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FIXED MOORINGS

DESIGN MANUAL 26.4
APRIL 1986

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Change Number	Description of Change	Date of Change	Page Changed

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ABSTRACT

Basic criteria and planning guidelines for the determination of loads on fixed moorings are presented for use by qualified engineers. The contents include types of fixed moorings, basic design philosophy, procedures for determining forces on moored vessels, procedures for determining forces on mooring elements, and example calculations.

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FOREWORD

This design manual is one of a series developed from an evaluation of facilities in the shore establishment, from surveys of the availability of new materials and construction methods, and from selection of the best design practices of the Naval Facilities Engineering Command, other Government agencies, and the private sector. This manual uses, to the maximum extent feasible, national professional society, association, and institute standards in accordance with NAVFACENGCOM policy. Deviations from these criteria should not be made without prior approval of NAVFACENGCOM Headquarters (Code 04).

Design cannot remain static any more than can the naval functions it serves or the technologies it uses. Accordingly, recommendations for improvement are encouraged from within the Navy and from the private sector and should be furnished to Commanding Officer, Chesapeake Division, (Code 406), Naval Facilities Engineering Command, Washington Navy Yard, Washington, DC 20374. As the design manuals are revised, they are being restructured. A Chapter or a combination of chapters will be issued as a separate design manual for ready reference to specific criteria.

This publication is certified as an official publication of the Naval Facilities Engineering Command and has been reviewed and approved in accordance with SECNAVINST 5600.16.

J.P. Jones, Jr.
Rear Admiral, CEC, U.S. Navy
Commander
Naval Facilities Engineering Command

HARBOR AND COASTAL FACILITIES DESIGN MANUALS

DM Number	Superseded Chapter in Basic DM-26	Title
26.1	1, 4	Harbors
26.2	2	Coastal Protection
26.3	1, 2, 3	Coastal Sedimentation and Dredging
26.4	5	Fixed Moorings
26.5	6	Fleet Moorings
26.6	7	Mooring Design Physical and Empirical Data

FIXED MOORINGS

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TABLES (Continued)

FIXED MOORINGS

Section 1. INTRODUCTION

1. SCOPE. This manual presents basic information required for the selection and design of fixed-mooring systems in protected harbors.

2. CANCELLATION. This manual, NAVFAC DM-26.4, Fixed Moorings, cancels and supercedes Chapter 5 of the basic Design Manual 26, Harbor and Coastal Facilities, dated July 1968, and Change 1, dated December 1968.

3. RELATED CRITERIA. Certain criteria related to fixed moorings appear elsewhere in the design manual series. See the following sources:

Subject	Source
Characteristics of Vessels	DM-26.6
Fender Systems and Fixed Mooring Separators	DM-25.1
Fleet Moorings	DM-26.5
Foundations and Earth Structures	DM-7.2
General Criteria For Waterfront Construction	DM-25.6
Pier Berths, Deck Fittings, Access Facilities	DM-25.1
Seawalls, Bulkheads, and Quaywalls	DM-25.4
Sedimentation	DM-26.3
Soil Dynamics, Deep Stabilization, and Special Geotechnical Construction	DM-7.3
Soil Mechanics	DM-7.1
Strength and Dimensional Characteristics of Chain, Wire, and Fiber Rope	DM-26.6
Structural Engineering	DM-2 Series
Utility Services for Fixed Moorings	DM-25.2
Water-Level Fluctuations	DM-26.1
Wave Forces on Mooring Structures	DM-26.2

4. DEFINITION. Navy moorings are classified as either fixed moorings or fleet moorings. A fixed mooring consists of a structural element, permanently fixed in position, to which a vessel is moored. These structural elements include platforms, cells, dolphins, spuds, or other similar structures. A fixed mooring includes the lines, sheaves, pulleys, spuds, deck fittings of mooring and breasting structures, separators, access trestles, catwalks, and other appurtenances permanently attached to the structure or provided by the station specifically for securing vessels to the structure. Lines and appurtenances provided by vessels are not a part of the fixed mooring.

A fleet mooring consists of a structural element, not permanently fixed in position, to which a vessel is moored. Fleet moorings are discussed in DM-26.5, Fleet Moorings.

5. DEFINITIVE DRAWINGS. A list of definitive drawings for fixed moorings is presented in Table 1.

TABLE 1
Definitive Drawings for Fixed Moorings

Description	NAVFAC Drawing Number
Offshore Tanker Facility	1404350, 1404351

Section 2. FIXED-MOORING SYSTEMS

1. FIXED MOORINGS. Fixed moorings vary from site to site, but the elements of any fixed-mooring system are basically the same. A typical fixed mooring is shown in Figure 1. The basic elements common to most fixed moorings include: mooring and breasting structures (including fendering), mooring lines, deck fittings, separators, and access trestles and catwalks.

2. MOORING AND BREASTING STRUCTURES. Mooring structures are designed for mooring loads. Breasting structures are designed to withstand both mooring and berthing loads. Structures commonly used as mooring and/or breasting structures are platforms, cells, and dolphins. Spuds are often used as mooring structures in moorings for floating drydocks. Each of the common mooring and breasting structures are discussed below.

a. Platforms. Platforms generally consist of an isolated concrete, steel, or timber deck (cap) supported on concrete, steel, or timber piling. A platform may be used as either a mooring structure (mooring platform) or a breasting structure (breasting platform). Mooring platforms are not designed to withstand the impact of berthing. Breasting platforms normally have a fendering system to absorb the impact of berthing vessels and may also be used to secure the vessel.

Mooring and breasting platforms may be designed to behave in a rigid or a flexible manner. An example of a rigid breasting platform is shown in Figure 2; the structure consists of a concrete deck (cap) supported by vertical, as well as battered, concrete piles. This structure is designed to resist large lateral loads, which are transferred primarily to the battered piles. The battered piles on the back side of the platform are loaded in compression (bearing), while the front batter piles are loaded in tension (uplift). Because the uplift capacity of a pile is generally small compared to its bearing capacity, it is desirable to provide a massive concrete cap to resist some of the uplift load. Vertical piles are provided to support the large deadweight of the cap. The fendering system in Figure 2 consists of a row of timber fender piles with a cluster of timber fender piles on each corner of the structure.

Two examples of flexible breasting platforms are shown in Figure 3. Both structures are supported by steel-pipe piles, which resist lateral loads. The structures differ from one another in the construction of the platform deck. The platform in Figure 3A has a deck composed of steel grating; the piles supporting the deck are held together with steel-pile braces. The platform in Figure 3B has a concrete deck. The steel-pipe piles deflect under load to provide energy absorption. Thus, fendering requirements may be reduced compared to those for a rigid structure as berthing energy can be absorbed both in the structure and in the fendering system.

Mooring and breasting platforms are generally used in lieu of cells for water depths greater than 40 feet. Rigid platforms are often used instead of cells in soft soils. Platforms can be designed to withstand large lateral loads and thus can accommodate large vessels.

