0.24 m width of tire = 40

Total number of tires on pipes per 30 m long FTB section = 8.6 x 40 = 344

Number of tire strings = 9.8 m long pipe/1.0 m diameter tires = 9

Number of tires per tire string = 10

Total number of tires on tire strings per 30 m long FTB section

= 9 x 10 x 8.6 = 774

Total number of tires = 1,120 x 1.1 (safety factor) = 1,230

Cost = 1,230 tires x \$0.00 = nil

Binding Material

Number of loops of binding material needed to fasten

tire strings to pipes = 10

Length of binding material per loop = 7 m

Total length of binding material per 30 m long FTB section

= 10 x 7 x 8.6 = 600 m

Cost, using conveyor belt edging = 600 m x 1.2 (safety factor)

x \$0.72/m = \$520

Flotation

1.28 m^3 foam/pipe x 8.6 pipes/30 m long FTB section

x 32 kg/m^3 = 350 kg foam

Cost = 350 kg x 1.1 (safety factor) x \$3.25 = \$1,250

Anchors

Same as PT-2, \$2,400

Mooring Lines

Same as PT-2, \$2,520

Connectors

4 connections/loop x 10 loops x 8.6 pole sections = 344 connections

Cost, 344 bolt-nut-washer connections x \$0.50/connection = \$88

Total Materials Costs

Using urethane foam to provide supplemental flotation, steel pipes for the poles, steel chain for the mooring lines, conveyor belt edging for the binding material, and concrete gravity anchors,

Cost = \$11,000/30 m long x 9.8 m wide PT-1 section
= \$365/m length of 9.8 m wide PT-1 section
= \$37/m^2 PT-1 section
= \$70,000 for the 190 m long FTB in Figure 36

10.4 Additional Costs

Costs in addition to those for materials include the following:

- Labour
- Transportation of materials to FTB construction site
- Rental of land-based equipment: tractor(s), crane, foam dispenser
- Rental of water-based equipment: small boat(s), tugboat, barge with a crane.

The labour required to assemble the 25 module x 10 module test section of Goodyear FTB in New Zealand was about 1.35 man-hours per module using a 5-man crew (Lyttelton Harbour Board, private communication). This time includes the cutting of conveyor belt edging, punching of bolt-holes, sealing and inserting plastic containers in the tire crowns, and assembling and interconnecting the modules. In the opinion of the engineer in charge, this labour time could be reduced to 0.9 man-hours per module with an experienced work crew. However, a more sophisticated form of supplemental flotation, such as urethane foam, or the drilling of holes to allow sediment to escape from the tires, would increase these labour requirements.

It is suggested that labour requirements to assemble Goodyear FTB's, including the cutting of conveyor belt edging, punching of bolt holes, foaming the tire crowns and assembling and interconnecting the modules, can be estimated at 2 man-hours per car tire module and 3 man-hours per truck tire module.

The labour required to assemble the 75 m long x 12 m wide PT-1 breakwater at Mamaroneck, New York was about 3000 man-hours or130 man-hours per pipe-pipe section (Rosenshein, private communication). This time includes the cutting of conveyor belt edging, punching of bolt holes, foaming and sealing 40 cm diameter pipes, assembling the FTB sections, placing them in the water, and joining the sections to form the final length of breakwater; it does not include the time to fabricate the anchors or to moor the breakwater. In the opinion of the contractor in charge of assembly, this labour time could be halved now that construction experience has been gained.

The amount of time required to moor and FTB, including towing the FTB to its site, placing anchors, and attaching mooring lines, depends on many factors including the FTB site's proximity to shore, the availability of barge-mounted cranes, and tidal fluctuations. It is expected that typical FTB's of 50 to 200 m length could be moored with gravity anchors in 2 to 8 days assuming an adequate barge-mounted crane, an FTB site reasonably close to shore, and no tidal complications (e.g. water depths at low tide too shallow to work in).

As a result of variable labour, transportation and rental costs, as well as the cost of construction materials used, the reported costs of completed Goodyear FTB's vary widely from \$6.50 to \$77/m^2. Estimates of total PT-breakwater costs vary from \$30 to \$100/m^2. A rule of thumb for estimating the total cost of an FTB built by a contractor would be to double the cost of materials. Remember that PT-breakwater beam requirements are less than those of a Goodyear FTB. Therefore, a higher unit area cost for a PT-breakwater is partly compensated by its smaller area.

From the costs of materials in sections 10.2 and 10.3, the Goodyear FTB designed in section 9 is considerably cheaper than the PT-breakwaters. Therefore, in general, unless space requirements demand the narrower beam width of a PT-breakwater, or the anchor-design wave height rules out the feasibility of the Goodyear design (see section 2.1), it appears that the Goodyear design is more economical than the PT-breakwater design. Of course, this conclusion can be affected by the as yet unknown differences in maintenance costs and service lives of the two designs. It seems likely that the sturdier PT-breakwaters will be able to function effectively for a longer period of time, and in larger waves, than the Goodyear FTB's.

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APPENDIX A: Definitions

APPENDIX A: Definitions

Bathymetry - The measurement of depths of water in oceans, seas and lakes; also information derived from such measurements.

Beam Width (of an FTB) - The width of breakwater in the direction of wave progress (for wave crests approaching parallel to the length of the FTB).

Breakwater - A structure protecting a shore area, harbour, anchorage or marina from waves.

Deep Water - Water so deep that surface waves are little affected by the bottom. Generally, water deeper than one-half the surface wavelength is considered deep water.

Diffraction (of water waves) - The phenomenon by which energy is transmitted laterally along a wave crest. When part of a set of waves is interrupted by a barrier, such as a breakwater, the effect of diffraction is manifested by propagation of waves into the sheltered region within the barrier's geometric shadow (see Figure A1).

Fetch - The horizontal distance, in the direction of the wind, over which waves are generated.

Lee - Shelter, or the side sheltered from the wind or waves.

Leeward - The direction toward which the wind is blowing relative to a vessel, structure or shoreline; the direction to which waves are travelling.

Refraction (of water waves) - The process by which the direction of a wave moving in shallow water at an angle to the bottom contours is changed. The part of the wave advancing in shallower water moves more slowly that that part advancing in deeper water, causing the wave crest to bend toward alignment with the underwater contours (see Figure A2).

Rubblemound Structure - A mound of random-shaped and random-placed stones protected with a cover layer of selected stones or specially made armour units.

Scope - The ratio of length of mooring line to the water depth.

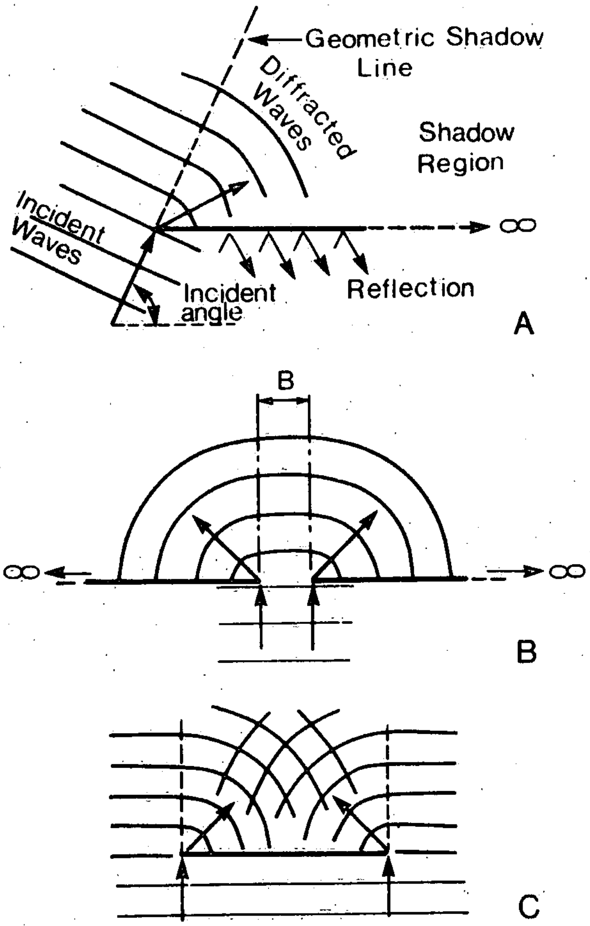


Figure A1. Wave diffraction behind a semi-infinite breakwater. B. Diffraction through a breakwater gap. C. Diffraction behind an island or offshore breakwater (Silvester, 1974).