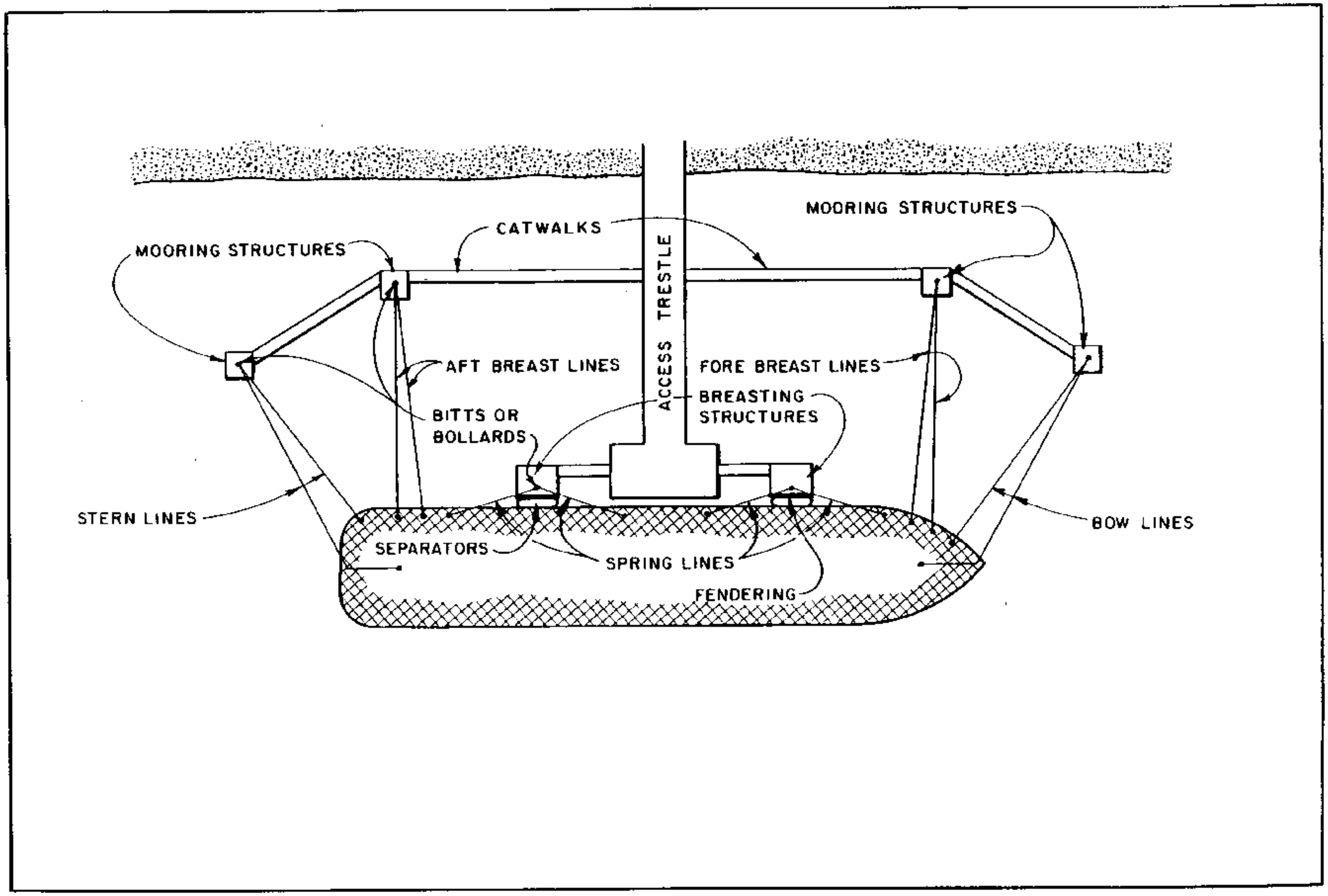


FIGURE 1
Typical Fixed Mooring

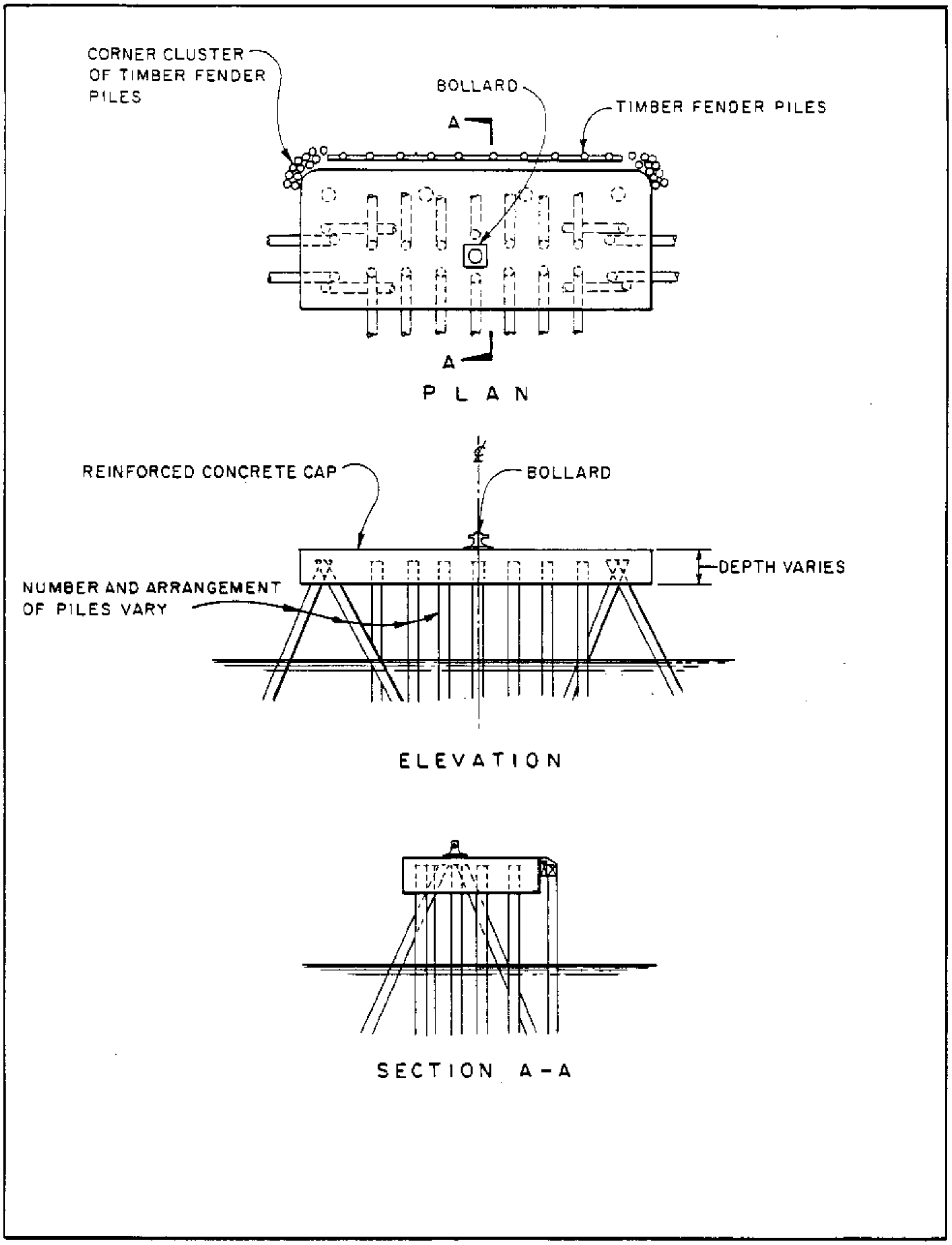


FIGURE 2
Rigid Breasting Platform

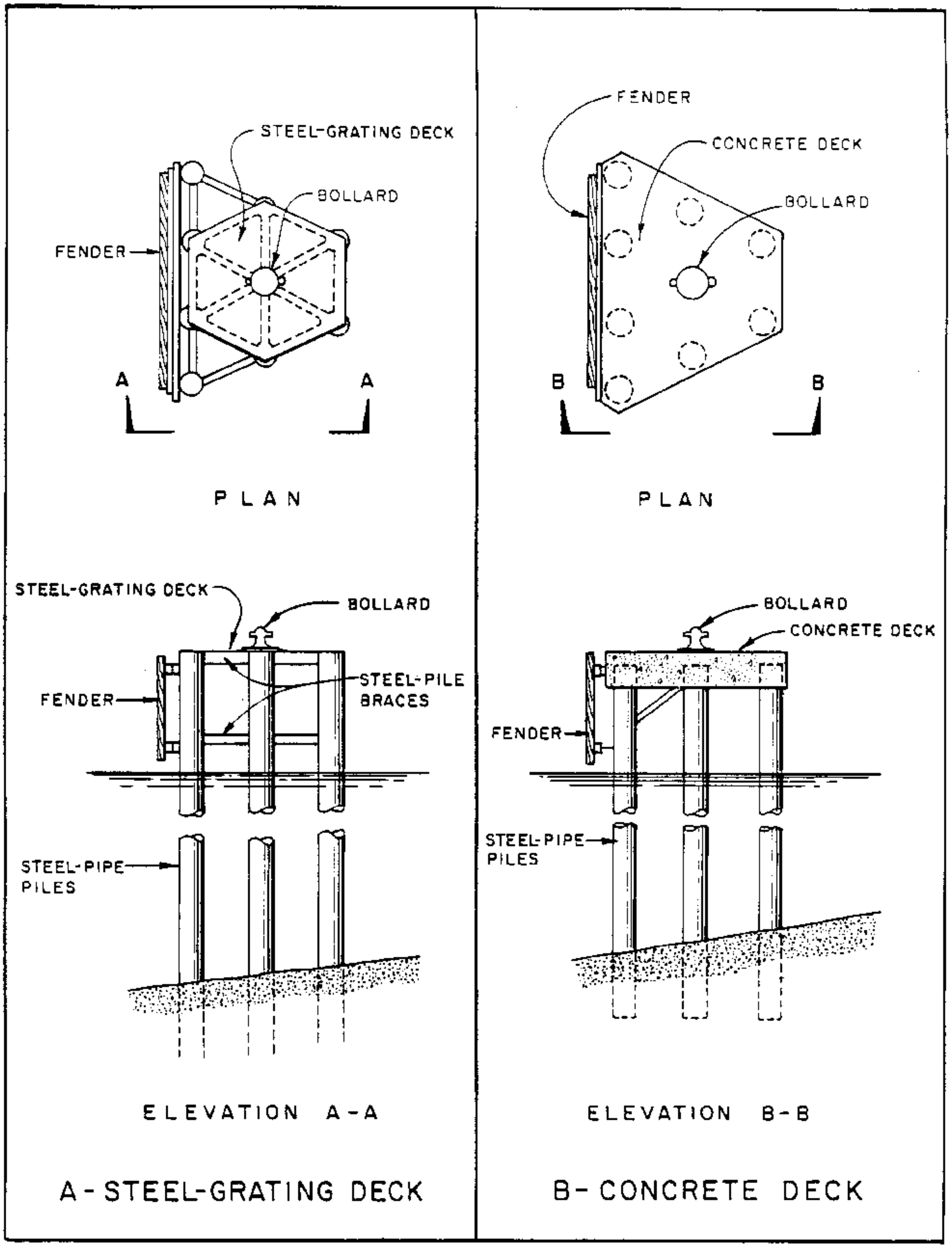


FIGURE 3
Two Types of Flexible Breasting Platforms

b. Cells. Mooring or breasting cells typically consist of round, isolated sheet-pile cofferdams or concrete caissons. Cells can be used as mooring or breasting structures; however, cells are most often used as breasting structures because they can withstand very large berthing loads.

Breasting cells are rigid structures which generally require a substantial fendering system to absorb berthing energy. Figure 4 presents a typical breasting cell. The structure consists of a cellular sheet pile filled with granular material. The cap of the structure is concrete, and rubber fenders are provided.

Mooring or breasting cells are generally used in water depths less than 40 feet. Mooring or breasting cells can be designed to accommodate large vessels.

c. Dolphins. Dolphins are generally flexible structures constructed of either timber piles or steel-pipe piles. Dolphins can be used as mooring or breasting structures.

Timber-pile dolphins typically consist of timber piles driven in clusters of three to 19 or more, wrapped at their tops with galvanized wire rope and connected with bolts and chocks of wood. Three-, seven-, and 19-pile mooring dolphins are shown in Figure 5A. One of the center piles of a thick cluster is extended so that a mooring line may be fastened to it. No fendering is required for a timber-pile breasting dolphin as the structure is quite flexible and can absorb berthing energy on its own. However, a timber-pile dolphin may fail under a berthing load when a vessel strikes one pile of the cluster, thus preventing distribution of, the load to the other piles. Consequently, the use of timber-pile clusters as breasting structures should be avoided.

Steel pipe-pile dolphins may consist of either one or a group of steel-pipe piles. Steel pipe-pile dolphins are particularly well-suited as breasting structures due to their flexibility. An example of a breasting dolphin with a single pipe pile is shown on the left in Figure 5B. This structure consists of a relatively large, single pipe pile with a cylindrical steel mooring post embedded in concrete at its top. A moderate timber fendering system is provided to supplement the structure in absorbing berthing energy. Figure 5B also shows a typical steel pipe-pile breasting dolphin with battered steel-pipe piles for resisting lateral load. A moderate rubber fendering system is provided. At some installations, use of a larger, single steel-pipe pile may be more economical than use of a group of smaller piles.

Timber-pile dolphins are typically used to moor smaller vessels than are platforms or cells. In general, timber-pile dolphins should not be used for lateral loads greater than 30 kips or in water depths greater than 35 feet. Steel pipe-pile dolphins may be used for larger loads and, if soil conditions are favorable, may be used in water depths exceeding 40 feet.

d. Spuds. A spud is a steel member, usually an H-pile or built-up section, used to secure a vessel to a pier or quaywall. Fixed moorings incorporating spuds are called spud moorings. Spud moorings are often used to moor floating drydocks, as shown in Figure 6A. Floating drydocks

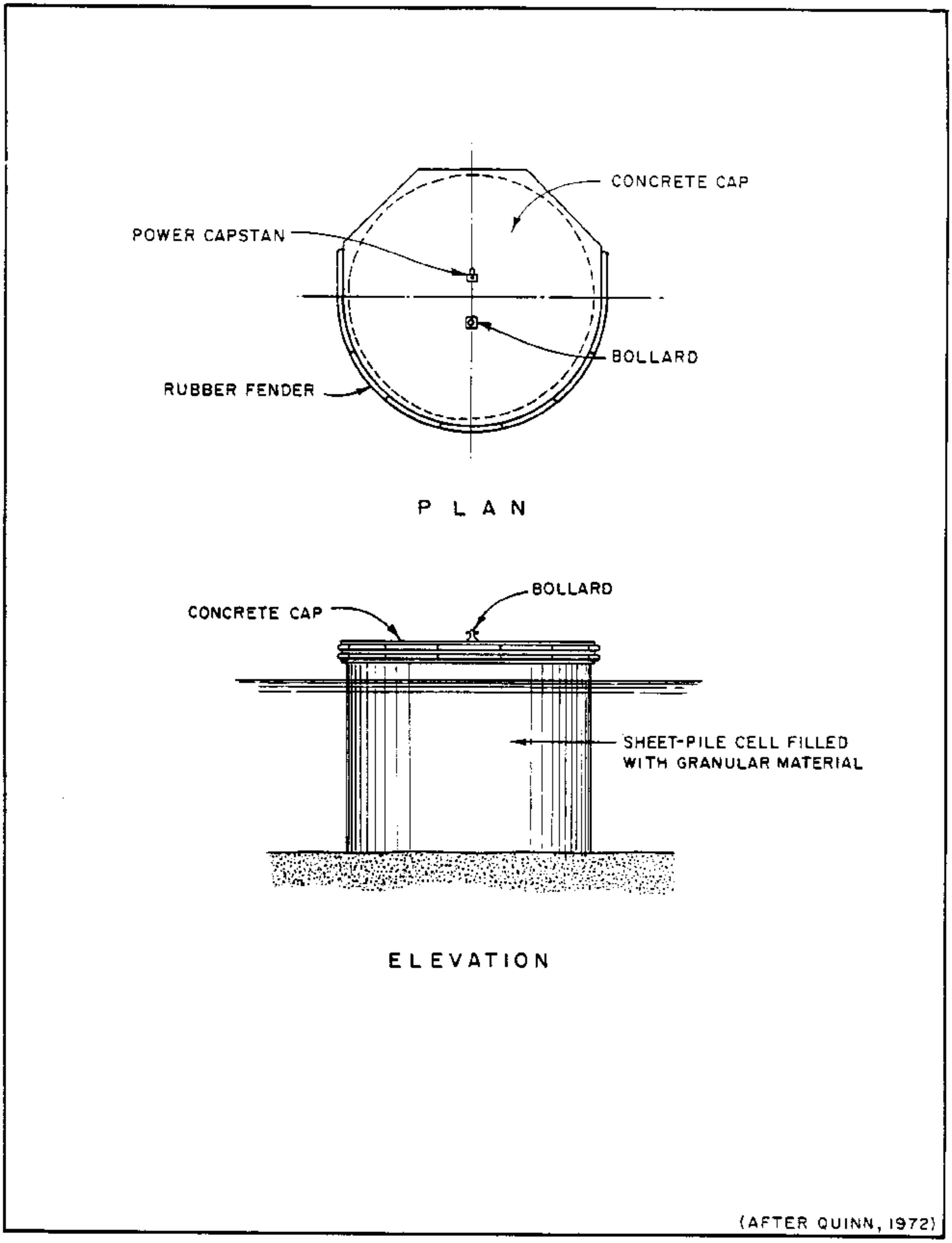


FIGURE 4
Breasting Cell

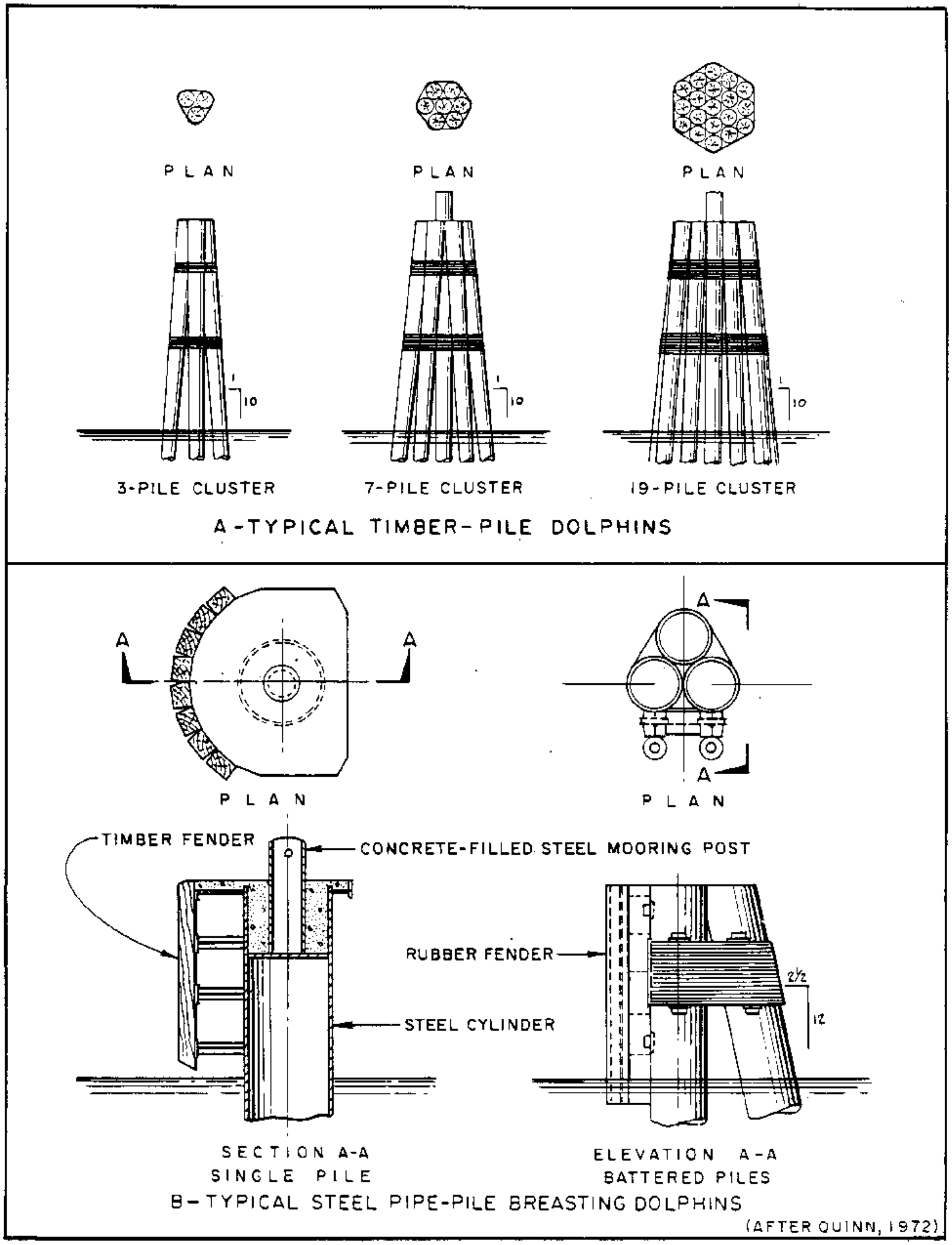
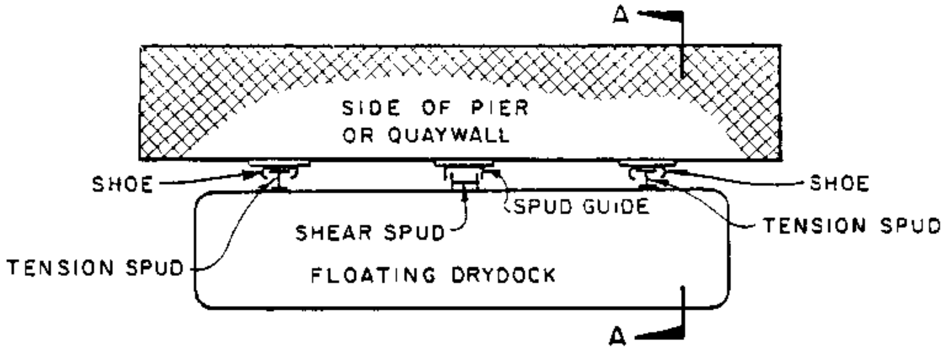
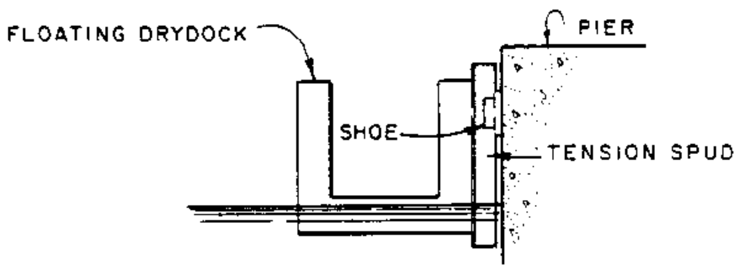


FIGURE 5
Dolphins



P L A N

A-SPUD MOORING FOR FLOATING DRYDOCK



SECTION A-A

B-TENSION SPUD

FIGURE 6
Spud Mooring

seldom leave their mooring; consequently, spud moorings are designed for mooring loads only. By definition, spuds are mooring structures.

Spuds are designed to resist either transverse loads (tension spuds) or longitudinal loads (shear spuds). Typically, the end spuds are tension spuds and intermediate spuds are shear spuds. Tension spuds can be designed to resist both transverse and longitudinal loads; in this case, the intermediate spuds are eliminated and only two spuds are required. Tension spuds are connected vertically to a pier or quaywall with a shoe (Figure 6B); shear spuds are connected with a spud guide. Shoes are connections which resist transverse loads, whereas guides resist longitudinal loads. Both connections allow the spuds to slide vertically.

3. MOORING LINES. Vessels are secured to mooring and/or breasting structures with mooring lines. Mooring lines are classified according to the type of load they resist (longitudinal or lateral) and their location on the vessel. Bow, stern, and breast lines resist lateral mooring loads and yaw moment on the vessel and are typically arranged as shown in Figure 1. Spring lines resist longitudinal mooring loads; a typical spring-line arrangement is also shown in Figure 1. The predominant load on a fixed mooring is generally the lateral load. Consequently, there are generally more bow, stern, and breast lines than spring lines.