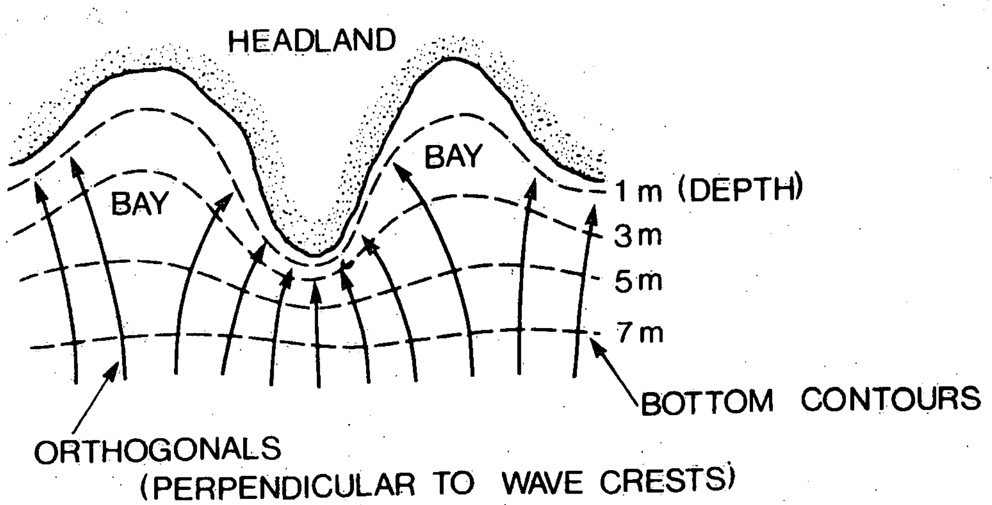


Figure A2 Refraction at an irregular shoreline (U.S. Army Corps of Engineers, 1977)

Shallow Water	-	Commonly, water of such depth that surface waves are noticeably affected by bottom topography. It is customary to consider water of depths less than one-half the surface wave length as shallow water.
Shoaling	-	The variation in wave height as a wave advances in shallow water. The amount of shoaling is a function of the water depth and the wavelength.
Significant Wave Height	-	The average height of the one-third highest waves of a given set of waves. This statistical wave parameter is commonly used to characterize the wave heights of a given set of waves. The maximum wave height within the same set of waves is typically between 1.5 and 2 times the significant wave height. For waves with a Rayleigh distribution, 13.5 percent of the waves can be expected to be higher than the significant wave height.
Wave Climate	-	The temporal distribution of waves at a particular site, usually classified by direction, significant wave height and period.
Wave Height	-	The vertical distance between a crest and the preceding trough.
Wavelength	-	The horizontal distance between similar points on two successive waves; the significant wavelength is the wavelength corresponding to the peak period.
Wave Period	-	The time for a wave crest to traverse a distance equal to one wavelength; the peak period is the period corresponding to the peak of the wave energy spectrum.
Wave Steepness	-	The significant wave height divided by the significant wavelength.
Windward	-	The direction from which the wind is blowing relative to a vessel, structure or shoreline.

APPENDIX B: Monthly Weather Summary

Environment Canada / Environnement Canada
Atmospheric Environment / Environnement atmosphérique

MONTHLY METEOROLOGICAL SUMMARY
SOMMAIRE MÉTÉOROLOGIQUE MENSUEL

MONTH/MOIS MARCH/MARS

AT/A HAMILTON AIRPORT ONTARIO

LAT 43° 10' N LONG 79° 56' W ELEVATION / ALTITUDE 237 METRES (ASL) / MÈTRES (NMM) STANDARD TIME USED / HEURE NORMALE UTILISÉE Eastern / de l'Est

DATE	Temperature Maximum / Maximale °C	Temperature Minimum / Minimale °C	Temperature Mean / Moyenne °C	Degree Days Heating / De chauffe base 18°C	Degree Days Growing / De croissance base 5°C	Rel. Humidity Maximum / Maximale %	Rel. Humidity Minimum / Minimale %	Thunderstorm / Orage	Rainfall / Pluie (hauteur) mm	Snowfall / Neige (hauteur) cm	Total Precip / Précip totale mm	Snow on Ground / Neige au sol cm	Average Speed / Vitesse moyenne km/h	Prevailing Direction / Direction dominante	Maximum Speed and Direction / Vitesse maximale et direction km/h		Bright Sunshine / Insolation effective** hours / heures
1	-11.2	-21.1	-16.2	34.2								2	10.6	N	N	19*	9.6
2	-8.4	-22.0	-15.2	33.2								1	10.6	NW	W	17*	9.6
3	-2.6	-14.5	-8.6	26.6								Tr	22.7	SW	SW	37	8.3
4	2.7	-6.2	-1.8	19.8								Tr	18.9	WSW	WSW	30*	5.5
5	0.9	-5.9	-2.5	20.5						4.2	6.0	1	13.2	WNW	NW	35	0.0
6	-2.8	-10.2	-6.5	24.5						Tr	Tr	2	17.9	WSW	WNW	33	7.7
7	-0.4	-8.1	-4.3	22.3						2.6	3.0	5	6.4	W	W	17*	4.7
8	-1.3	-7.2	-4.3	22.3					1.4	6.2	12.4	3	22.4	ENE	ENE	37	0.0
9	-0.8	-11.4	-6.1	24.1								9	17.2	W	WSW	35	7.5
10	4.7	-4.0	0.4	17.6					3.0	0.2	3.2	7	26.7	SSW	WNW	52*	5.4
11	-1.8	-9.8	-5.8	23.8						0.8	0.8	2	40.3	W	W	52*	9.7
12	-5.4	-13.2	-9.3	27.3								3	16.0	E	ENE	20	9.7
13	-2.1	-8.5	-5.3	23.3					Tr	2.8	3.6	2	23.7	ENE	ENE	33	0.0
14	0.0	-4.3	-2.2	20.2						0.4	0.4	6	23.8	WNW	WNW	46*	3.9
15	-1.0	-7.5	-4.3	22.3								4	19.6	NW	WNW	30	9.7
16	2.0	-7.5	-2.8	20.8					Tr		Tr	1	22.3	ENE	NE	32	7.2
17	8.5	-0.5	4.0	14.0					8.7		8.7	Tr	25.3	S	WNW	37	0.0
18	1.1	-3.6	-1.3	19.3						0.8	1.2	1	34.5	WNW	WNW	46*	8.7
19	8.7	-1.8	3.5	14.5								Tr	19.1	SW	SSW	30	8.8
20	13.4	3.5	8.5	9.5	3.5				7.4		7.4		21.6	SSW	SW	33*	8.0
21	5.7	-0.8	2.5	15.5					31.1	1.4	32.9		33.2	NW	NW	61	0.0
22	-0.8	-3.0	-1.9	19.9						Tr	Tr	1	35.8	NW	NW	57	0.0
23	0.2	-2.1	-1.0	19.0					Tr	Tr	Tr	Tr	11.4	svrl	SSW	19	0.0
24	1.9	-0.2	0.9	17.1					5.6	0.4	6.0	Tr	24.5	ENE	ENE	37	0.0
25	0.8	-1.0	-0.1	18.1						0.2	0.2		25.1	WNW	NW	35	1.0
26	4.7	-0.8	2.0	16.0									9.9	NNW	W	17*	0.7
27	7.9	-1.3	3.3	14.7									9.5	ENE	NE	20*	7.0
28	6.7	0.2	3.5	14.5									17.6	ENE	ENE	26	0.2
29	4.8	1.6	3.2	14.8					5.0		5.0		23.3	NE	ENE	27	0.0
30	5.8	1.2	3.5	14.5									26.7	ENE	ENE	43	9.1
31	2.8	1.4	2.1	15.9					23.4		23.4		31.2	ENE	ENE	41*	0.0
Mean / Moyenne	1.4	-5.4	-2.0	Total 620.1	Total 3.5	n/a	n/a	Total 0	Total 85.6	Total 20.0	Total 114.2		21.3	Prevailing / Dominante ENE	Maximum NW	61	Total 142.0
Normal / Normale	3.9	-4.7	-0.4	582.5	8.4			n/a	39.6	16.5	56.1		n/a	n/a			140.9

DEGREE-DAY SUMMARY – SOMMAIRE DE DEGRÉS-JOURS

Below 18°C / Au-dessous de 18°C	This Year / Année en cours	Previous Year / Année précédente	Normal / Normale	Above 5°C / Au-dessus de 5°C	This Year / Année en cours	Previous Year / Année précédente	Normal / Normale
Total for Month / Total du mois	620.1	502.2	582.5	Total for Month / Total du mois	3.5	28.0	8.4
Accumulated since July 1 / Accumulée depuis le 1er juillet	3483.2	3575.7	3391.1	Accumulated since April 1 / Accumulée depuis le 1er avril	2059.4	2116.8	2188.8

	Days with Total Precipitation / Jours avec précipitations totales (mm)					Days with Snowfall / Jours avec chute de neige (cm)				
	0.2 or more / ou plus	1.0 or more / ou plus	2.0 or more / ou plus	10.0 or more / ou plus	50.0 or more / ou plus	0.2 or more / ou plus	1.0 or more / ou plus	2.0 or more / ou plus	10.0 or more / ou plus	50.0 or more / ou plus
	15	12	11	3	0	11	5	4	0	0

UDC 551.506.1 (713.53)
* Indicates more than one occurrence.
** Sunshine recorder at Royal Botanical Gardens. Tr = trace.

Subscription Price: $1.00 monthly, $10.00 per calendar year (January to December)
Prix d abonnement: mensuel $1.00, annuel $10.00 (janvier à decembre)

COMPARATIVE RECORDS
RELEVES COMPARATIFS

Hamilton Airport Ontario MONTH / MOIS: MARCH / MARS 1980

Temperature/Température - °Celsius
Precipitation/Précipitation - Millimetres (mm)
Rainfall/Hauteur de pluie - Millimetres (mm)
Snowfall/Hauteur de neige - Centimetres (cm)
Wind speed/Vitesse du vent - Kilometres per hour/par heure (km/h)
Station pressure/Pression à la station - Kilopascals (kPa)

	This month / Ce mois-ci		Previous year / Année précédente		Normal / Normale	Record for the month / Record pour le mois: Highest / Maximum absolu			Lowest / Minimum absolu			Years of record / Années d'observations
	Value / Relevé	Date	Value / Relevé	Date		Value / Relevé	Day / Jour	Year / Année	Value / Relevé	Day / Jour	Year / Année	
Highest temperature / Température la plus élevée	13.4	20	19.3	23		23.4	30	1977				21
Lowest temperature / Température la plus basse	-22.0	2	-13.6	15					-22.0	2	1980	21
Mean monthly temperature / Température mensuelle moyenne	-2.0		1.8		-0.4	3.4		1973	-6.6		1960	21
Total monthly rainfall / Hauteur totale mensuelle de pluie	85.6		73.2		39.6	116.1		1976	0.0		1967	21
Total monthly snowfall / Hauteur totale mensuelle de neige	20.0		3.9		16.5	48.3		1960	3.9		1979	21
Total monthly precipitation / Précipitation totale mensuelle	114.2		76.4		56.1	151.7		1976	26.2		1967	21
No of days with measurable precipitation / Nombre de jours avec précipitation mesurable	15		16			22		1976	13		svrl	9
Greatest rainfall in one day / Hauteur de pluie maximale en une journée	31.1	21	13.2	29		31.1	21	1980				10
Greatest snowfall in one day / Hauteur de neige maximale en une journée	6.2	8	1.9	14		17.5	2	1976				10
Greatest precipitation in one day / Précipitation maximale en une journée	32.9	21	13.2	29		35.1	2/17	73/76				21
Maximum rainfall recorded in / Hauteur de pluie maximale enregistrée en												
5 minutes	1.5	21	1.9	29		2.5	4	1974				9
10 minutes	2.3	21	2.8	29		4.1	4	1974				9
15 minutes	3.0	21	3.2	29		5.1	4	1974				9
30 minutes	4.0	21	3.6	29		6.4	5	1973				9
60 minutes	5.5	21	5.6	29		8.9	4	1974				9
24 consecutive hours / heures consécutives												
Mean wind speed (km/h) / Vitesse moyenne du vent (km/h)	21.3		18.7			22.5		1974	16.1		1971	10
Maximum speed (1 min.) (km/h) / Vitesse maximale (1 min.) (km/h)	NW 61	21	SW 48 W 48*	13 14		SW 77	15	1973	NW 48	4	1971	10
Maximum gust speed (km/h) / Pointe du vent maximale (km/h)	NW 89	21	WSW 83	14		WSW126	15	1973	WSW 70	19	1978	9
Total hours of sunshine / Total des heures insolation	142.0		150.8		140.9	181.1		1977	96.9		1973	20
Mean station pressure (kPa) / Pression moyenne à la station (kPa)	n/a											
Greatest station pressure (kPa) / Pression maximale à la station (kPa)	n/a											
Least station pressure (kPa) / Pression minimale à la station (kPa)	n/a											

CLIMATOLOGICAL DATA FOR THE PAST 10 YEARS
DONNÉES CLIMATOLOGIQUES POUR LES 10 DERNIÈRE ANNÉES

Year / Année	Maximum temp / Temp maximale	Minimum temp / Temp minimale	Mean temp / Temp moyenne	Rainfall / Hauteur de pluie	Snowfall / Hauteur de neige	Total precip / Précip totale	Mean windspeed / Vitesse moyenne des vents	Maximum windspeed / Vitesse maximale des vents (gust)	Hours sunshine / Heures insolation	Heating degree days / Degrés-jours de chauffe	Growing degree days / Degrés-jours de croissance		
1970	6.7	-13.9	-1.8	35.6	14.2	52.8	15.0		141.6				
1971	12.2	-11.7	-2.6	9.1	46.2	55.6	16.1		136.0				
1972	8.3	-15.0	-3.2	73.9	24.4	97.5	misg		119.6				
1973	20.0	-9.4	3.4	114.6	18.3	132.6	20.9	WSW 126	96.9				
1974	17.2	-17.2	-0.6	34.3	22.9	60.5	22.5	WNW 74	125.7				
1975	10.0	-17.8	-2.4	44.7	35.8	86.9	19.3	W 81	144.5				
1976	18.2	-13.9	1.3	116.1	32.3	151.7	misg	SW 108	121.5	518.5	32.8		
1977	23.4	-10.6	2.4	63.6	31.6	94.3	21.0	E 87	181.1	482.7	38.1		
1978	7.6	-18.3	-4.0	50.9	8.9	59.9	17.8	WSW 70	misg	680.8	0.0		
1979	19.3	-13.6	1.8	73.2	3.9	76.4	18.7	WSW 83	150.8	502.2	28.0		
1980	13.4	-22.0	-2.0	85.6	20.0	114.2	21.3	NW 89	142.0	620.1	3.5		

WIND SUMMARY (Kilometres per hour)
SOMMAIRE DES VENTS (Kilomètres par heure)