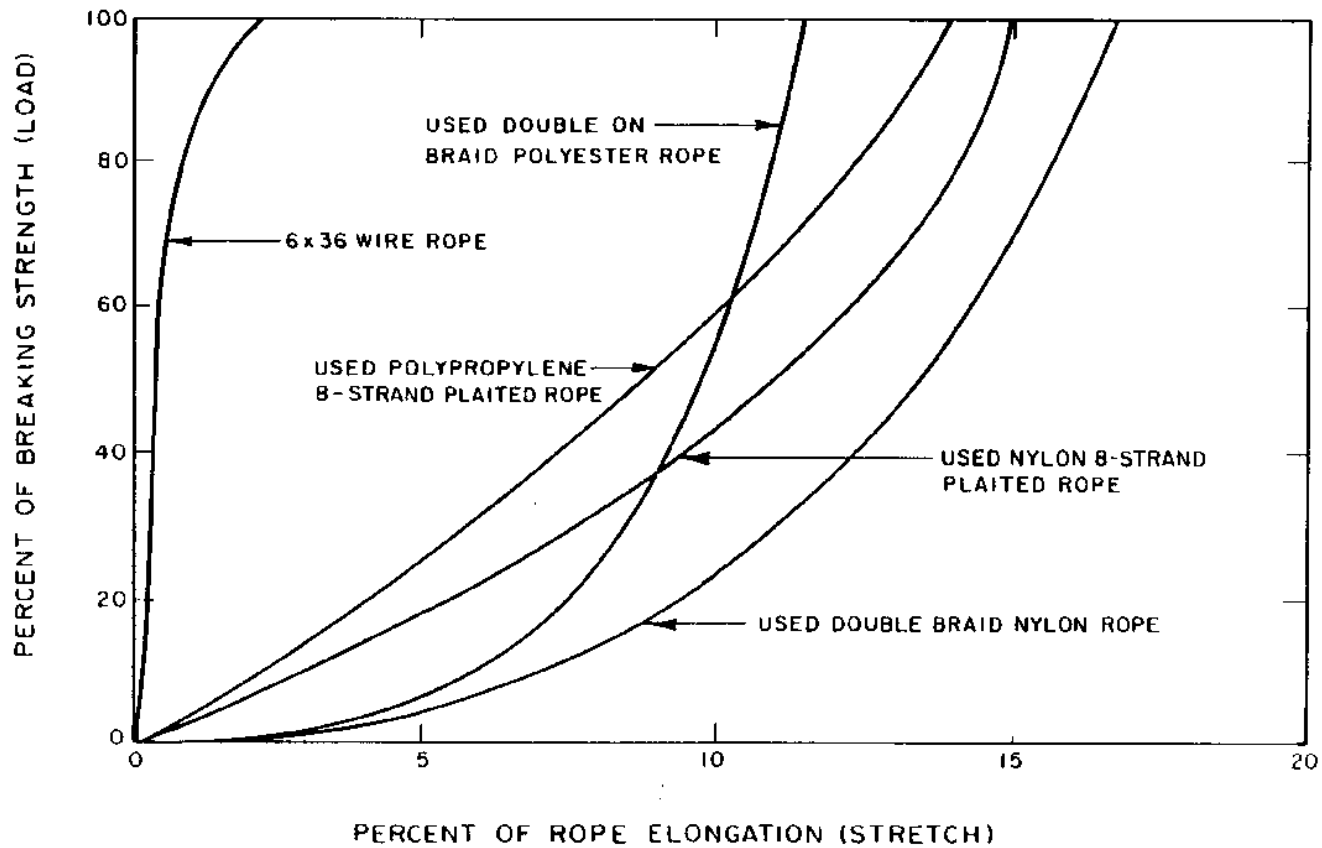
a. Types of Mooring Lines. There are four types of mooring lines used to secure a vessel to a fixed mooring: natural-fiber rope, synthetic-fiber rope, wire rope, and mooring chain. Natural-fiber, synthetic-fiber, and wire rope are most often used at fixed moorings which service active vessels. Mooring chain may be used to moor inactive vessels.

b. Characteristics of Mooring Lines. The most important characteristics of a mooring line are its strength, elasticity, and construction.

(1) Strength. For a given rope diameter, wire rope is the strongest, followed by synthetic-fiber rope and then natural-fiber rope. Breaking strengths of several types of mooring rope are given in Tables 5 through 9 of DM-26.6, Section 4.

(2) Elasticity. The elasticity of mooring rope can be summarized in a plot of the percent of breaking strength (load) versus percent of rope elongation (stretch). Figure 7, which presents schematic load-elongation curves for various types of mooring rope, indicates that wire rope is considerably less elastic than the other rope types. The curves in Figure 7 are representative of "used" rope (which has undergone an initial, nonrecoverable elongation). Elasticity of mooring rope varies among manufacturers; hence, it is necessary to obtain load-elongation curves of "used" rope directly from the manufacturer.

Most synthetic mooring lines are polyester, polypropylene, or nylon, or a combination of these materials. Kelvar rope is also available, but due to its relative inelasticity, it may not be desirable for mooring installations (Flory et al., 1977).



NOTE: THESE TYPICAL CURVES ARE PRESENTED FOR COMPARISON PURPOSES ONLY. CURVES WILL VARY WITH MANUFACTURER.

(AFTER OCIMF, 1977)

FIGURE 7

Typical Load-Elongation Curves for Various Types of Mooring Ropes

(3) Construction. Synthetic ropes vary in type of construction. For information on rope construction, see Flory et al. (1977) and Tables 5 through 9 in DM-26.6. In general, eight-strand and double-braid rope are preferred for use in moorings (Flory et al., 1977). Three-strand rope is not recommended as it has a tendency to hockle. Hockles, which greatly reduce the strength of a rope, result from twisting a laid rope in a direction opposite to the direction of the lay. Hockles resemble knots in a rope.

c. Design. A vessel normally carries its own mooring lines; consequently, fixed-mooring design seldom involves sizing mooring lines. However, the size, length, composition, and arrangement of mooring lines affect fixed-mooring design. Therefore, it is generally necessary to determine the type and arrangement of mooring lines carried by the vessel(s) for which the fixed mooring is designed.

d. Load Equalization. A load-equalization system consists of an arrangement of sheaves through which a continuous line passes. The system is designed to equalize tension in breast lines and prevent overloading of one line. Load-equalization systems have been used to moor inactive vessels at the U.S. Naval Shipyard, Bremerton, Washington.

4. DECK FITTINGS. Deck fittings are used to secure mooring lines to mooring and breasting structures. Some common deck fittings are described below.

a. Bollards and Bitts. A bollard is a short, steel column with a base plate. Bollards are used to secure mooring lines to mooring and breasting structures. They are available in various shapes and for various load capacities. A bitt is similar to a bollard except that the bitt is a double column. For further discussion and drawings of bollards and bitts, refer to DM-25.1, Section 6.

b. Quick-Release Hooks. A quick-release hook is a device designed to allow a mooring line to be released from the hook by pulling a lever arm on the hook with a tag line from the vessel. Quick-release hooks allow a vessel to depart from its berth without shore assistance. For further discussion and drawings of quick-release hooks, refer to DM-25.1, Section 6.

c. Capstans. A Capstan is a winch with vertical spindles which are used to pull mooring lines from a vessel to shore. Capstans are necessary when the mooring line cannot be retrieved by hand. For further discussion and drawings of capstans, refer to DM-25.1, Section 6.

5. SEPARATORS. Separators are used in fixed moorings to prevent damage due to movement of berthed vessels. Separators may be used between the vessel and breasting structures, as shown in Figure 1, or between adjacent vessels when they are moored in groups. For further discussion and drawings of typical separators, see DM-25.1, Section 7.

6. ACCESS TRESTLES AND CATWALKS. Access trestles, provided at most fixed moorings, are used for transfer of cargo and personnel from vessel to shore.

Access treaties are typically arranged as shown in Figure 1. Catwalks are generally provided for access by pedestrians to mooring and breasting structures, as shown in Figure 1. For more discussion on access facilities, See DM-25.1, Section 8.

7. METRIC EQUIVALENCE CHART. The following metric equivalents were developed in accordance with ASTM E-621. These units are listed in the sequence in which they appear in the text of Section 2. Conversions are approximate.

40 feet = 12.2 meters
30 kips = 13 608 kilograms
35 feet = 10.7 meters

Section 3. BASIC DESIGN PROCEDURE

1. FIXED-MOORING DESIGN. Design of a fixed mooring consists of three major steps: determination of the mooring layout, evaluation of environmental conditions and associated loads, and design of mooring components. A flow chart outlining the design process is shown in Figure 8. This section discusses each element of the design process qualitatively. Specific design procedures are given in Section 4.

2. DETERMINATION OF MOORING LAYOUT.

a. Mooring Site. Fixed moorings should be located at well-protected sites in order to minimize environmental loads. Most fixed moorings are located within harbors. Wherever possible, the mooring should be oriented so that the longitudinal axis of the vessel is parallel to the direction of the prevailing winds, waves, and/or currents.

b. Vessel Type. The vessel(s) expected to use the mooring must be determined. Most moorings are designed to accommodate several vessel types. Vessel characteristics, including length, breadth, draft, displacement, broadside wind area, and frontal wind area, must be determined for each of these vessels. These characteristics are presented in Tables 2, 3, and 4 of DM-26.6, Section 3, for fully loaded and light-loaded conditions.

c. Mooring Configuration. Figure 9 shows a typical fixed mooring. The configuration of breasting structures, mooring structures, and mooring lines depends upon mooring usage; space available for mooring; size of vessels to be accommodated; environmental conditions; mooring and berthing loads; tolerance for vessel movement; number, type, and size of mooring lines available on vessels; location of the attachment of the mooring lines on the vessel; preferential existing ship traffic patterns and turning-circle procedures of the local harbor; and power or other existing utility accessibility. The book of plans for a particular vessel, which provides information on mooring-line attachment points (such as chocks, winches, and bollards), can be obtained from the shipyard responsible for that vessel.

(1) Breasting Structures. A minimum of two breasting structures are normally required at a fixed mooring. Breasting-structure location affects the amount of berthing energy which must be absorbed by the fendering system of the mooring. Costa (1973), in a theoretical analysis of the dynamics of berthing, showed that the amount of berthing energy transmitted to a fender (and breasting structure) decreases as the distance between the center of gravity of the vessel and the point of contact between the fender and the vessel increases. Therefore, the designer should place breasting structures as far apart as possible. However, the fenders on the breasting structures must contact the parallel middle body of the vessel. Piaseckyj (1977) reported that the most common spacing of breasting structures was 30 percent of the overall length (LOA) of the berthing vessel, but that spacing from 22 to 50 percent of the overall length has been used. Values from 30 to 50 percent of overall length of the vessel are recommended. (See Figure 9.)

(2) Mooring Structures. Mooring structures should be placed symmetrically about the transverse centerline of the mooring in order to obtain a balanced distribution of mooring loads. Mooring structures should be

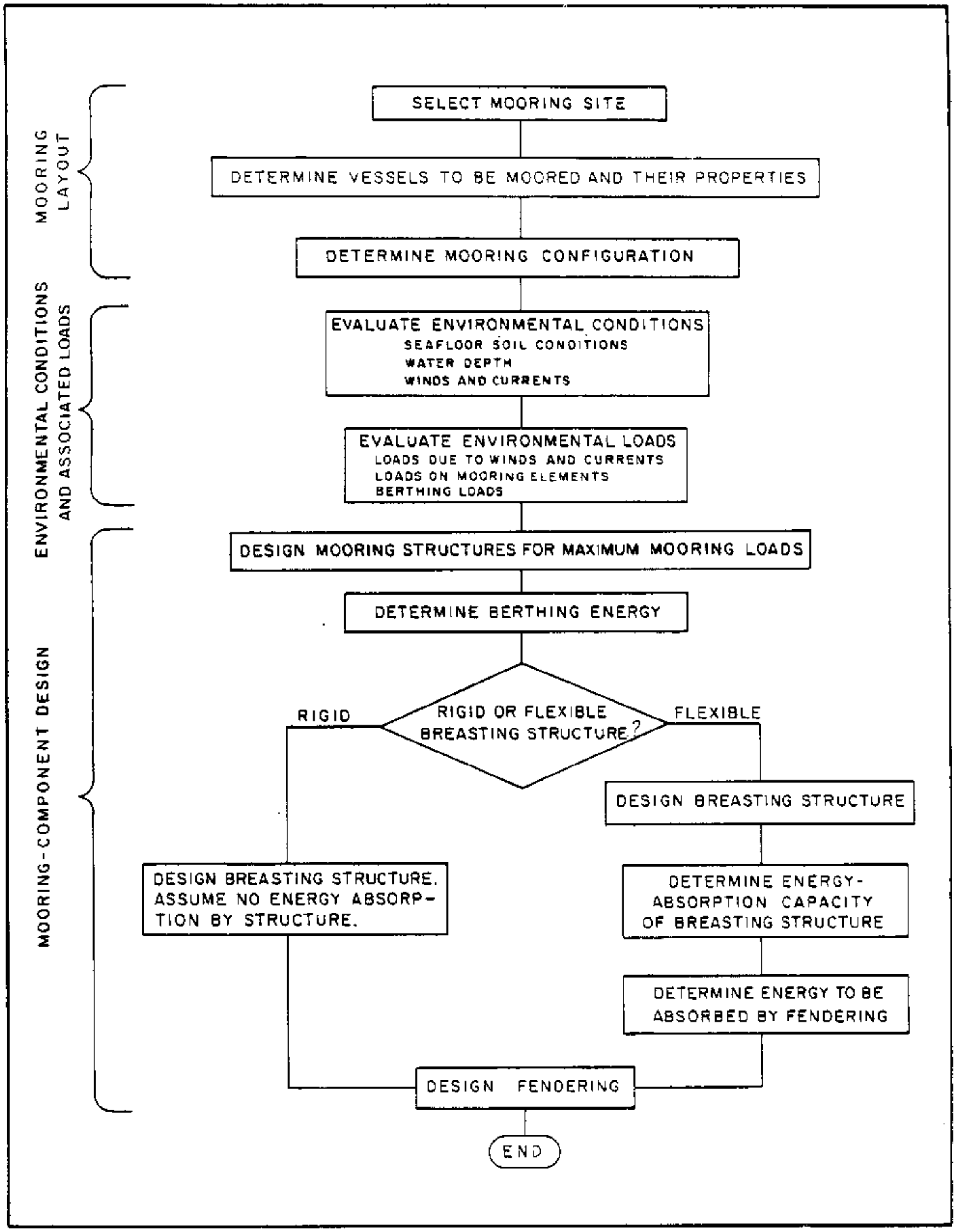


FIGURE 8
Basic Design Procedure for a Fixed Mooring

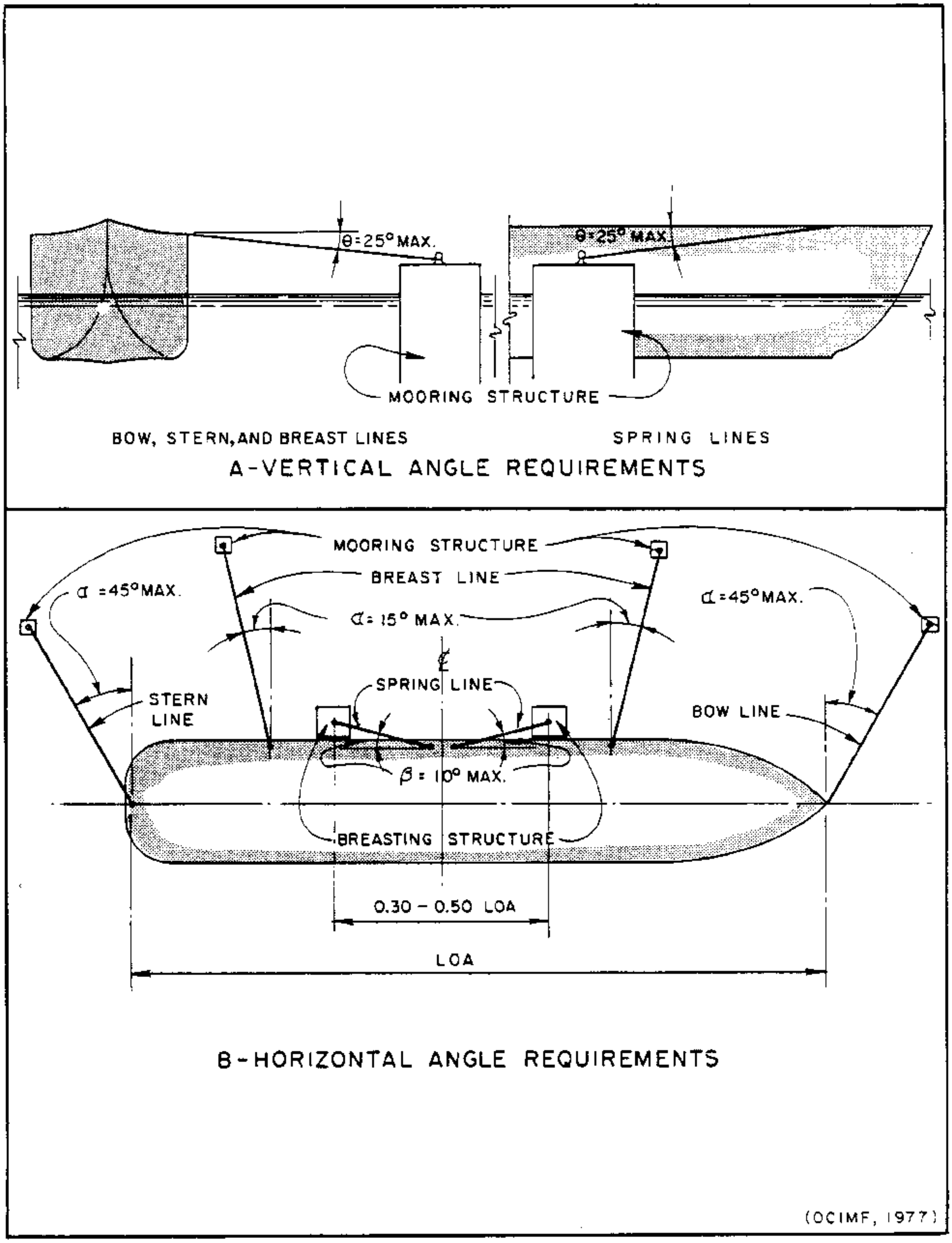


FIGURE 9
Line Angles for a Typical Fixed Mooring

located so that the mooring lines are parallel to the load to be restrained. Small vessels may require only two mooring structures, while larger vessels may require four or more. Mooring-structure decks should be located 5 feet above the highest water level under operational conditions (including tides, storm surge, and waves).

(3) Mooring Lines. Figure 9 shows angle requirements for bow, stern, breast, and spring lines for a typical fixed mooring. Maximum mooring-line angles should be observed for an efficient mooring-line arrangement. Mascenik (1976) suggests bow and stern lines are relatively inefficient in restraining a moored vessel due to poor orientation and long length (higher elasticity). In many cases, well-arranged breast and spring lines can provide an efficient mooring within the length of the moored vessel. However, in some cases, bow and stern lines may be required to assist the vessel during berthing maneuvers.

(a) Bow, stern, and breast lines. Bow, stern, and breast lines are provided to resist lateral mooring loads. For bow, stern, and breast lines, the vertical angle, [theta], with the horizontal should be 25 degrees or less. (See Figure 9A.) Vertical angles of lines depend upon the height of the mooring structure and the mooring-line length. Bow, stern, and breast lines are more efficient in resisting lateral load for smaller vertical angles.

For bow and stern lines, the horizontal angle, [alpha], with the transverse centerline of the vessel should be 45 degrees or less. (See Figure 9B). For breast lines, the horizontal angle, [alpha], with the transverse centerline of the vessel should be 15 degrees or less.

(b) Spring lines. Spring lines resist longitudinal loads. For spring lines, the vertical angle, [theta], with the horizontal should be 25 degrees or less. (See Figure 9A.) Spring lines are more efficient in resisting longitudinal load for smaller vertical angles. The horizontal angle, [beta], with the longitudinal axis of the vessel should be 10 degrees or less. (See Figure 9B.)

(c) Effect of tide and vessel displacement. Line angles are affected by changes in tide level and changes in vessel displacement (loaded versus ballasted conditions). The designer should make sure that line-angle requirements are maintained for anticipated fluctuations in tide level and vessel displacement. Variations in tide level and vessel displacement can result in increased mooring-line loads unless the lines are tended (heaved in or let out at various tide levels).

The effect of tide on mooring-line tension is illustrated in the following example. A 100-foot used polypropylene (8-strand) mooring line has a vertical angle, [theta], of 10 degrees at low tide. The line has a pretension of 5 percent of its breaking strength, which, according to the load-elongation curve in Figure 7, corresponds to a 1-percent elongation (99-foot unloaded length). If the vessel rises 8 feet at high tide and the mooring line is not tended, the line will stretch to a length of 103.3 feet (4.3-percent elongation). From Figure 7, the mooring-line load corresponding to 4.3-percent elongation is 21 percent of breaking strength. Thus, the increase in tide level increases the mooring-line load 420 percent from its low-tide pretension. If a wire line were used instead of the polypropylene line, it would have reached its breaking strength when it stretched to 101.1 feet (2.1-percent extension). It is clear that tide level has an important effect upon mooring-line loads, even in the absence of applied wind and current loads. Therefore, the effect of tide on mooring loads must be investigated.

(d) Effect of mooring-line composition. Fixed moorings which incorporate wire lines are "stiff" moorings, which allow relatively little movement of the moored vessel under applied loading. This is advantageous at some mooring facilities where unloading operations require minimal vessel motion. The disadvantages of fixed moorings incorporating wire lines are as follows: the wire lines fire more difficult to tend than synthetic lines, variations in tide levels can dramatically increase line loads, and the "stiff" mooring may respond poorly to dynamic loads.

Fixed moorings which incorporate synthetic lines (that is, lines composed of nylon, polypropylene, or polyester) are "soft" moorings, which permit relatively large movement of the vessel under applied loading. Synthetic lines are easier to handle than wire lines. Also, an increase in line load due to a variation in tide level is not as severe in a synthetic line as it is in a wire line. However, fixed moorings incorporating synthetic lines may allow large vessel movements under applied loading.

Wire lines fitted with, 35 to 50 feet of synthetic line on the shore end or vessel end of the line have been used at some commercial mooring facilities. Wire lines fitted with these "synthetic tails" are easier to handle than wire lines alone; furthermore, these tails give added elasticity to wire lines, which may provide for a more favorable response to dynamic loads. Finally, because they stretch, wire lines fitted with synthetic tails are not subject to extreme variations in line load from tidal variations as are wire lines without tails. However, Mascenik (1976) reported that the use of wire tails is questioned because some parting of tails has occurred. Where synthetic tails are used, they should be sized with a breaking strength of 140 percent of the breaking strength of the wire rope (Mascenik, 1976).

3. EVALUATION OF ENVIRONMENTAL CONDITIONS AND ASSOCIATED LOADS.

a. Environmental Conditions. Environmental conditions important to mooring design include seafloor soil conditions, water depth, winds, currents, and waves.

(1) Seafloor Soil Conditions. Seafloor soil conditions must be evaluated in order to properly select and design fixed moorings. Some types of mooring and breasting structures can be eliminated based upon geotechnical considerations. For example, mooring platforms may be more desirable for relatively soft soils than mooring cells. For information concerning geotechnical investigations, evaluation of seafloor soil conditions, and design of foundations, see DM-7.1, DM-7.2, and DM-7.3.

(2) Water Depth. Mooring-site bathymetry and water-level fluctuations must be investigated to assure that there is adequate depth for vessels using the mooring, to determine mooring-line geometry, to determine line-load fluctuations due to tidal variations, and to determine current loads on the

vessel. Current loads are sensitive to the ratio of vessel draft to water depth.

Factors contributing to water-level fluctuations include astronomical tides, storm surge, seiche, and tsunamis. These phenomena are discussed in DM-26.1, Section 2. The design water level at a mooring site is controlled primarily by the astronomical tide. However, the other factors mentioned above can be significant and must be investigated.

Harbor sedimentation produces significant variations in bottom elevation. The potential for long-term changes in bottom elevation must be investigated. Fixed moorings should be located in areas which require minimal maintenance dredging. Harbor shoaling and current Navy dredging requirements are discussed in DM-26.3.

(3) Winds. Wind loads on moored vessels are important to fixed-mooring design. The duration of a wind event affects the magnitude of the wind-induced load on the moored vessel. A wind gust with a speed 50 percent higher than the average windspeed, but lasting only a couple of seconds, may cause little or no response of a moored vessel. On the other hand, repeated wind gusts with only slightly higher-than-average windspeed, with duration near the natural period of a vessel-mooring system, can excite the vessel dynamically and result in mooring-line loads in excess of the mean mooring-line loads. Hence, it is necessary to establish a standard wind duration which will provide reliable estimates of steady-state, wind-induced loads on moored vessels. Winds of longer or shorter duration should be corrected to this level. Based upon analytical considerations and previous experience, a 30-second-duration wind speed has been chosen as the standard for determining wind-induced loads on moored vessels. This value is less than the 1-minute duration recommended by Flory et al. (1977) for large tankers, but seems appropriate for naval vessels.

The most reliable method for determining design windspeed at a site is to analyze wind measurements taken at or near the site over an extended period of time. Windspeeds are reported according to a variety of definitions, including fastest-mile, peak-gust, 1-minute average, 10-minute average, and hourly average. The fastest-mile windspeed is defined as the highest measured windspeed with duration sufficient to travel 1 mile. For example, a reported fastest-mile windspeed of 60 miles per hour is a 60-mile-per-hour wind that lasted for 1 minute. On the other hand, a fastest-mile windspeed of 30 miles per hour would have lasted 2 minutes. Peak-gust windspeed measures a wind of high velocity and very short duration.

Fastest-mile and peak-gust windspeeds are generally the most useful measurements for determining design windspeeds at a mooring site, for several reasons. First, they represent the highest wind recorded during a period of observation. Secondly, they can be converted to a 30-second-duration wind-speed. Finally, these measurements are available at most naval facilities. (This is particularly true for the peak-gust windspeed).

(a) Data sources. Sources for windspeed data are summarized in Table 3, Section 4.

(b) Windspeed adjustments. Windspeed data must be adjusted for elevation, duration, and overland-overwater effects in order to represent conditions at the mooring site. First, the windspeed must be adjusted to a standard elevation; this is particularly true when comparing data measured at several locations near the mooring site. The design windspeed must also be adjusted to an elevation suitable for determining wind loads on a moored vessel dependent upon the geometry of that vessel. However, for the purposes of determining the design windspeed, the wind measurements are corrected to a standard elevation of 10 meters (33.33 feet). Secondly, the windspeed must be corrected to a 30-second-duration windspeed. Finally, because most wind measurements are taken at inland sites over land, rather than at the mooring site over water, it is necessary to correct for overland-overwater effects. These adjustments must be made before the probabilistic analysis, discussed below, is done. Procedures for making the above adjustments are given in Section 4.

(c) Determining maximum windspeed. In order to achieve an economical and safe mooring design, the maximum windspeed is determined using probabilistic methods. Probabilistic analysis of wind measurements taken at or near a site will provide an estimate of how frequently a given windspeed will occur or be exceeded (probability of exceedence) during the design life of the mooring. The return period of a windspeed, estimated from the probability of exceedence, is defined as the average length of time between occurrences of that windspeed. The concept of statistical return period is useful for determining the design windspeed. For example, a 50-year design windspeed indicates that a windspeed equal to or greater than the 50-year design windspeed will occur, on the average, once every 50 years. The 50-year windspeed (windspeed with a 50-year return period) is used for design of fixed moorings, although estimates of more-frequent (1-year, 10-year) and less-frequent (75-year, 100-year) windspeeds are useful for planning purposes. Operational criteria may require that a vessel leave a mooring at a given windspeed which is less than the design windspeed. In this case, the fixed mooring would be designed for the operational criteria unless there is a possibility that, under some circumstances, a vessel would remain at the mooring during higher winds.

Procedures for determining the probability of exceedence and the return period for various windspeeds based upon measured data are presented in Section 4. The results of a probabilistic analysis can be conveniently presented as shown in Figure 10, which is an example plot of probability of exceedence (left ordinate) and return period (right ordinate) versus 30-second windspeed (abscissa).

(4) Currents. Current can play a major role in the layout and design of a fixed mooring. Current loads on a moored vessel can be very high. To reduce these loads, it is desirable to moor vessels headed into the current. Currents may also affect the ability of a vessel to maneuver into the mooring.

(a) Tidal currents. Tidal currents are the most common type of current in Navy harbors. They range in speed from less than 1 knot to about 6 knots. Ideally, the designer should obtain data on current velocity and direction, and on the variation of these parameters, both areally and with

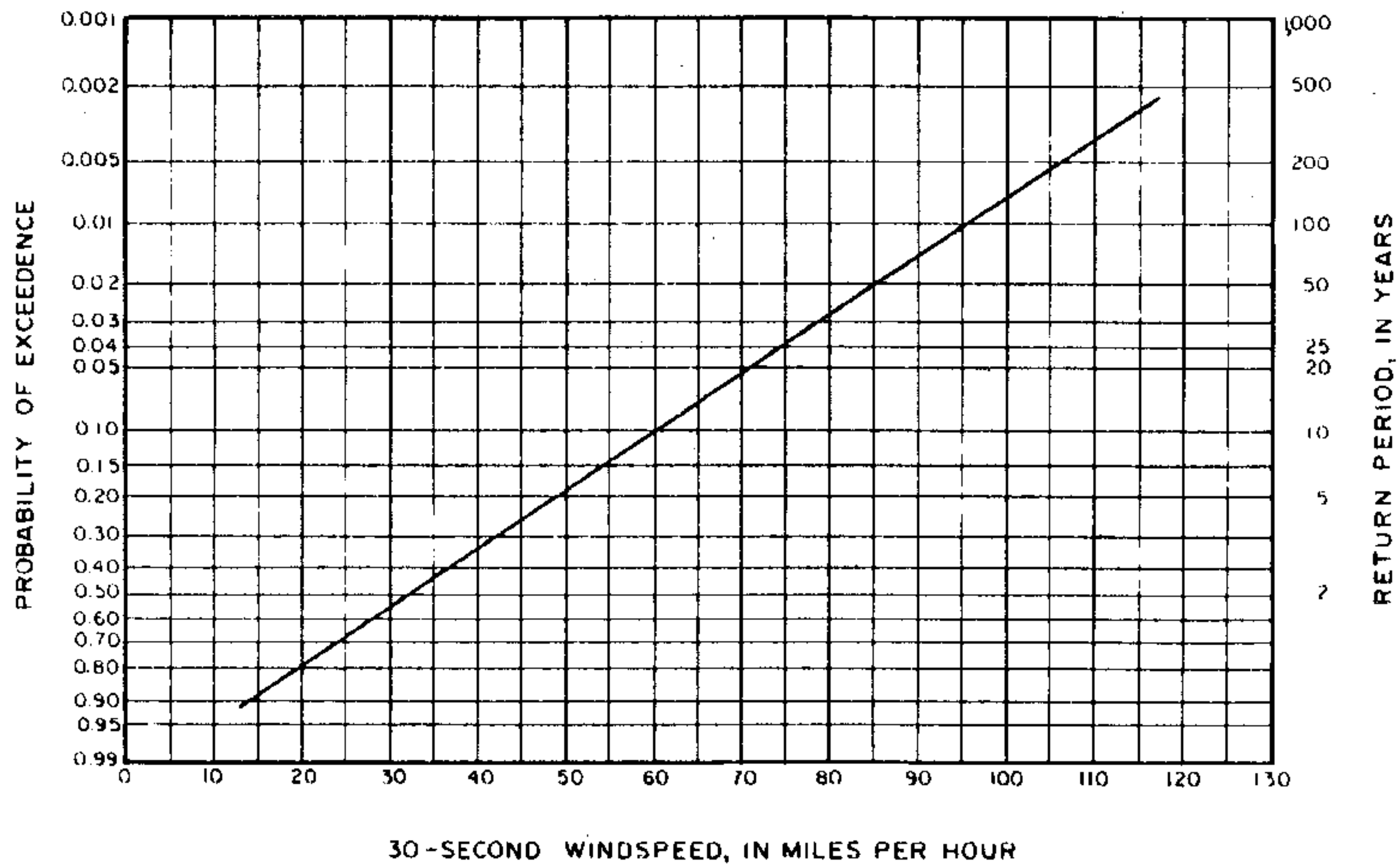


FIGURE 10
Example Plot of Probability of Exceedence and Return Period Versus 30-Second Windspeed

depth. Determination of tidal currents is best achieved by direct measurement. Where measurements are not available, current speeds may be estimated using physical or numerical models. If the harbor geometry is simple and other appropriate assumptions are valid, the procedures presented in DM-26.1, Subsection 2.9, may be used to determine tidal-current velocities.