Hamilton Airport

MONTH / MOIS: MARCH / MARS 1980

Date	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Peak Gust / Rafale maximum	Hour / Heure
1	W 7	W 7	WSW 7	W 7	W 7	WNW 7	WNW 11	N 7	N 7	N 7	N 9	NNE 13	NNW 9	NNW 15	N 15	N 19	NNW 15	NNW 19	NNW 15	NW 13	NNW 15	NNW 13	N 7	N 4	NNW 32	1441
2	N 7	N 6	NW 6	NNW 9	NNW 7	NW 9	WNW 7	W 11	WNW 11	WNW 9	W 11	W 11	NW 11	WNW 7	NW 11	WNW 15	W 17	W 17	W 17	W 11	NW 7	WSW 13	WSW 13	WSW 11		
3	WSW 15	SW 13	WSW 11	WSW 15	SW 17	SW 13	SSW 15	SW 19	SW 15	SW 22	SW 30	WSW 24	SW 30	SW 30	SW 32	SW 33	SW 37	SW 28	WSW 32	SW 22	SW 22	SW 22	SW 26	SW 22	WSW 50	1513
4	WSW 30	WSW 30	WSW 24	WSW 26	SW 24	SW 22	SSW 19	SW 19	SW 19	SW 22	SW 22	WSW 22	WSW 17	WSW 26	SW 19	WSW 20	WSW 20	WSW 19	WSW 11	WSW 7	SW 6	S 9	S 9	S 11	SW 39	0221
5	S 7	S 11	S 9	S 9	SSE 7	SSE 6	ESE 7	E 4	ENE 4	ENE 4	E 7	C	C	WNW 9	W 15	W 15	WNW 24	WNW 33	WNW 28	NW 35	WNW 30	W 15	WSW 19	WSW 19	NW 48	1926
6	W 26	WNW 19	WNW 24	WNW 33	W 19	W 17	W 22	WSW 13	WSW 15	WSW 22	WSW 20	WSW 26	WSW 22	W 19	SW 26	SW 20	SW 24	SW 17	SW 15	SSW 7	S 7	S 6	SSW 7	S 4	WNW 44	0229
7	S 6	C	C	C	C	C	WNW 4	C	SSW 6	SW 9	W 11	WSW 9	W 17	W 17	W 7	C	SW 6	SSE 4	C	N 7	ENE 11	E 15	ESE 13	ENE 11		
8	ENE 17	ENE 22	ENE 22	ENE 26	ENE 30	ENE 28	ENE 28	ENE 26	ENE 28	ENE 30	ENE 30	NE 30	NE 35	ENE 37	NE 28	NNE 19	NNE 22	N 17	N 19	N 11	W 7	W 4	WNW 11	WNW 11	ENE 52	1233
9	W 11	W 13	W 15	W 13	W 15	W 17	W 19	W 17	W 13	W 9	WSW 11	W 13	WSW 19	WSW 20	WSW 20	WSW 30	WSW 35	WSW 28	WSW 30	WSW 20	SW 15	WSW 13	SW 9	S 7	WSW 48	1602
10	S 9	SSW 15	SSW 19	SSW 26	SW 26	SW 22	SW 22	SSW 19	SW 15	SSW 22	SSW 24	SSW 26	SSW 33	SSW 30	SSW 24	SSW 35	SSW 19	SSW 22	SW 28	SSW 24	WSW 32	WNW 52	WNW 52	WNW 44	W 63	2010
11	WNW 33	WNW 35	W 35	W 37	W 37	W 37	W 41	W 41	W 46	W 44	W 48	W 52	W 52	W 52	W 37	W 37	WNW 30	WNW 41	WNW 37	WNW 33	W 33	W 33	W 33	W 30	W 69	1623
12	W 15	W 17	W 15	WNW 19	WNW 15	NW 17	NW 19	NNW 20	NE 7	N 19	NNW 13	NNW 15	NNW 11	ESE 7	ENE 13	ENE 19	ENE 20	ENE 19	E 17	E 19	E 11	E 17	E 22	E 19		
13	E 20	E 22	E 26	E 28	E 24	E 32	ENE 30	ENE 33	ENE 32	ENE 30	ENE 30	ENE 28	ENE 28	ENE 28	E 22	E 22	E 20	E 17	E 13	ENE 17	ENE 15	ENE 17	ENE 19	ENE 15	E 46	1015
14	NE 13	NE 9	ENE 6	ENE 7	ENE 4	C	NNW 6	WNW 9	WNW 28	WNW 20	NW 28	NW 39	NW 30	WNW 37	WNW 46	WNW 46	WNW 46	W 37	W 30	WNW 28	WNW 28	W 24	NW 28	WNW 22	WNW 59	1328
15	WNW 24	WNW 30	NW 28	NW 22	NW 28	NW 28	NW 24	NW 28	NW 22	NW 26	NW 22	NW 24	WNW 22	W 26	W 22	WNW 19	WNW 17	WNW 17	WNW 11	N 11	NNE 7	C	C	ENE 13	NW 46	0145
16	ENE 13	ENE 7	E 13	E 15	E 17	E 19	E 20	ENE 22	ENE 24	ENE 28	ENE 28	ENE 28	ENE 28	ENE 28	ENE 28	NE 32	NE 30	NE 30	NE 30	NE 26	NE 22	ENE 19	NE 19	ENE 9	ENE 41	1003
17	SSE 9	SSE 15	S 15	S 26	SSW 26	S 22	S 24	S 22	S 24	SSW 22	SSW 24	SSW 30	S 30	S 30	S 26	SSW 24	SSW 24	SSW 26	SW 24	WSW 30	W 35	W 30	WNW 37	WNW 32	WNW 56	2212
18	WNW 33	WNW 35	WNW 41	WNW 37	WNW 37	WNW 46	WNW 44	WNW 33	W 37	WNW 41	WNW 37	WNW 41	WNW 41	W 46	WNW 39	WNW 39	W 41	W 37	W 26	W 20	SW 19	SW 20	SW 19	WSW 20	WNW 67	1314
19	WSW 19	WSW 19	WSW 17	SW 15	SW 15	SW 15	SW 15	SW 15	SW 19	SW 22	SW 20	SSW 19	SW 20	SSW 26	SSW 28	SSW 30	SSW 28	SSW 20	S 15	S 13	SSE 13	SSW 11	SSW 26	SW 19	SSW 39	1447
20	SW 22	SSW 19	SSW 22	SW 20	SSW 20	SSW 22	SSW 17	SSW 20	SSW 22	SSW 19	SW 33	SW 30	WSW 32	SSW 30	SW 33	WSW 28	WSW 24	SW 19	S 13	SSE 13	SSE 19	E 11	E 20	ESE 11	SW 43	0948
21	E 20	ENE 15	N 15	ENE 15	ENE 17	ENE 20	ENE 24	ENE 20	NE 26	ENE 26	NE 26	NNE 22	NNE 20	NNW 28	NW 37	NW 43	NW 44	NW 54	NW 56	NW 61	NW 52	NW 46	NW 56	NW 54	NW 89	1918
22	NW 56	NW 57	NW 52	NW 48	NW 52	NW 56	NW 54	NW 48	NW 48	NW 46	NW 37	NW 37	NW 30	NNW 30	NNW 28	NW 30	NW 30	NW 28	NNW 26	NNW 20	N 7	W 11	WNW 13	NNW 15	NW 76	0220
23	ENE 13	NW 11	WNW 15	NW 6	NW 7	NNW 6	NW 7	W 7	W 13	S 15	WSW 15	WSW 11	SSW 19	SW 15	SW 11	SSW 15	SSW 11	SW 7	E 13	ENE 13	ENE 11	ENE 7	NE 11	E 17		
24	ENE 19	ENE 20	ENE 22	ENE 22	ENE 20	ENE 17	ENE 24	ENE 22	ENE 22	ENE 26	ENE 22	ENE 30	ENE 33	ENE 37	NE 30	NE 32	NE 30	NE 33	NE 22	NNE 22	NNE 20	NNE 19	NNE 22	W 22	NE 44	1330
25	W 22	W 17	W 20	WSW 20	WSW 24	WSW 28	NW 35	WNW 28	NW 28	NW 28	WNW 28	WNW 28	WNW 28	WNW 32	WNW 26	WNW 30	WNW 33	NW 26	WNW 26	NW 24	NW 22	W 13	WSW 17	W 19	NW 48	0759
26	W 13	WNW 13	W 17	W 7	NNW 15	N 17	NNW 15	NNW 13	N 17	NNW 11	NNW 7	C	N 17	C	ESE 9	ESE 6	ESE 6	SSW 7	SW 9	WSW 9	SW 7	WSW 9	WSW 7	N 7		
27	C	C	C	C	C	C	C	ENE 7	ENE 7	E 7	SSE 6	SSE 15	SSE 9	SSE 15	SSE 15	SE 17	ESE 15	ENE 17	ENE 13	ENE 15	NE 15	NE 20	NE 20	ENE 15		
28	NE 13	NNE 13	NE 13	NE 11	NE 7	NE 17	NE 15	NE 15	NE 17	ENE 20	ENE 20	ENE 24	ENE 24	ENE 26	ENE 24	ENE 19	ENE 20	ENE 17	ENE 15	ENE 17	ENE 15	ENE 17	ENE 19	NE 24		
29	ENE 13	NE 15	NE 11	NE 17	NE 15	NE 17	NNE 22	NE 19	NE 22	NNE 26	NE 26	NE 33	NE 37	NE 33	ENE 33	ENE 30	ENE 37	ENE 33	ENE 26	NE 22	ENE 15	NE 22	NE 19	NNE 15	ENE 52	1553
30	NNE 19	N 13	NNE 15	NNE 24	NNE 17	NE 17	NNE 19	NNE 19	NNE 22	NE 30	ENE 30	ENE 24	NE 30	NE 33	ENE 35	ENE 39	ENE 43	ENE 37	E 30	E 26	E 28	E 28	E 30	E 33	ENE 63	1541
31	ENE 41	ENE 41	ENE 37	NE 37	NE 35	NE 33	NE 35	NE 37	ENE 37	ENE 37	NE 41	NE 35	NE 30	NE 30	NE 30	NE 32	NE 28	NE 28	ENE 26	ENE 22	ENE 22	ENE 22	E 20	E 13	ENE 54	0749

On indique un vent d'ouest par la lettre "W".

C = calm

*Indicates later occurrences of same speed
*Indique des données postérieures de la même vitesse.