Estimates of the peak flood and ebb tidal currents for numerous locations on the Atlantic coast of North America and the Pacific coasts of North America and Asia are published in tables by the U.S. Department of Commerce, National Ocean Survey (NOS). The published values are for specific locations, generally within harbors. Because tidal currents can vary significantly within a harbor, currents obtained from the NOS tidal-current tables must be used with caution unless they are values reported directly at the mooring site.

Tidal currents vary in speed and reverse direction during the tidal cycle, but the forces induced by tidal currents are normally treated statically. Exceptions may occur, and these must be investigated on a site-by-site basis.

(b) River discharge. Currents resulting from river discharge can also be significant. Estimates of currents due to river discharge are best achieved by direct measurement or by analysis of existing flow records.

(c) Wind-driven currents. Wind-driven currents are surface currents which result from the stress exerted by the wind on the sea surface. Wind-driven currents generally attain a mean velocity of about 3 to 5 percent of the mean windspeed at 10 meters above the sea surface. The magnitude of the current decreases sharply with depth. The direction of the current is roughly that of the wind. Wind-driven currents are seldom a factor in protected harbors, but they must be investigated when they exceed 0.5 knots. Methods for estimating wind-driven currents are presented in Bretschneider (1967).

(d) Probability of currents. The probabilistic nature of current speed and direction at a given site should be taken into account. A probabilistic estimate of the speed and direction of tidal currents can be determined only by extensive field measurements or through physical or numerical modeling; however, neither time nor budget is normally available to generate these data. Therefore, maximum flood and ebb currents should be used for fixed-mooring design unless more detailed information is available. This design criterion is reasonable for two reasons. First, these currents occur often; thus, there is a reasonable probability that these currents will occur simultaneously with the design windspeed. Secondly, while a vessel could conceivably be subject to higher current speeds than the peak values, the higher currents would be of short duration. Hence, the impact of higher-than-average peak flood or ebb current speeds would not be too great. The statistical probability of river flows, which may be obtained from records of peak yearly flood flow, should be analyzed using the probabilistic methods described for wind in Section 4.

(5) Waves. Waves can exert significant dynamic loads on moored vessels and mooring elements sited in unprotected waters. This manual assumes moorings are sited in a protected harbor; therefore, dynamic

analysis of moored vessels is not considered herein. If there is doubt as to whether or not a mooring is located in a protected harbor, or if prior experience at the site indicates that wave action may affect mooring design, then wave conditions must be investigated.

Waves important to the design of fixed moorings fall into three categories: short waves, long waves, and waves generated by passing vessels. Short waves are wind-generated waves with periods of 20 seconds or less; those generated locally are referred to as seas and those generated great distances away are called swell. Moorings located in protected harbors are generally sheltered from short waves by structures, such as breakwaters or jetties. However, if the mooring is located near the harbor opening, it may be exposed to sea and swell, and the assumption of a protected harbor may not be valid. If the harbor is sufficiently large, local winds may generate seas within the harbor of sufficient size to affect the moored vessel.

Waves with periods ranging from greater than 20 seconds to several minutes are classified as long waves. Long-wave energy is capable of causing oscillations in a harbor. This phenomenon, called seiche, is discussed in DM-26.1, Subsection 2.8.

Waves generated by passing vessels can be important to the design of a fixed mooring. This is particularly true when the mooring is sited in a narrow channel where other vessels pass close to the moored vessel.

In general, the most reliable methods for determining design-wave conditions use measurements taken at the site; however, this information is seldom available. Consequently, the methods described in DM-26.2, Sections 1 and 2, for obtaining wave data and estimating short-wave conditions must be used. Methods for estimating the possibility of mooring problems associated with long waves are lacking. It is best to rely on previous experience at the mooring site. In the same way, potential for problems associated with waves generated by passing ships must be determined based on previous experience.

(6) Unusual Conditions. The potential for the occurrence of unusual conditions must be investigated. Design may require significant deviations from the standard procedures presented in this manual. Table 2 presents a summary of unusual environmental conditions which require analysis not covered by this manual. If the occurrence of these conditions is probable, the designer should consult the Naval Civil Engineering Laboratory (NCEL) or CHESNAVFAC-FPO-1 for specialized mooring designs.

b. Environmental Loads. Wind, currents, and waves produce loads on moored vessels. Static wind and current loads are discussed in detail below. A brief discussion of dynamic loads due to waves follows.

Static loads due to wind and current are separated into lateral load, longitudinal load, and yaw moment. Flow mechanisms which influence these loads include friction drag, form drag, circulation forces, and proximity effects. The predominant force-generating mechanisms are friction drag and form drag. Circulation forces play a secondary role. Proximity effects are important in multiple-vessel moorings and in moorings sited in very restricted channels.

TABLE 2
Unusual Environmental Conditions Requiring Special Analysis

Condition	Special Analysis Required
Waves[1]	>/=1.5 feet for small craft >/=4 feet for larger vessels
Winds	>/=60 knots
Hurricanes and Typhoons[1]	All cases where these are possible
Seiche[1]	Any evidence of seiche based upon prior experience
Currents	>/=3 knots
Tidal Variations	>/=8 feet
Ice	Free-floating ice

[1]Requires dynamic analysis

(1) Load Due to Wind. Loads on moored vessels due to wind result primarily from form drag. The general equation Used to determine wind load is:

$$F_{w} = 1/2 \, \rho_{a} V_{w}^{2} A_{w} C_{DW} \qquad (3\text{-}1)$$

WHERE: F_{w} = load due to wind

ρ_{a} = mass density of air

V_{w} = wind velocity

A_{w} = projected area exposed to wind; may be either side area or end area

C_{DW} = wind-force drag coefficient which accounts for form drag and friction drag

The value of A_{w} differs for lateral load and longitudinal load: the side area is used for determining lateral load, and the end area is used for determining longitudinal load. The wind-force coefficient, C_{DW}, also differs for lateral load and longitudinal load: C_{DW} is a function of the angle at which the wind impinges upon the vessel. The value of C_{DW} is based upon model-test results. Section 4 presents methods for determining the lateral and longitudinal wind-force drag coefficients.

(2) Load Due to Current. Current loads developed on moored vessels result from form drag, friction drag, and propeller drag. Lateral forces are dominated by form drag. Form drag is dependent upon the ratio of vessel draft

to water depth: as the water depth decreases, current flows around, rather than underneath, the vessel. Longitudinal forces due to current are caused by form drag, friction drag, and propeller drag. The general equation used to determine current load is:

$$F_c = 1/2 \rho_w V_c^2 A_c C_{DC} \qquad (3\text{-}2)$$

WHERE: F_c = load due to current

ρ_w = mass density of water

V_c = current velocity

A_c = projected area exposed to current; may be either below-water side or end areas, hull surface area, or propeller area

C_{DC} = current-force drag coefficient

Methods for determining lateral and longitudinal current loads are presented in Section 4. Current-load estimates are not as reliable as those for wind loads. However, the procedures presented in this manual provide conservative results.

(3) Load Due to Waves. Wave-induced loads on moored vessels can dominate wind and current loads for moorings sited in unprotected, high-energy environments. As the mooring site is moved into protected areas, these forces diminish, and the previously discussed wind and current loads begin to dominate. Quantitative analysis of wave-induced forces is beyond the scope of this manual; however, a qualitative discussion is provided to give information on the magnitude, character, and relative importance of wave-induced loads.

The hydrodynamic response of a moored vessel in the presence of waves can be resolved into an oscillatory response and a static response (wave-drift force). The oscillatory response is characterized by vessel movements in six degrees of freedom (three translational: heave, sway, and surge, and three rotational: yaw, pitch, and roll) with associated mooring-line loads that occur with roughly the same period as that of the incoming waves. Theoretical analysis of the oscillatory response of a moored vessel is achieved through the coupled solution of six simultaneous equations of motion for the vessel mooring system. Solution of these equations is complicated. An outline of the solution is presented in DM-26.1, Subsection 2.8. The static wave drift force on a moored vessel in regular waves (that is, in waves with the same height and period) is usually small compared to the oscillatory wave load. However, ocean waves are generally irregular (that is, waves which vary in height and period) and may be characterized by groups of high waves. The static drift force present in regular waves will slowly oscillate with the period of wave grouping in irregular waves. If the period of slow drift oscillation is close to the natural period of the moored-ship system, then large mooring loads may result.

Numerical models have been used to determine wave loading on moored vessels. Some of these numerical techniques are discussed in Van Oortmerssen (1976) and Webster (1982). Physical models, although expensive time-consuming, are considered the most reliable means for determining wave loading (Flory et al., 1977).

(4) Multiple-Vessel Moorings. Wind and current loads on multiple-vessel moorings are greatly influenced by the sheltering effect of the first vessel on leeward vessels. The procedures and data necessary to determine the loads and moments induced on multiple-moored vessels by either wind or currents are extremely limited. The only data that are directly applicable for this purpose were collected at the David Taylor Model Basin (DTMB) shortly after World War II; these were summarized graphically in the previous edition of Design Manual 26. Altmann (1971) noted that these data are not fully applicable to contemporary multiple-vessel mooring problems because only identical vessels were examined and no systematic variation of lateral separation distance was investigated. Altmann (1971) has also indicated a number of deficiencies in the data themselves.

A contemporary multiple-vessel mooring arrangement consists of a tender with one or more identical vessels moored in parallel fashion alongside the tender. There are currently no model-test results for this type of mooring arrangement. Methods for determining loads on vessels in multiple-vessel moorings with both identical and nonidentical vessels are presented in Section 4.

c. Loads on Mooring Elements.

(1) General. Wind and current produce a lateral load, a longitudinal load, and a yaw moment on a moored vessel. Theses loads displace and rotate the vessel relative to its position before the loads were applied (Figure 11). The applied loads are resisted by the mooring system made up of mooring lines, mooring structures, and breasting structures. For static equilibrium, the applied loads must equal the restoring loads of the mooring system, according to the following equations:

$$\sum F_x = 0 \tag{3-3}$$

$$\sum F_y = 0 \tag{3-4}$$

$$\sum M_{C.G.} = 0 \tag{3-5}$$

WHERE: $\sum F_x$ = sum of the applied and restoring loads along the longitudinal axis of the vessel

$\sum F_y$ = sum of the applied and restoring loads along the lateral axis of the vessel

$\sum M_{C.G.}$ = sum of the applied and restoring yaw moments about the center of gravity of the vessel

Applied wind and current loads must be distributed to mooring lines and fenders to determine loads on fixed-mooring structures. Mooring lines, fenders, and fixed-mooring structures deflect under load, and provide a restoring force proportional to deflection. The elasticity of the mooring system (mooring lines, mooring structures, and breasting structures) must be known to evaluate loads on mooring elements.

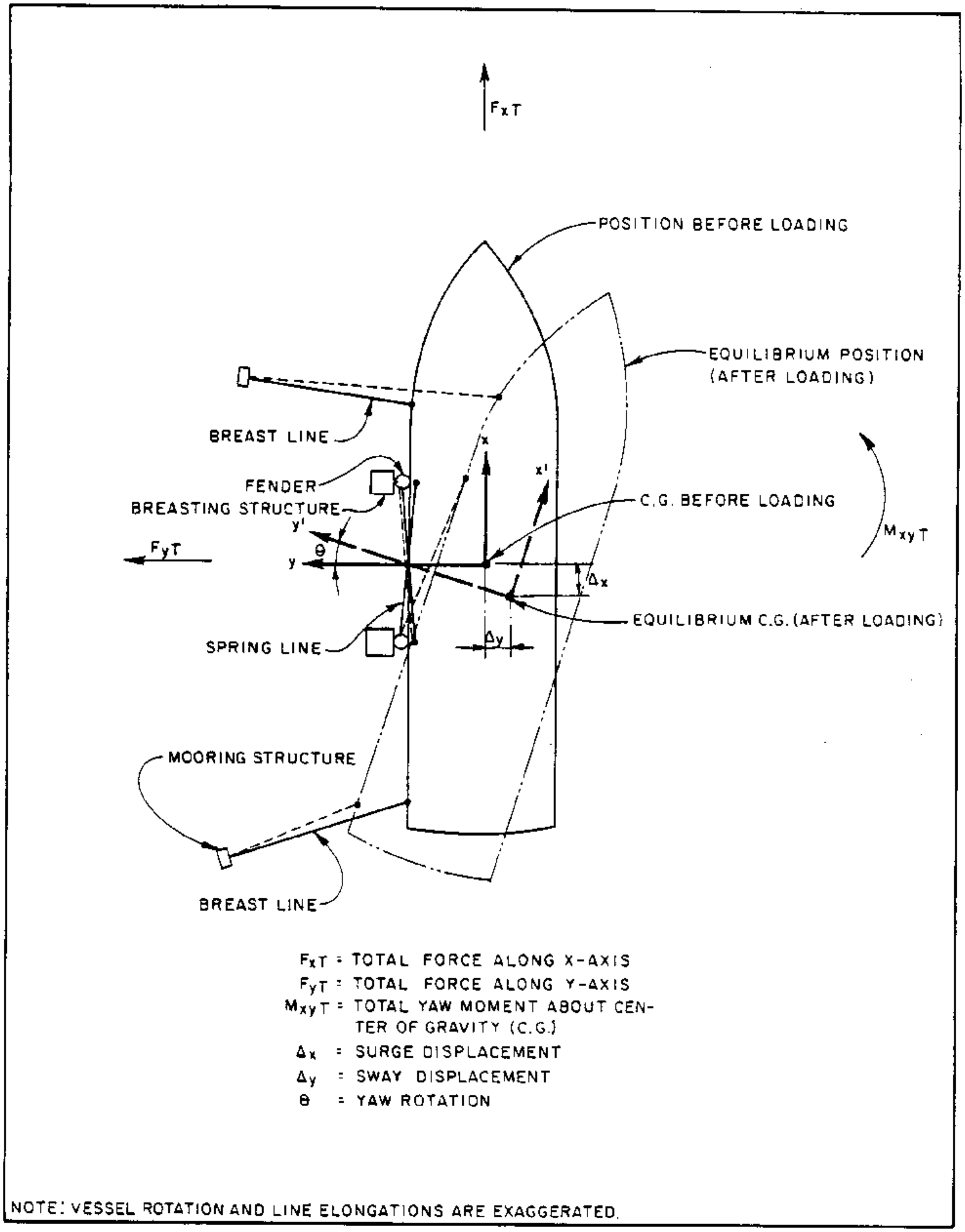


FIGURE 11
Vessel Response to Static Wind and Current Loading

Mooring-line elasticity depends upon line length, diameter, composition, and construction. Longer mooring lines are more elastic than shorter lines of the same material. Larger-diameter lines are less elastic than smaller-diameter lines of the same material. Figure 7 provides a comparison of the elasticity of mooring lines of varying composition. Load-elongation curves similar to those in Figure 7 should be obtained from the mooring-line manufacturer. The effect of mooring-line construction on mooring-line elasticity can be determined from the manufacturer's catalogs.

Mooring-structure elasticity is considerably less than that of the lines attached to the structure. Thus, mooring structures are normally treated as rigid structures.

Breasting-structure elasticity depends upon the characteristics of its fendering system and the characteristics of the structure itself. Information on the elasticity of the fender should be obtained from the manufacturer; some examples may be found in DM-25.1, Section 5. In some cases, the breasting structure may be designed to deflect under loading; if so, the elasticity of the fender-structure system should be determined. (See DM-7).

Loads in mooring lines/mooring structures and breasting structures are determined by finding the equilibrium position of the vessel under applied load, as outlined below:

(a) Determine the total lateral load, longitudinal load, and yaw moment on the vessel due to wind and current.
(b) Determine mooring-line configuration and the properties of each of the mooring lines. Calculate a load-deflection curve for each of the mooring lines.
(c) Determine breasting-structure location and select fenders. Construct a load-deflection curve for each breasting structure.
(d) Assume an initial displacement and rotation of the vessel (new orientation) under the applied load.
(e) Determine the deflection in each of the mooring lines and breasting structures/fenders corresponding to the vessel orientation.
(f) Determine the forces in each of the mooring lines and breasting structures/fenders from the above mooring-line deflections.
(g) Sum the forces and moments according to the above equations, accounting for all the mooring-line loads, breasting-structure/fender loads, and applied wind and current loads.
(h) Determine if the restraining forces and moments due to all the mooring-line loads and breasting-structure/fender loads balance out the applied forces and moments due to wind and current.
(i) If the above forces and moments do not balance, then the vessel is not in its equilibrium position under the applied load. A new vessel orientation must be assumed.
(j) Steps (d) through (i) are repeated until the equilibrium position of the vessel is determined.

The above procedure can be solved using the computer program presented in Appendix B of DM-26.5. Simplified methods for determining the mooring-line loads are summarized below.

(2) Simplified Procedure for Determining Mooring Loads on Mooring Elements. The first step in the simplified procedure is to determine the total applied lateral and longitudinal loads and yaw moment and to resolve the applied loads into lateral loads at the bow and stern of the vessel and longitudinal load. Lateral load and longitudinal load are analyzed individually.

Three situations occur in the analysis of lateral mooring loads. First, lateral loads at the bow and stern act in the same direction and move the vessel away from the mooring (Figure 12A). In this case, lateral mooring loads are taken entirely by the mooring lines in tension. Secondly, lateral loads at the bow and stem act in the same direction and move the vessel toward the mooring (Figure 12a). In this case, lateral mooring loads are taken entirely by the breasting structures. Finally, lateral loads at the bow and stern act in opposite directions; lateral load at one end of the vessel is restrained by mooring lines, while lateral load at the opposite end of the vessel is restrained by a breasting structure (Figure 12C). Mooring-load analyses for each of the above situations are described below as Case 1, Case 2, and Case 3, respectively.

(a) Lateral load and yarn moment--Case 1: mooring-line loads. The method used to analyze mooring-line loads is taken from "Guidelines and Recommendations for Safe Mooring of Large Ships at Piers and Sea Islands," (Oil Companies International Marine Forum (OCIMF), 1977). This simplified method is used to determine the distribution of loads in mooring lines. However, it is an approximate method and must be used with judgment. The detailed procedure is given in Section 4.

Limitations of the simplified mooring-line analysis procedure are as follows:

(1) The mooring layout must be reasonably symmetrical.
(2) Vertical mooring-line angles, [theta], must be less than 25 degrees.
(3) Horizontal mooring-line angles, [alpha], on bow and stern must be less than 45 degrees.
(4) Mooring lines must be of identical material, construction, and diameter.
(5) Mooring lines for lateral load (breast, bow, and stern) must be effectively grouped at the bow and stern.
(6) Line loads are assumed to be zero when there is no applied load despite the fact that the lines are assumed to be pretensioned.
(7) Synthetic and natural rope are ignored in the analysis if the vessel is moored with both synthetic or natural rope and wire rope.

This procedure assumes that mooring-line tension is linearly proportional to line extension. In fact, mooring-line tension is generally nonlinearly proportional to line extension. However, when a small pretension is applied to take the slack out of the line, the lines may be assumed to behave

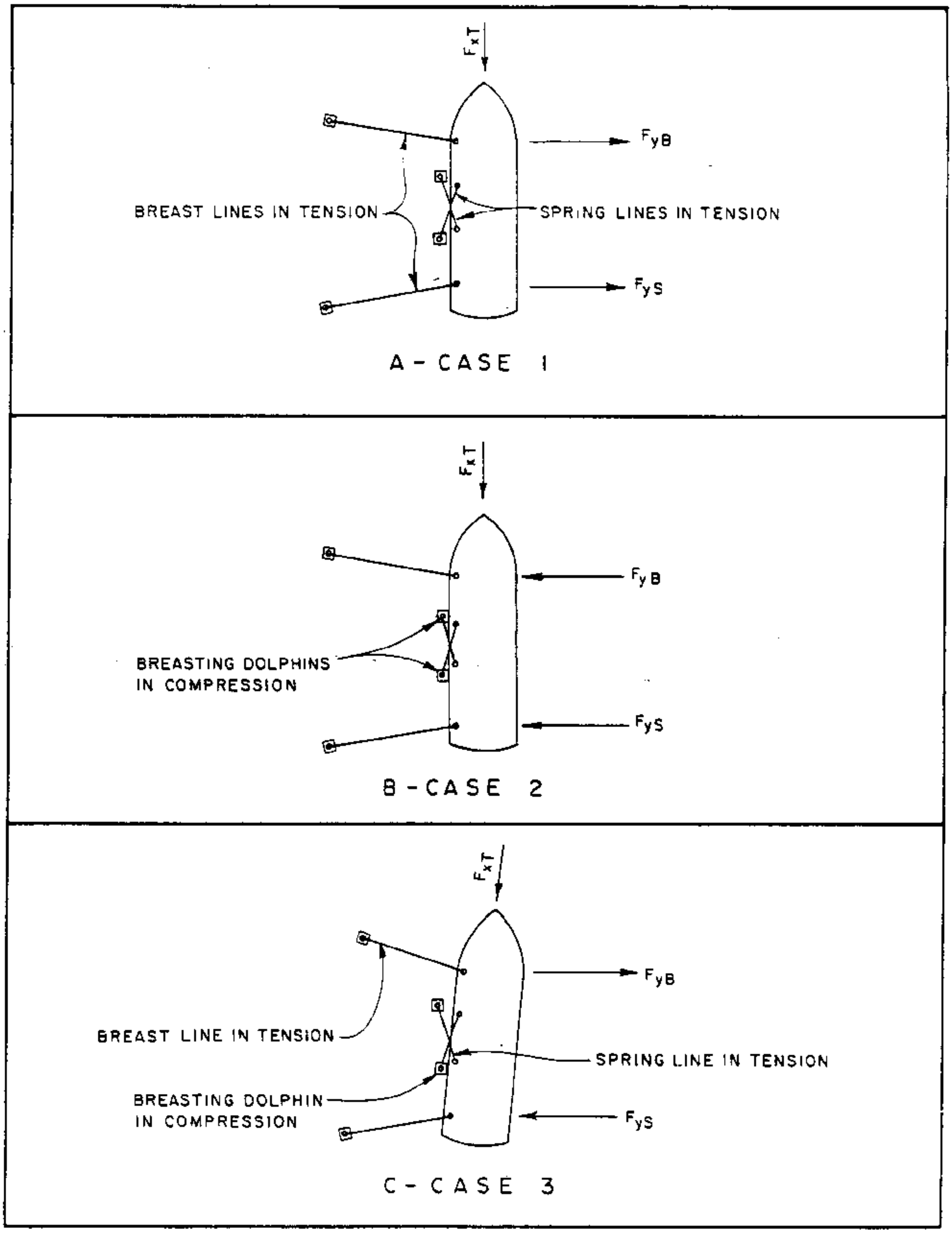


FIGURE 12
Mooring-Load Analysis

linearly. This way, the distribution of loads among the mooring lines depends only upon the mooring geometry.

The tension developed in any one mooring line is proportional to the quantity cos[alpha] cos[theta]/L, where [alpha] is the horizontal angle of the mooring line with the transverse axis of the vessel, [theta] is the vertical angle of the mooring line with the horizontal, and L is the length of the mooring line (Figure 9). The term cos[alpha] cos[theta]/L may be thought of as a stiffness term: the shorter the line, the higher the tension in the line. This is consistent with the fact that shorter lines are less elastic than longer lines of identical material; thus, shorter lines assume more of the load than longer lines. The component of tension in the lateral direction is proportional to cos^{2}[alpha] cos^{2}[theta]/L. The total load in a mooring line is the sum of the distributed applied load and the mooring-line pretension.

The simplified procedure assumes that lateral loads are restrained primarily by breast lines and, to a lesser degree, by bow and stern lines. The lateral restraint lines are assumed to be grouped near the bow and near the stern of the vessel. This allows one to analyze mooring lines at the bow and at the stern separately.

(b) Lateral load and yaw moment--Case 2: breasting-structure loads. When the applied loads move bath the bow and stern of the vessel toward the fixed-mooring structures, the load is restrained by the breasting structures. Lateral load is assumed to be taken by the breasting structures. The mooring loads on the breasting structures are determined using the principle of static equilibrium. Typical fixed-mooring configurations have two breasting structures, as shown in Figure 12B. A simple approach to analysis assumes that the vessel is "simply supported" by the breasting structures, with the applied lateral load acting at a distance halfway between the structures. Detailed solution procedures are presented in Section 4.

(c) Lateral load and yaw moment--Case 3: combination of mooring-line and breasting structure loads. For certain combinations of applied load, a portion of the applied lateral load is restrained by a breasting structure, while the remaining portion of the lateral load is restrained by the mooring lines at the opposite end of the vessel. This requires an analysis consisting of a combination of the above two cases. The lateral load at one end of the vessel is assumed to be taken entirely by the breasting structure as a point load. The lateral load on the opposite end of the vessel is assumed to be, taken entirely by the mooring lines grouped at that end of the vessel. Analysis of load distribution among the mooring lines is carried out using the procedure described under Case 1, above. The lateral load taken by the breasting structure is determined by taking moments about the breasting structure accounting for each of the mooring lines which provide lateral restraint. This analysis provides reasonable results; details of this procedure are provided in Section 4. For final design at critical installations, the computer program provided in Appendix B of DM-26.5 should be used.

(d) Longitudinal load. Longitudinal load is restrained by spring lines. The method for determining the distribution of longitudinal load among, spring lines is similar to that for bow, stem, and breast lines in Case 1. However, the angle, [alpha], used for bow, stern, and breast replaced by [beta] (the horizontal angle of the line with the longitudinal axis of the vessel). Detailed solution procedures are presented in Section 4.

(e) Maximum mooring loads. The maximum loads on mooring lines (sum of applied loads and pretension) and breasting structures must be determined. Maximum loads are determined by evaluating load due to combinations of wind, current, tide level, and vessel displacement.

d. Loads on Spud Moorings. The motion of a vessel in a spud mooring is restrained by spuds. The attachments for the vessel are considered to be rigid; therefore, the process of distributing mooring loads is simplified. The following procedure is used to analyze mooring loads on spud moorings. Details of this procedure are given in Section 4.

(1) Determine the total longitudinal force, lateral force, and yaw moment.
(2) Establish an initial layout of the spuds. The spuds should be located symmetrically around the centerline of the vessel.
(3) Distribute the longitudinal load equally among the shear spuds.
(4) Distribute the lateral load and yaw moment to each of the tension spuds by dividing the lateral load by the number of tension spuds and resolving the moment to these spuds using their respective moments of inertia (about the center of gravity of the spuds).

Figure 13 shows a tension-spud mooring at extreme high water (minimum dock draft) and at extreme low water (maximum dock draft). At extreme high water (Figure 13A), the bottom end of the spud must extend at least 4 feet below the centerline of the shoe. At extreme low water (Figure 13B), the top end of the spud must extend at least 4 feet above the centerline of the shoe. The above clearances must also be satisfied for shear spuds and their guides.

e. Berthing Loads. A berthing vessel will approach a fixed mooring with a certain kinetic energy, called the berthing energy. This berthing energy must be absorbed by the berthing structure and/or its fendering system. The most common method for determining berthing energy is to use the energy equation:

$$KE_B = 1/2\ W/g V_N^2 C_B C_H \quad (3\text{-}6)$$

WHERE: KE_B = berthing energy (kinetic energy of docking vessel)