APPENDIX C: Shallow and Deep Water Wave Forecasting Curves

Example

U = 80 km/hr = 50 mph
F = 10 km = 32,800 feet
d = 1.5 m = 5 feet
H = 1.8 feet = 0.55 m
T = 3.3 s

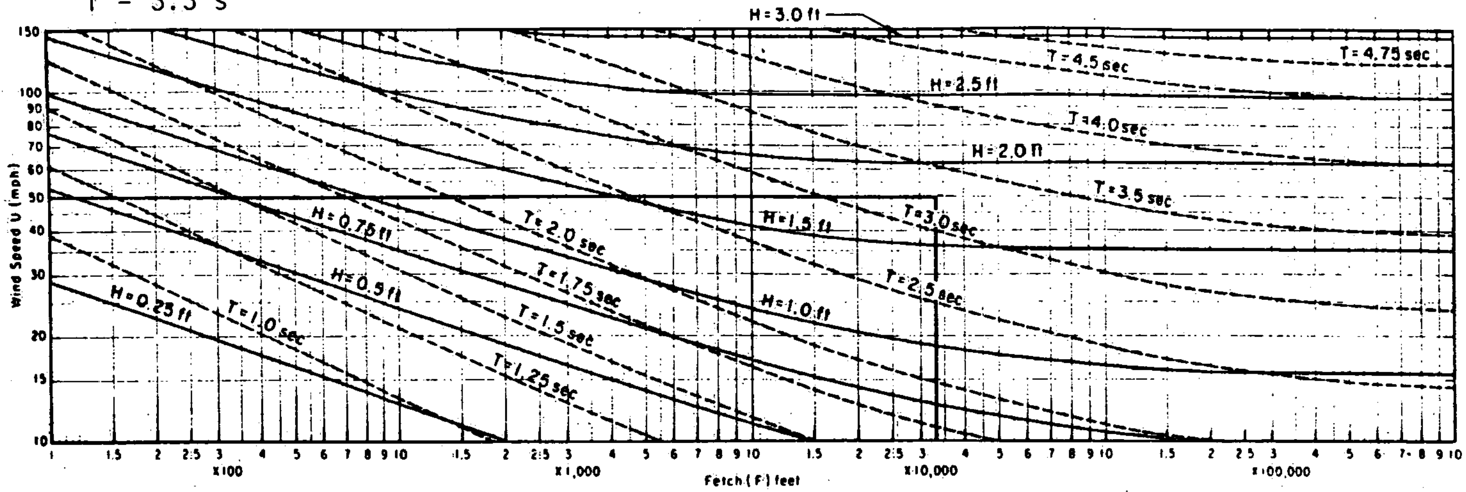


Figure C1 Forecasting Curves for Shallow-Water Waves. Constant Depth = 5 feet (1.5 m) (U.S. Army, CERC, 1977)

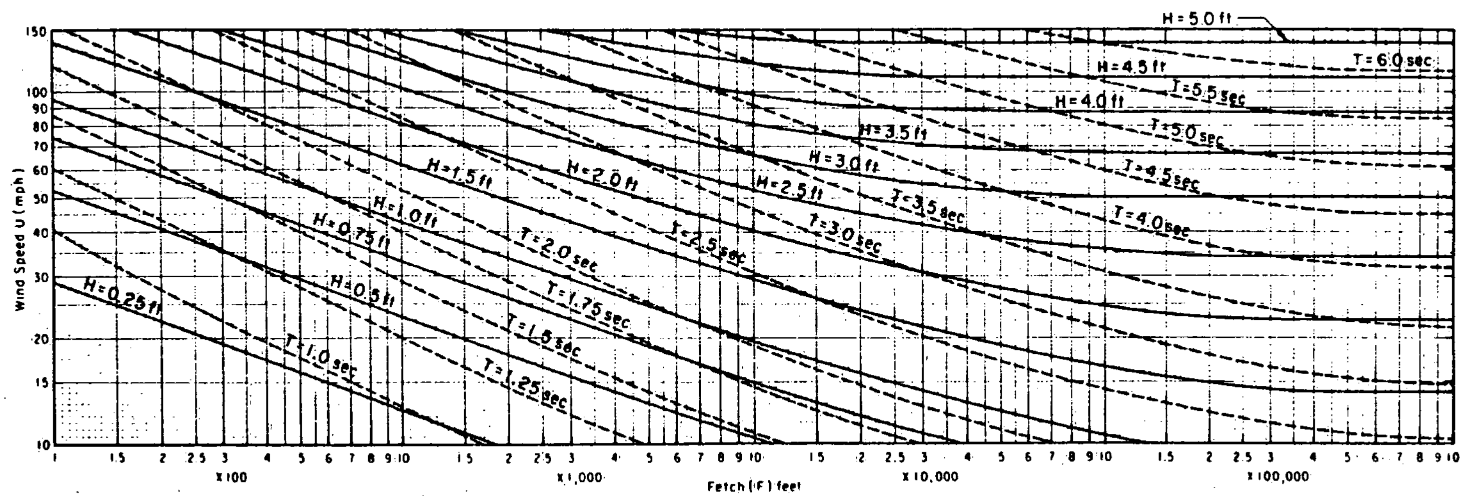


Figure C2 Forecasting Curves for Shallow-Water Waves. Constant Depth = 10 feet (3.0 m) (U.S. Army, CERC, 1977)

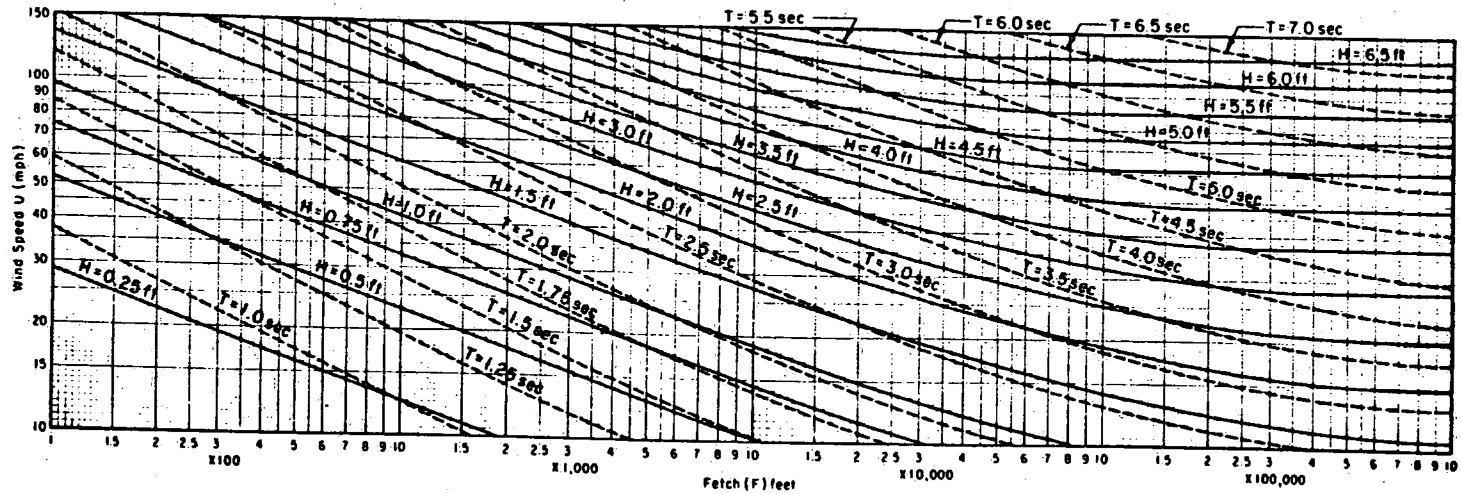


Figure C3 Forecasting Curves for Shallow-Water Waves. Constant Depth = 15 feet (4.6 m) (U.S. Army, CERC, 1977)

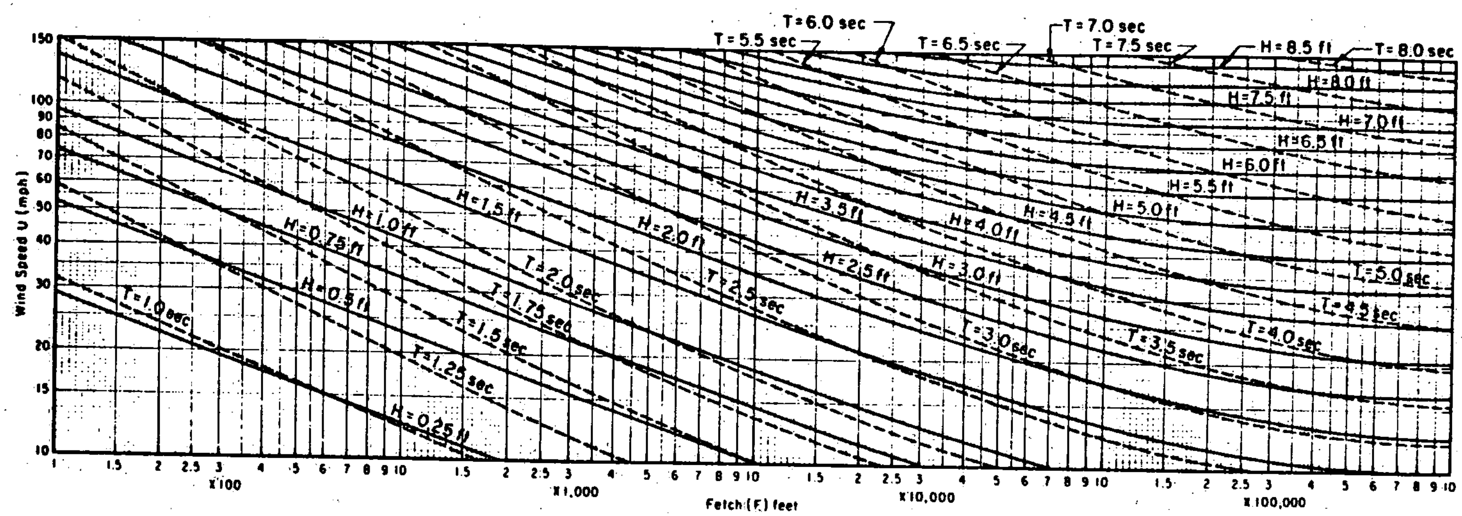


Figure C4 Forecasting Curves for Shallow-Water Waves. Constant Depth = 20 feet (6.1 m) (U.S. Army, CERC, 1977)