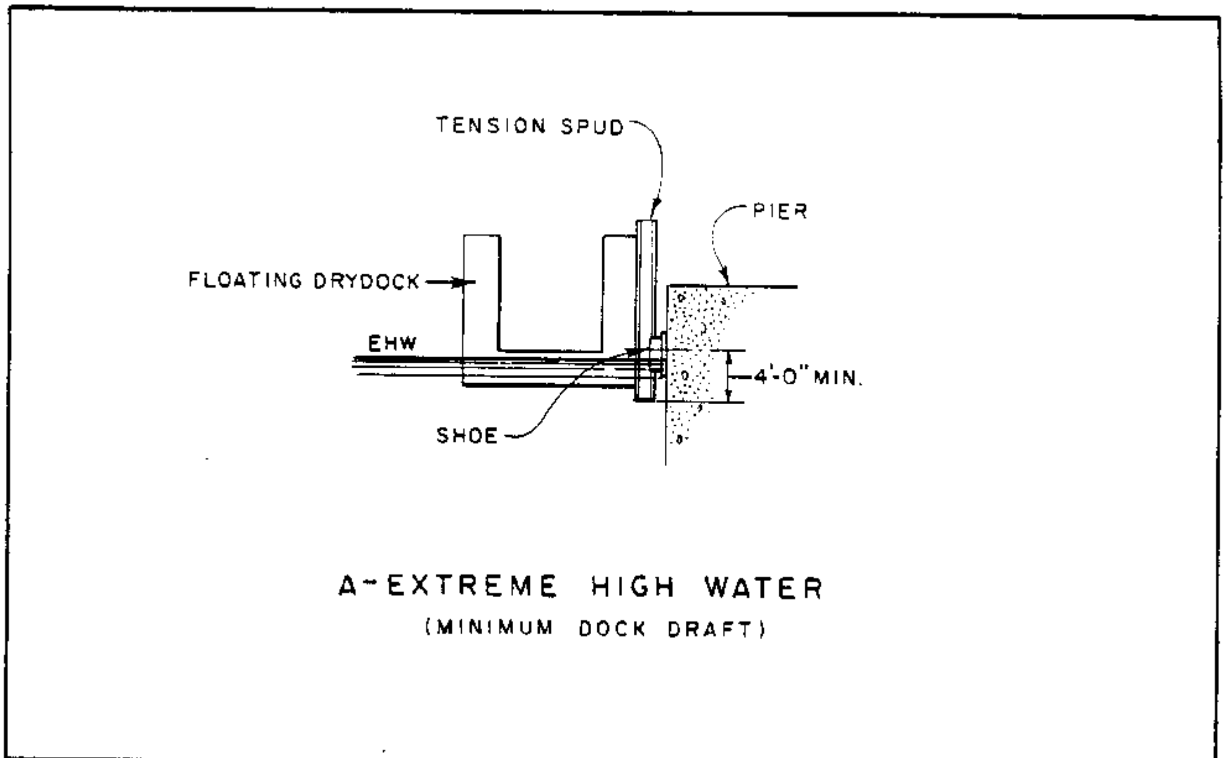
W = weight of vessel

g = gravitational acceleration

V_N = normal component of approach velocity

C_B = berthing coefficient

C_H = hydrodynamic mass coefficient



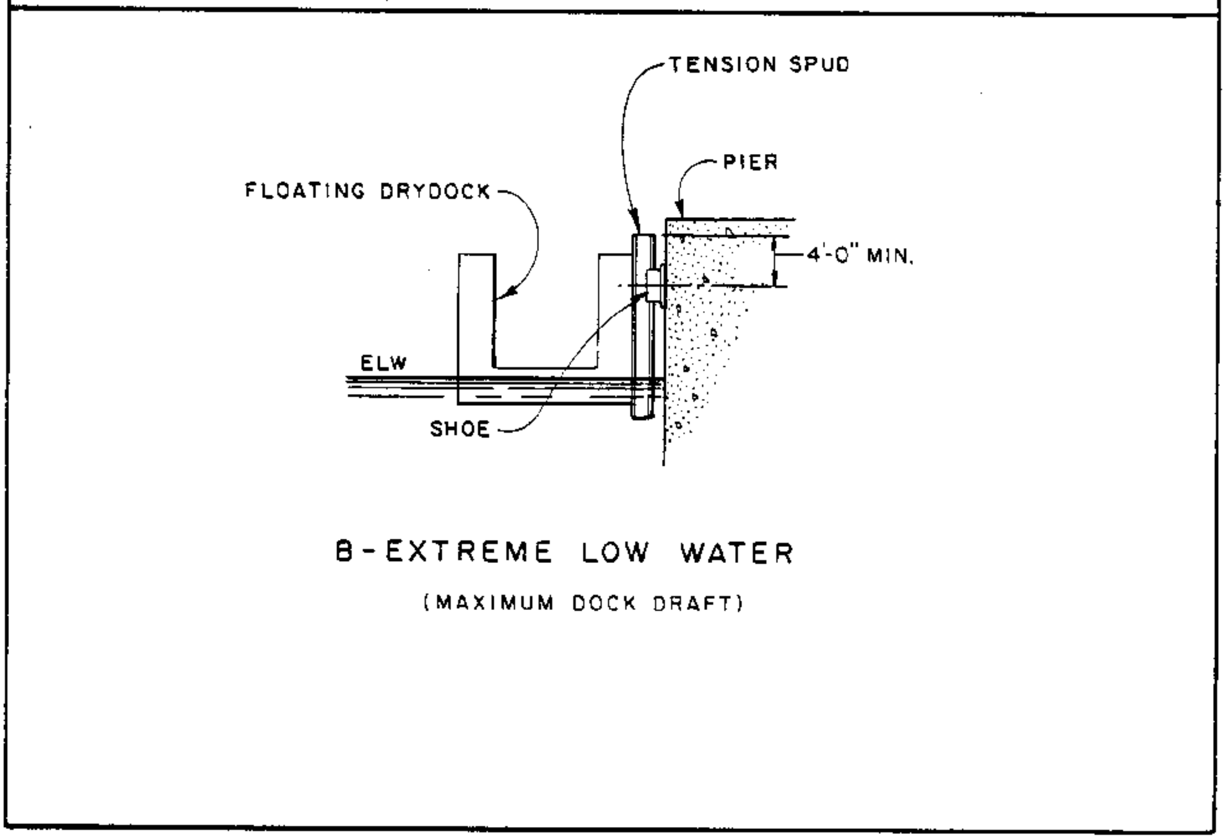


FIGURE 13
Spud Clearance Requirements

Determining berthing energy requires knowledge of the berthing maneuver (such as angle of approach, velocity, and effects of tugs), the mass of the vessel, the hydrodynamic effects of the vessel, and environmental loads on the vessel. Approach velocity is difficult to predict due to the uncertainty of the berthing maneuver. Methods for selecting the approach velocity, berthing coefficient, and hydrodynamic mass coefficient are presented in Section 4. Due to the uncertainties involved in the calculation of berthing energy, it is good practice to allow for reserve energy absorption in the design of breasting structures.

4. DESIGN OF MOORING COMPONENTS.

a. Probabilistic Approach To Design. A probabilistic approach to mooring design is used to evaluate uncertainties in environmental conditions at the mooring site, uncertainties in accurately predicting mooring forces, and uncertainties concerning material strength of the mooring-system hardware.

(1) Uncertainties in Environmental Conditions.

(a) Windspeed. The uncertainty associated with determining a design windspeed is reduced by using the probabilistic approach described in Subsection 3.3.a.(3). Fixed moorings must be designed for a windspeed with a 50-year return period, unless operational criteria dictate that the vessel leave the mooring at a windspeed less than the 50-year windspeed. For a mooring with a 5-year life expectancy, there is about a 9.6-percent chance that the mooring will be subjected to the 50-year windspeed. Similarly, there is about an 18-percent chance that a mooring with a 10-year life expectancy will be subjected to the 50-year windspeed. Operational criteria at some fixed moorings may require a vessel to leave the mooring at windspeeds less than the 50-year event. In this case, the mooring should be designed for the maximum operational windspeed rather than the 50-year windspeed.

(b) Currents. There are generally insufficient data to perform a probabilistic analysis of tidal currents. Consequently, the design tidal current shall be the larger of the maximum flood or ebb current at the site. Wind-driven-current statistics can be derived from wind data. River-discharge data can be analyzed and probabilities determined using methods similar to those described for wind.

(2) Uncertainties in Predicting Forces. Uncertainties involved in determining wind- and current-induced loads on moored vessels should be recognized. Wind loads are relatively accurate (+/- 10 to 15 percent of predicted value), while current loads are more uncertain and may be as high as +/- 30 percent of the predicted value for currents with speeds greater than 3 knots.

(3) Uncertainties in Material Strength. There is some uncertainty in the actual strength of mooring lines, mooring and breasting structures, the fendering system, and the soil. Hence, a factor of safety is applied to the design of fixed-mooring elements, and a working load, which is considerably less than the breaking or yield strength, is designated.

The uncertainties in mooring-line strength are associated with variations in manufacturing quality of the line and the degradation of mooring-line

strength with time as the line is exposed to the marine environment. Specific recommendations for working loads on mooring lines are presented in Section 4. Working loads for structural materials such as steel, concrete, and wood are presented in DM-2. Factors of safety concerning design of fendering systems are given in DM-25.1. Factors of safety concerning soil strength are presented in DM-7.

b. Design of Mooring and Breasting Structures. Several alternative mooring structures should be investigated. Site conditions and restrictions, applied loads, costs, and previous experience at the site will determine the optimum structure to be employed in the design. The mooring-structure design is based upon the rated capacity of the deck fitting secured to the structure, in addition to other live and dead loads.

(1) Energy Absorption. Fixed-mooring systems should be capable of absorbing berthing and mooring energy. Berthing energy must be absorbed by breasting structures and/or their fendering systems. Mooring energy, associated with vessel movements due to the dynamic loading of wind, waves, and current, must be absorbed by breasting and mooring structures. Dynamic analysis of fixed moorings is not presented in this manual. The following discussion is limited to analysis of the absorption of berthing energy by breasting structures.

Berthing energy is absorbed by a breasting structure and its fendering system according to the following general equation:

$$KE_B = KE_s + KE_f \qquad (3\text{-}7)$$

WHERE: KE_B = berthing energy

KE_s = berthing energy absorbed by the breasting structure

KE_f = berthing energy absorbed by the fendering system

For rigid breasting structures (such as cells and rigid platforms), the berthing energy is absorbed almost entirely by the fendering system. For flexible breasting structures (such as steel and timber dolphins and flexible platforms), the berthing energy is absorbed by both the structure and the fendering system. Where structural and foundation conditions are favorable, significant cost savings may be realized with a flexible design.

(2) Load-Deflection Curve. A plot of restraining force versus deflection is known as a load-deflection curve. A schematic example of a load-deflection curve is shown in Figure 14. The load-deflection curve provides information on the energy-absorbing capabilities of a breasting structure. This information is obtained by applying the concepts of work and energy to the load-deflection curve. The principle of work-energy dictates that the work done on the fixed-mooring system should equal the area under the load-deflection curve. This work, equal to the berthing energy of the vessel, must be absorbed by the mooring system.

A vessel approaches a breasting structure with a berthing energy, KE_B, which must be absorbed by the breasting structure through deflection of the breasting structure and/or its fendering system. Furthermore, a breasting

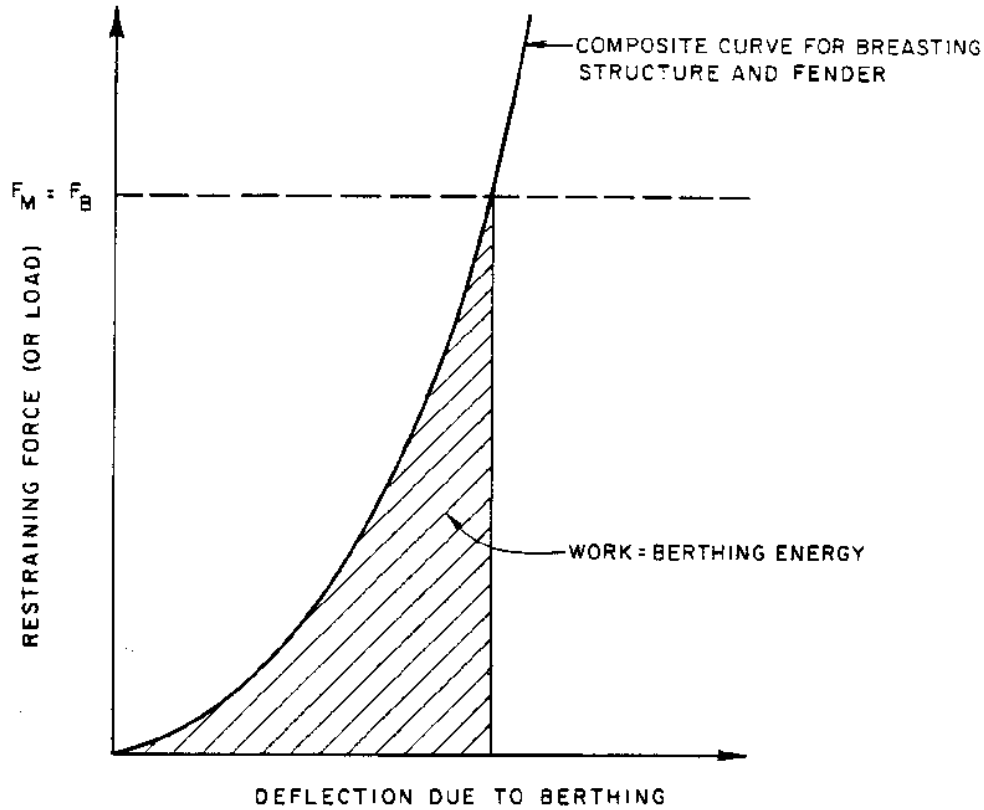


FIGURE 14
Load-Deflection Curve

structure must be designed to withstand the maximum static wind and current load (mooring energy, F_M) acting on it. In general, for an economical structure, it is desirable to absorb the berthing energy in the fender-structure system such that the berthing load, F_B, developed in the structure is equal to the maximum static wind and current load (mooring load) on the structure (Figure 14). There may be situations where either the mooring or the berthing load is dominant. For example, for an extremely high berthing energy, it may not be possible to design a fendering system soft enough to absorb the berthing energy at a load equal to the mooring load. In this case, the load associated with berthing would be higher than the mooring load.

5. METRIC EQUIVALENCE CHART. The following metric equivalents were developed in accordance with ASTM E-621. These units are listed in the sequence in which they appear in the text of Section 3. Conversions are approximate.

5 feet = 1.5 meters
100 feet = 30.5 meters
99 feet = 30.2 meters
8 feet = 2.4 meters
103.3 feet = 31.5 meters
101.1 feet = 30.8 meters
35 feet = 10.7 meters
50 feet = 15.2 meters
1 mile = 1.61 kilometers
60 miles per hour = 96.6 kilometers per hour
30 miles per hour = 48.3 kilometers per hour
33.33 feet = 10 meters
1 knot = 0.5 meter per second
6 knots = 3.1 meters per second
0.5 knot = 0.26 meter per second
4 feet = 1.2 meters
3 knots = 1.5 meters per second

Section 4. DESIGN OF FIXED MOORINGS

1. INTRODUCTION. This section provides equations, graphs, and tables necessary for fixed-mooring design. Detailed procedures are presented for each element of the design process. Section 3 provides a qualitative discussion of the design process.

2. MOORING LAYOUT. It is assumed that the mooring site, the vessel, and the mooring configuration are given prior to commencement of detailed design. It is generally necessary to investigate several mooring layouts because the loads in mooring lines and on mooring and breasting structures are not known at this stage of the design. Often the designer will have to analyze several vessels for a given mooring configuration.

Mooring-line geometry and breasting- and mooring-structure location are determined using the procedure outlined in Figure 15. The mooring-line angles must be checked at low tide for a fully-loaded vessel and at high tide for a light-loaded vessel.

3. ENVIRONMENTAL CONDITIONS.

a. Seafloor Soil Conditions. Seafloor soil conditions must be investigated in order to design fixed-mooring structures. Refer to DM-7 for soil-investigation requirements.

b. Design Water Depth. Determine the bottom elevation and the anticipated range of water elevation expected at the mooring site. Bathymetric charts are usually available from National Ocean Survey (NOS). The primary cause of water-level fluctuations is the astronomical tide. Estimates of the maximum high and low water levels due to tide for most naval harbors are given in DM-26.1, Table 6. A summary of tide levels for U.S. locations is given in Harris (1981).

c. Design Wind. Steps for wind-data analysis, discussed below, are summarized in Figure 16. This procedure involves some concepts of probability, which are discussed in Appendix A of DM-26.5.

(1) Obtain Wind Data. Collect available windspeed data for the site. Data which give the annual maximum wind speed (extreme wind) and direction for each year of record are required. In most situations, the annual maximum windspeeds are either fastest-mile or peak-gust values. A minimum of 20 years of annual extreme windspeed data is desired for a good estimate of the 50-year design windspeed.