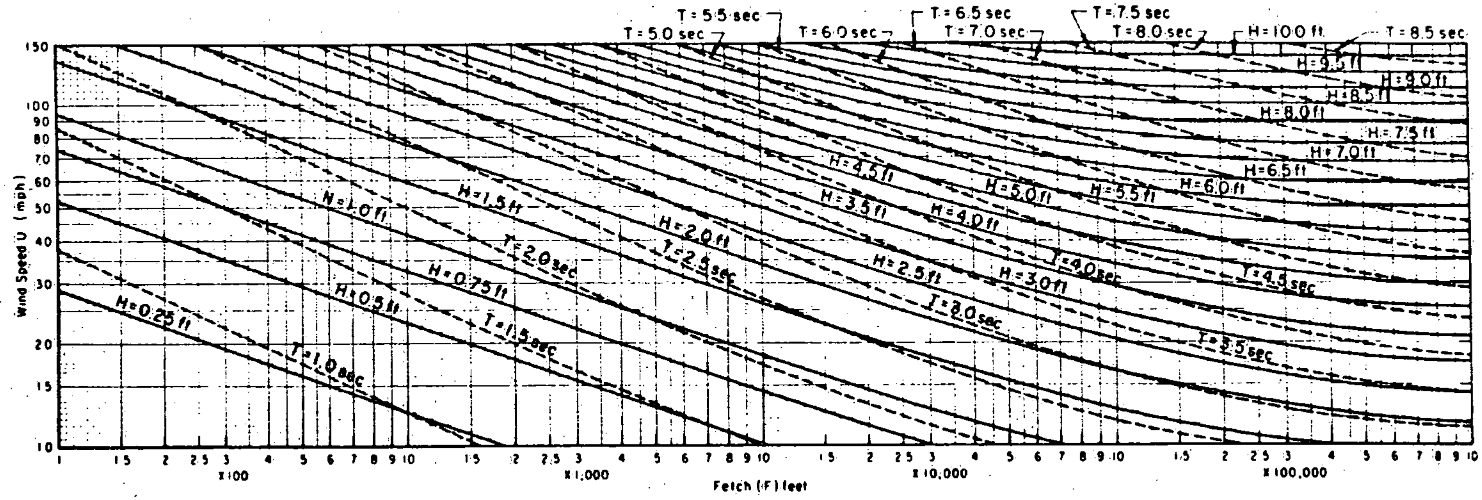


Figure C5 Forecasting Curves for Shallow-Water Waves. Constant Depth = 25 feet (7.6 m) (U.S. Army, CERC, 1977)

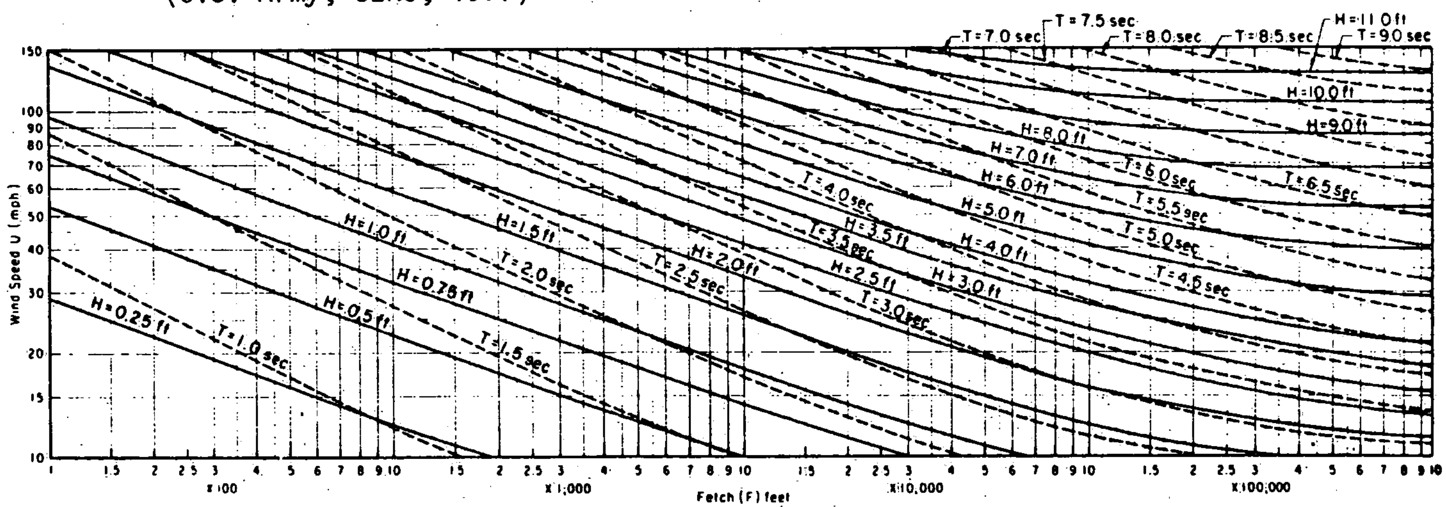


Figure C6 Forecasting Curves for Shallow-Water Waves. Constant Depth = 30 feet (9.1 m) (U.S. Army, CERC, 1977)

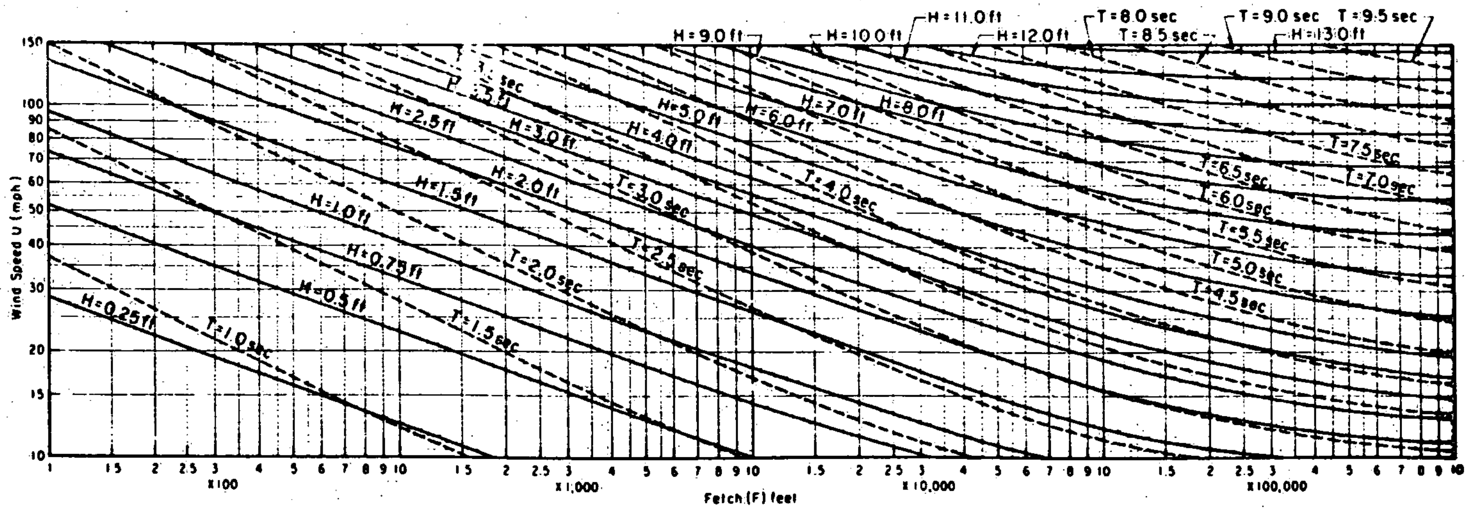


Figure C7 Forecasting Curves for Shallow-Water Waves. Constant Depth = 35 feet (10.7 m) (U.S. Army, CERC, 1977)

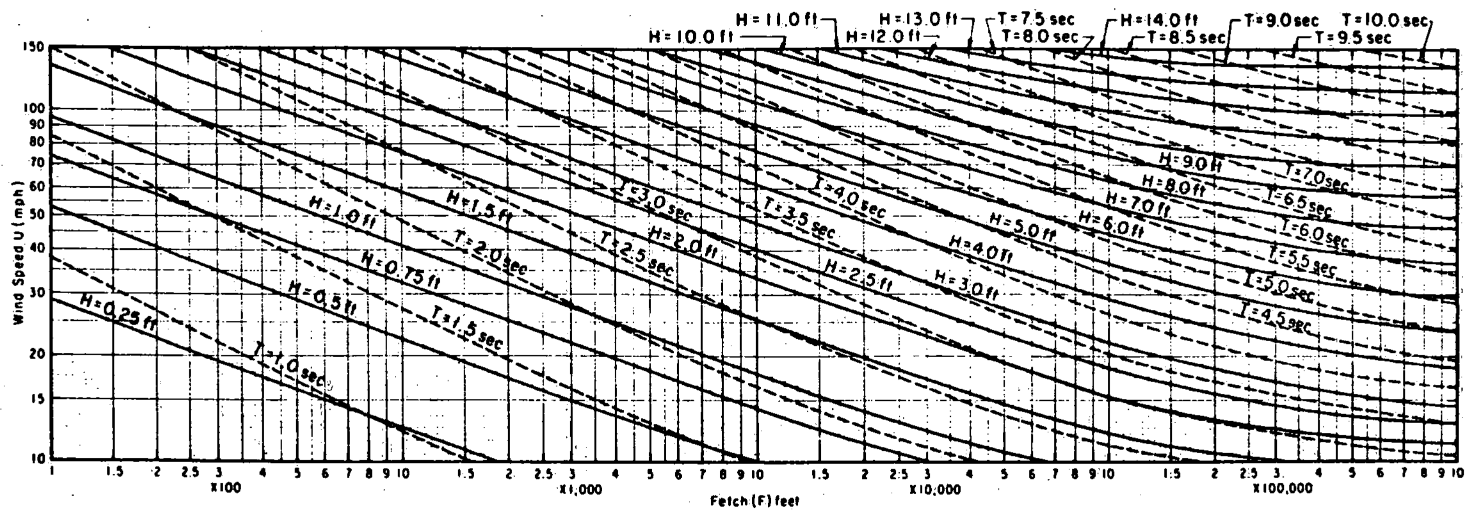


Figure C8 Forecasting Curves for Shallow-Water Waves. Constant Depth = 40 feet (12.2 m) (U.S. Army, CERC, 1977)

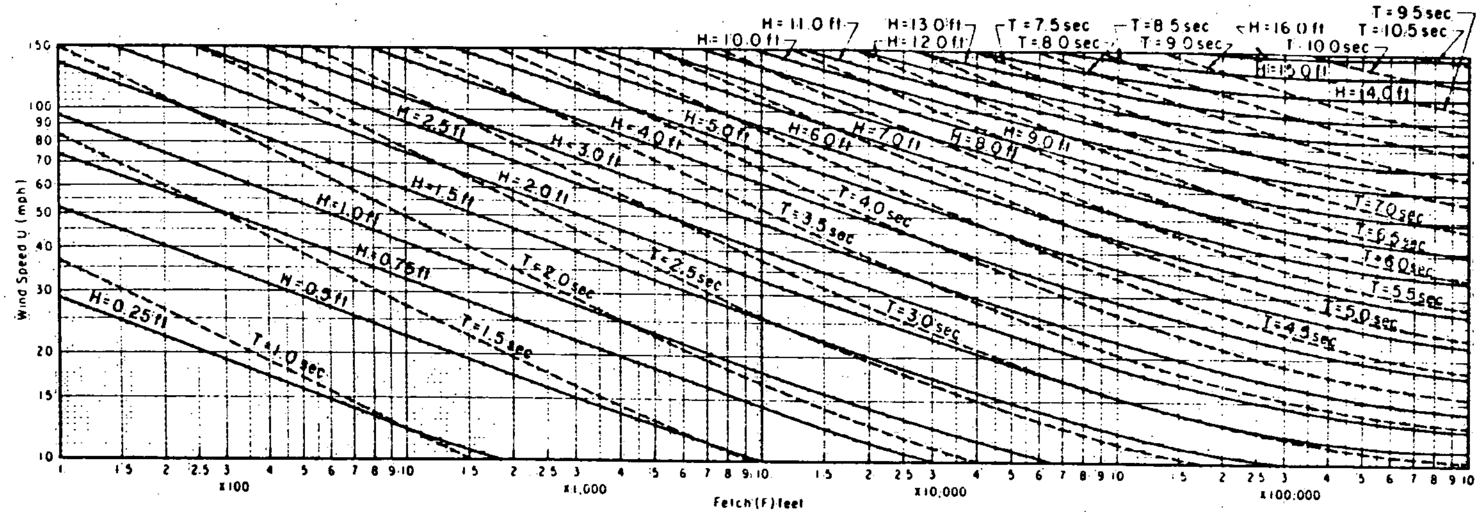


Figure C9 Forecasting Curves for Shallow-Water Waves. Constant Depth = 45 feet (13.7 m) (U.S. Army, CERC, 1977)

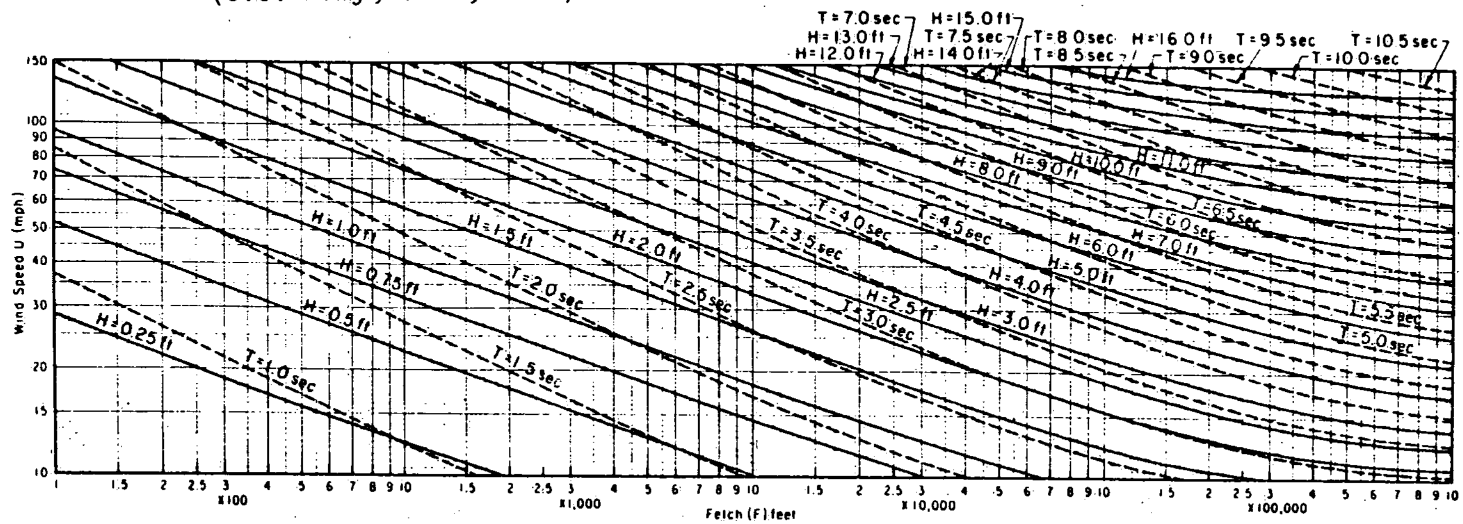
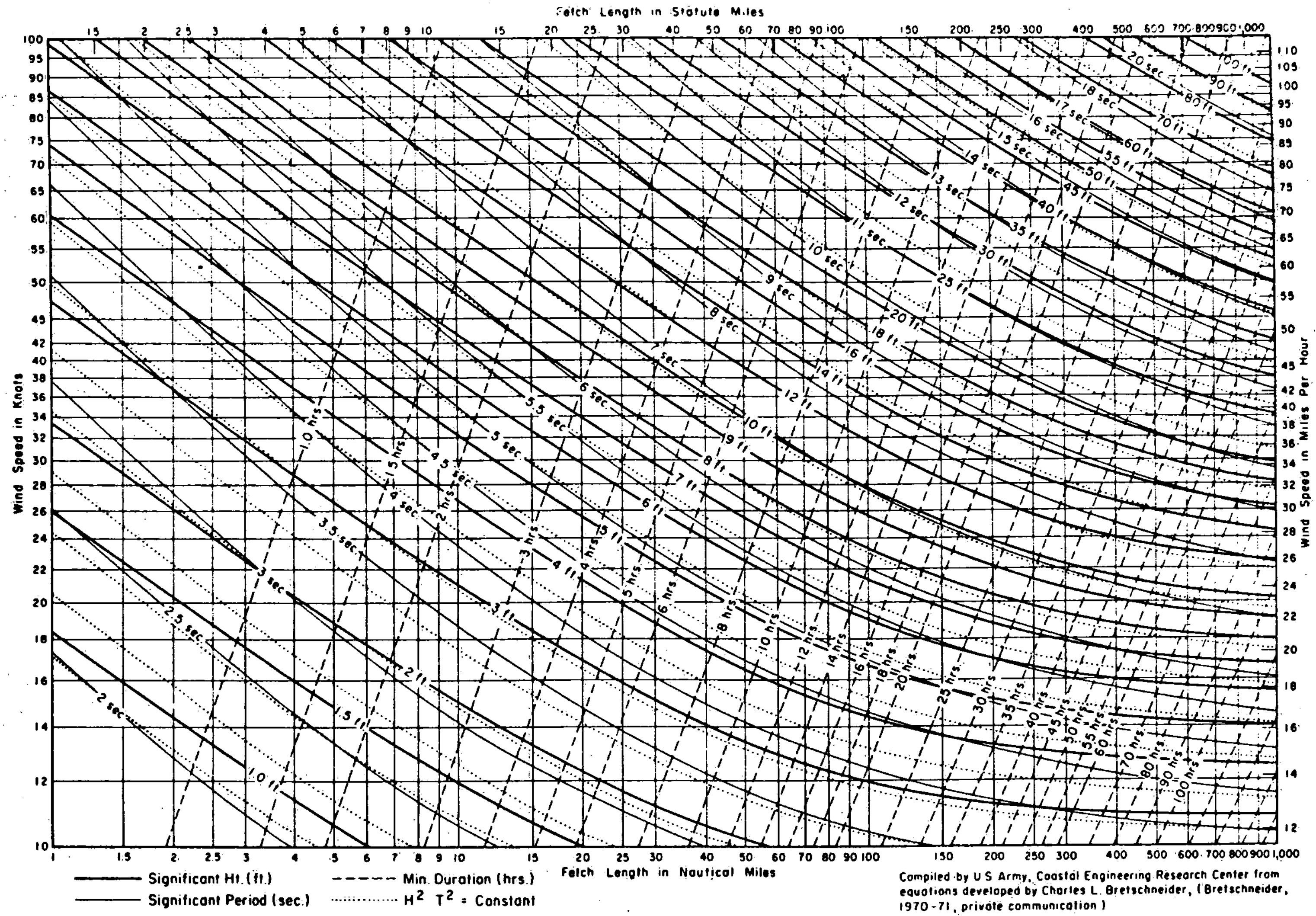


Figure C10 Forecasting Curves for Shallow-Water Waves. Constant Depth = 50 feet (15.2 m) (U.S. Army, CERC, 1977)



1 km = 0.54 naut. miles
1 km/hour = 0.54 knots

Figure C11 Deepwater Wave Forecasting Curves as a Function of Wind Speed, Fetch Length, and Wind Duration (for Fetches 1 to 1,000 miles) (U.S. Army, CERC, 1977)

APPENDIX D: FTB Flotation Calculations

APPENDIX D: FTB Flotation Calculations

An analysis of the static forces on a floating car tire breakwater in fresh water is presented in order to assess the FTB's factor of safety against sinking. The following car tire data from Harms (1979a) has been used in the analysis:

Tire's outer diameter	=	0.635 m
Tire's inner diameter	=	0.349 m
Tire's tread width	=	0.190 m
Density	=	1200 kg/m^3
Weight in air	=	7.62 kg
Weight in water (assuming no air trapped in tire)	=	1.27 kg
Weight, applied to crown of tire, required to submerge a newly installed vertical tire	=	5.00 kg

Thus, a vertical car tire whose crown is full of air, experiences an excess buoyant force of about 5 kg in fresh water. Therefore, the trapped air in one tire is capable of providing a buoyant force of 5+1.27=6.27 kg. This implies that the volume of trapped air can be as large as 6.27 ℓ.

A body's factor of safety against sinking is the ratio of its potential buoyant force to its gravitational forces. The gravitational forces consist of the submerged tire weight, the submerged weight of the binding material, mooring lines and connectors, as well as the weight of marine growth, debris and sediment trapped inside the tires.

Typical weights per tire for the binding material, mooring lines and connectors have been estimated for the car tire FTB's designed in Section 9, using information from Section 10.

<u>Goodyear FTB</u>

Binding Material - 885 m/2520 tires = 0.35 m/tire

Using conveyor belt edging (submerged density $\simeq$200 kg/m^3), the weight is 0.35 m long x 0.1 m wide x 0.012 m thick x 200 kg/m^3 = 0.0875 kg/tire.

Using lightweight steel chain (submerged weight $\simeq$2.45 kg/m), the weight is 0.35 m long x 2.45 kg/m=0.86 kg/tire.

Mooring Lines - 206 m/2520 tires = 0.082 m/tire

Using regular steel chain (submerged weight $\simeq$3.2 kg/m), and assuming that none of the mooring lines are lying slack on the bottom, the weight is 0.082 m x 3.2 kg/m=0.26 kg/tire.

Connectors - 16 connections/module x 20 tires/module=0.8 connections-/tire

Using 12.5 mm diameter nuts, washers and bolts (50 mm long), the submerged weight per connection is about 75 g. Therefore the weight of connectors is about 0.06 kg/tire.

Thus the submerged weight of construction materials in a Goodyear FTB is typically 0.41 kg/tire when using conveyor belt edging as the binding material, regular steel chain for the mooring lines, and steel connectors. This weight increases to 1.18 kg/tire if lightweight steel chain is used as the binding material rather than conveyor belt edging.

PT-Breakwater

Binding Material - 1140 m/2870 tires = 0.40 m/tire

Using conveyor belt edging, the weight is 0.40 m long x 0.1 m wide x 0.012 m thick x 200 kg/m^3 = 0.095 kg/tire.

Mooring Lines - 525 m/2870 tires = 0.18 m/tire

Using regular steel chain, the weight is 0.18 m long x 3.2 kg/m = 0.59 kg/tire.

Connectors - 616 connections/2366 tires = 0.26 connections/tire

Using steel nuts, washers and bolts, the weight is 0.02 kg/tire.

Poles - Although newly installed wood poles would be positively buoyant, it is assumed that the poles are neutrally buoyant. This would be representative of marine piling after several years submergence.

Thus, the submerged weight of construction materials in a PT-breakwater is typically less than or equal to 0.68 kg/tire.

Assuming the tire crowns to be full of air, the factor of safety against a newly installed FTB sinking can be estimated as follows:

	1	2	3	$\frac{1}{2+3}$
	Potential Buoyant Force (kg/tire)	Submerged Weight of Tire (kg/tire)	Submerged Weight of Construction Materials (kg/tire)	Factor of Safety Against Sinking
Goodyear FTB with conveyor belt edging as binding material.	6.27	1.27	0.41	3.7
Goodyear FTB with lightweight steel chain as binding material.	6.27	1.27	1.18	2.6
PT-2 made of car tires and marine piles, with conveyor belt edging as binding material.	6.27	1.27	0.68	3.2

These factors of safety should be regarded as estimates only. However, they account for the well known fact that a newly installed FTB will float without the provision of supplemental flotation (Shaw and Ross, 1977; DeYoung, 1978; Harms, 1979a).

The magnitudes of these factors of safety will be reduced by the additional submerged weight of debris, marine growth and trapped sediment, and also by the smaller buoyant force corresponding to a smaller volume of trapped air (due to air leaking out or dissolving in water, lack of air recharge, or the use of smaller tires). Clearly, if the volume of air trapped in each tire is half its capacity (i.e 3.1 ℓ /tire), and if the weight of accumulated debris, marine growth and trapped sediment is about 0.5 kg/tire, the factor of safety against sinking for a Goodyear FTB reduces to 1.4, if using conveyor belt edging as the binding material, and to 1.05 if using lightweight steel chain as the binding material.

The provision of supplemental flotation (Sections 4.6 and 7.4) attempts to ensure that a buoyant force sufficient to keep the breakwater floating is always available, even in the absence of air recharge. The provision of 225 g urethane foam in the crown of a tire (Section 7.4) provides a buoyant force of 7 kg (slightly more than the natural buoyant force due to a tire crown full of air). The use of a 4 ℓ plastic container jammed in the crown of a tire provides a buoyant force of 4 kg (assuming no other trapped air in the crown of a tire).

Because continued flotation is essential to the success of an FTB, it is recommended that a minimum of 4 kg, and preferably 7 kg, of supplemental flotation be provided in <u>each</u> car tire of a Goodyear FTB or wood pole PT-breakwater.