Several possible sources for obtaining windspeed data are presented in Table 3. These are discussed below:

(a) Naval Oceanography Command Detachment. The Naval Oceanography Command Detachment is a source of wind data for naval harbors world-wide. Wind data available through the Naval Oceanography Command Detachment are summarized in "Guide to Standard Weather Summaries and Climatic Services," NAVAIR 50-1C-534 (1980). The most useful of the standard wind summaries available at the Naval Oceanography Command Detachment for mooring design is the table of extreme winds. This table, available for a large number of

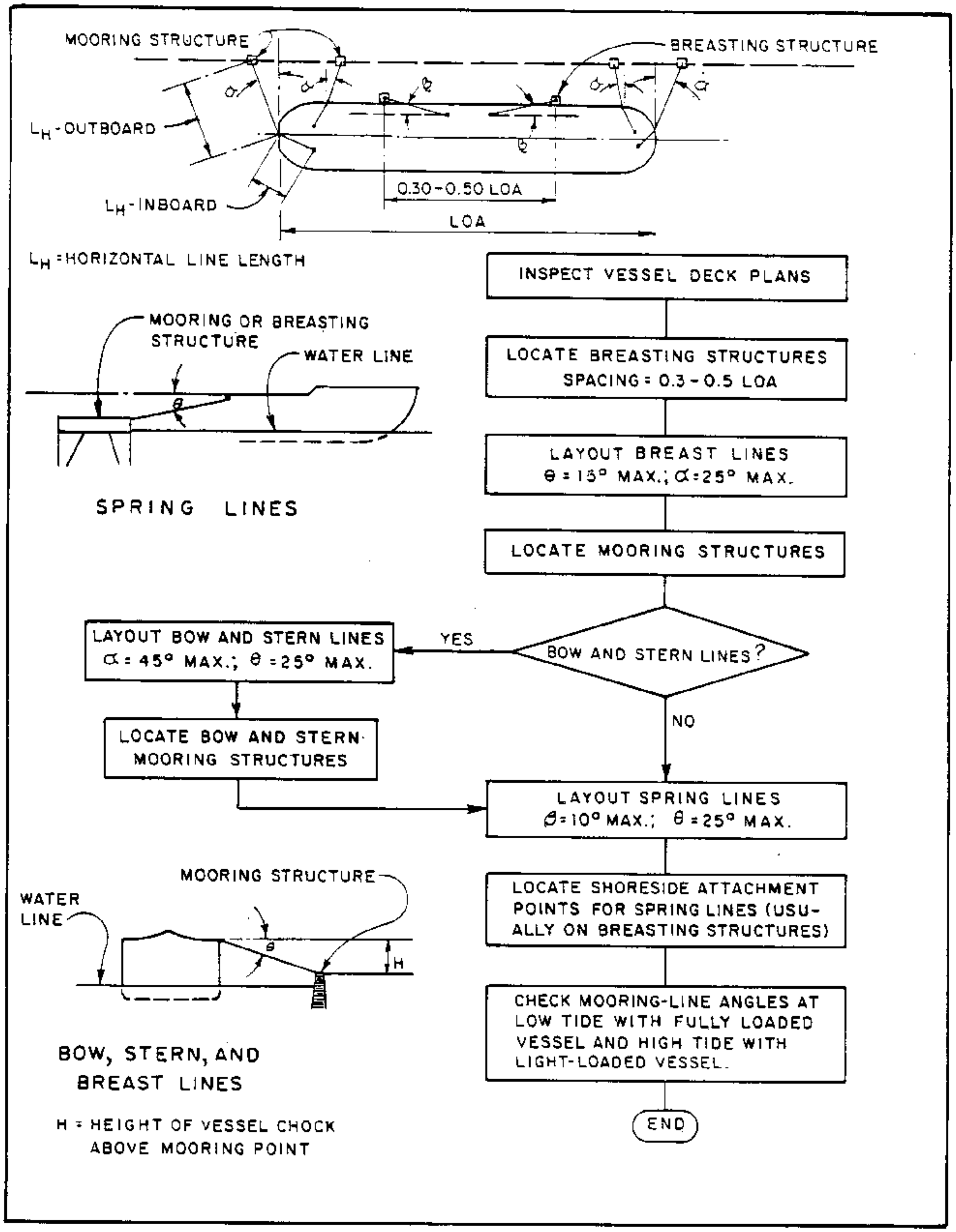


FIGURE 15
Fixed-Mooring Layout Procedure

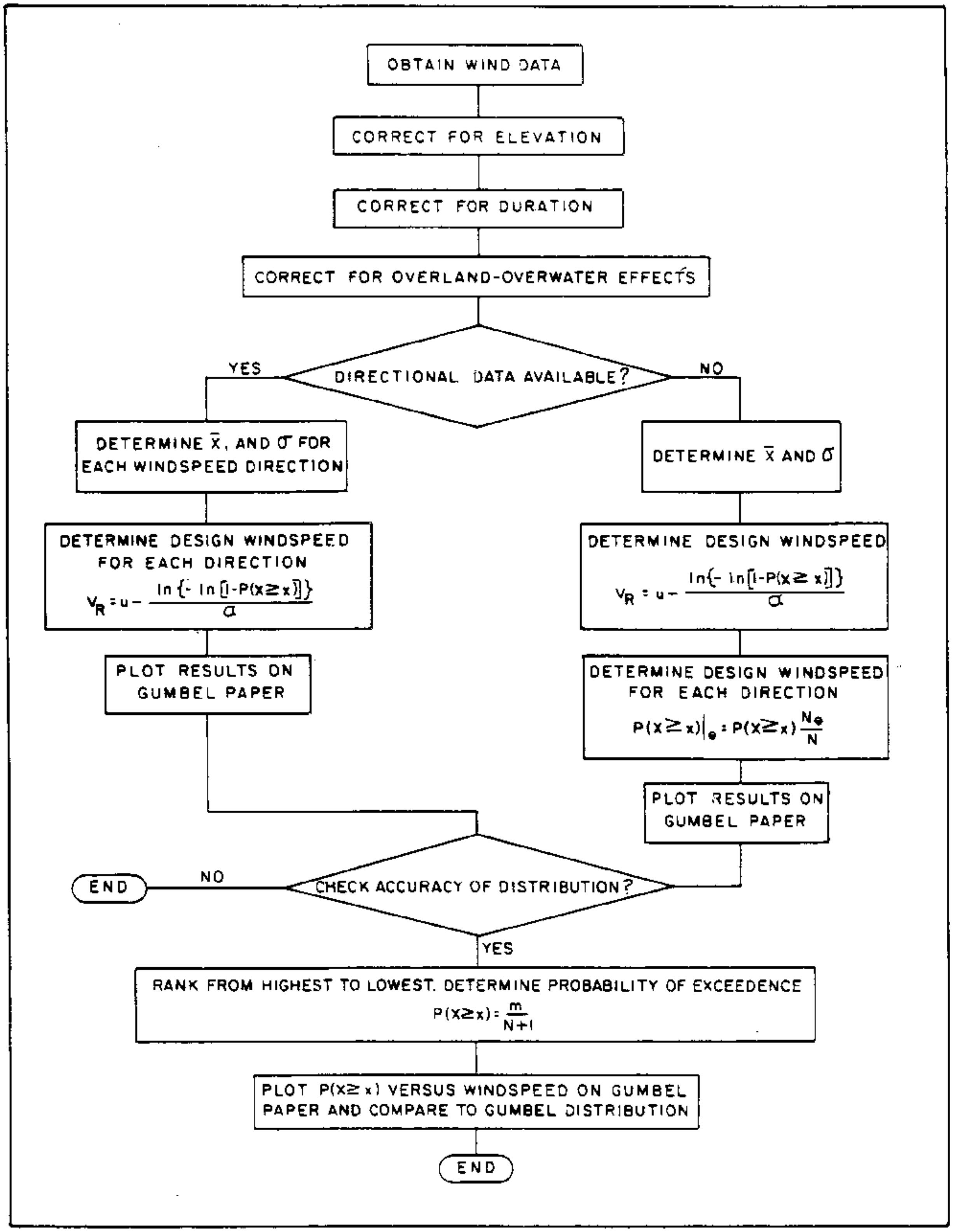


FIGURE 16
Procedure for Wind-Data Analysis

TABLE 3
Sources of Wind Data

- Naval Oceanography Command Detachment, Federal Building, Asheville, North Carolina 28801
- National Climatic Data Center (NCDC), Federal Building, Asheville, North Carolina 28801
- Naval Environmental Prediction Research Facility, Monterey, California 93940
- Wind records from local wind stations

naval sites, provides the extreme peak-gust windspeed (and its direction) for each month of each year of record. This standard summary provides sufficient information to determine extreme winds for all directions combined, but provides insufficient information to determine extreme winds for each direction individually. Extreme peak-gust windspeed for each direction for each year of record is required to determine extreme winds for each direction (for example, using eight compass points). The Naval Oceanography Command Detachment is presently planning to provide directional extreme winds as a standard product, and summaries of directional extreme-wind statistics for naval harbors should be available in the future.

(b) National Climatic Data Center (NCDC). The National Climatic Data Center has wind data for the continental United States and United States territories. Wind data available at NCDC for the continental United States are cataloged in the "National Wind Data Index" (Changerey, 1978). Extreme-wind data available at NCDC are generally fastest-mile windspeeds. Changerey (1982a, 1982b) gives extreme windspeeds (that is, 2- to 1,000-year winds) for a number of east coast and Great Lakes sites, some of which are near naval facilities. The results do not give directional extreme winds, but do give extreme winds for all directions. Wind data, sufficient for determining directional extreme winds, are available at NCDC; the cost for these data varies from site to site.

(c) Naval Environmental Prediction Research Facility. Climatological data for naval harbors throughout the world are presented in a series of publications from the Naval Environmental prediction Research Facility. Turpin and Brand (1982) provide climatological summaries of Navy harbors along the east coast of the United States. Climatological data for United States Navy harbors in the western Pacific and Indian Oceans are summarized in Brand and Blelloch (1976). Climatological data for United States Navy harbors in the Mediterranean are summarized in Reiter (1975). The above publications provide information on the following: harbor geography and facilities; susceptibility of the harbor to storms, such as tropical cyclones, hurricanes, and typhoons; wind conditions at the harbor and the effects of local topography; wave action; storm surge; and tides. The publications have been prepared to provide guidance for determining when a vessel should leave a harbor; the publications may not be sufficiently detailed to provide design windspeeds. However, they will help the designer determine the threat of storms at the site and provide a good background on local climatology.

The designer must not use data from summarized hourly average wind statistics, such as those presented in the Summary of Synoptic Meteorological Observations (SSMO). These average data are not annual maximum values and do not report the infrequent, high-velocity windspeeds necessary to predict extreme-wind events for design use. If average summaries are the only data available, it is best to obtain the original observations and analyze these data for extreme statistics.

(2) Correct for Elevation. The level at which windspeed data are recorded varies from site to site. Windspeed data should be transformed to a standard reference level of 33.33 feet or 10 meters. Adjustments are made using the following equation, which accounts for the wind gradient found in nature:

$$V_{33.33} = V_h \left(\frac{33.33}{h}\right)^{1/7} \qquad (4\text{-}1)$$

WHERE: $V_{33.33}$ = windspeed at elevation of 33.33 feet above water or ground level

V_h = windspeed at elevation h

h = elevation of recorded wind above water or ground level, in feet

(3) Correct for Duration. Figure 17 presents a graph which allows one to correct windspeeds ranging from 1 second to 10 hours in duration to a 30-second-duration windspeed. This figure gives a conversion factor, C_t, which is used to determine the 30-second windspeed as follows:

$$V_{t=30\ \text{seconds}} = \frac{V_t}{C_t} \qquad (4\text{-}2)$$

WHERE: $V_{t=30\ \text{seconds}}$ = windspeed with a 30-second duration

V_t = windspeed of given duration, t

C_t = conversion factor = $\dfrac{V_t}{V_{t=30\ \text{seconds}}}$

Peak-gust windspeed statistics give no information on the duration of the wind event; therefore, these data cannot be accurately corrected to a 30-second duration. Based on Figure 17, an 8-second peak gust is 1.1 times faster than a 30-second wind. As an approximation, peak-gust windspeeds should be reduced by 10 percent to obtain the 30-second windspeed. This will provide a reasonably conservative estimate of the 30-second wind speed for fleet-mooring design. Where detailed information on the duration of peak gusts can be obtained (that is, from an actual wind anemometer trace at the site), Figure 17 can be used to make more accurate estimates of 30-second sustained windspeeds.

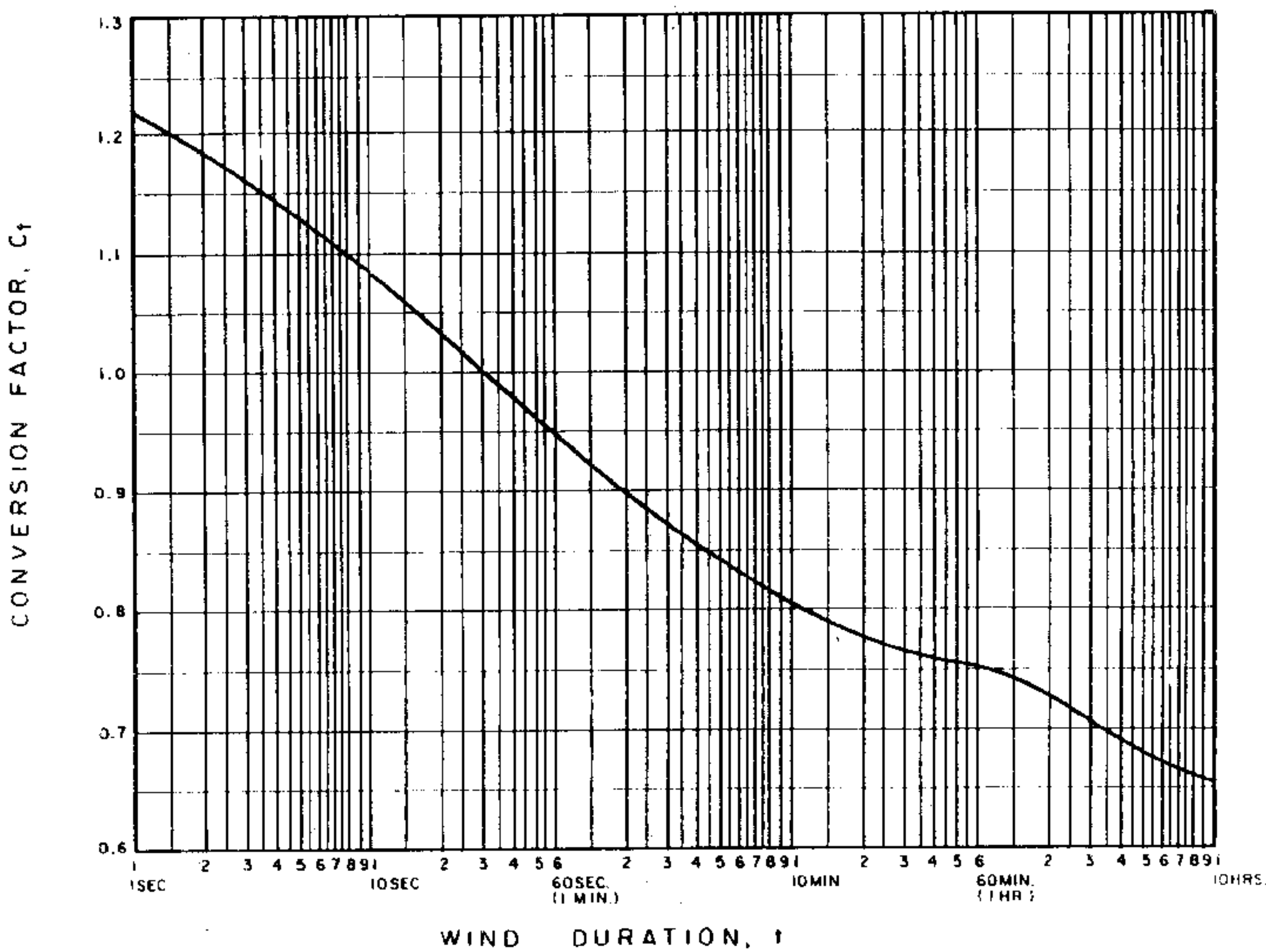


FIGURE 17
Windspeed Conversion Factor, C_t, as a Function of Wind Duration, t

Fastest-mile wind statistics give wind duration directly. The fastest-mile windspeed is a wind with duration sufficient to travel 1 mile. Figure 17 can be used to correct the windspeed to the 30-second-duration wind. For example, a conversion factor, C_t, of 0.945 is applied to a 60-mile-per-hour fastest-mile windspeed (60-second duration) to convert it to a 30-second-duration windspeed.

Figure 17 can be used to convert hourly average windspeeds to the 30-second windspeed. However, unless the hourly average windspeeds are annual extreme values, they cannot be used directly to estimate extreme conditions.

(4) Correct for Overland-Overwater Effects. Windspeed data recorded at inland stations, V_L, must be corrected for overland-overwater effects in order to obtain the overwater windspeed, V_W. This overland-overwater correction for protected harbors (fetch lengths less than or equal to 10 miles) is achieved using the following equation (U.S. Army Corps of Engineers, 1981):

$$V_W = 1.1\ V_L \qquad (4\text{-}3)$$

WHERE: V_W = overwater windspeed

V_L = overland windspeed adjusted for elevation and duration

Subsection 2.3.b.(1)(c) of DM-26.2 provides an overland-overwater correction for fetch lengths greater than 10 miles.

(5) Determine Windspeed Probability.

(a) Determine mean value and standard deviation. Determine the mean value, $\bar{x}$, and standard deviation, σ, for each windspeed direction:

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \qquad (4\text{-}4)$$

$$\sigma = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2 \qquad (4\text{-}5)$$

WHERE: $\bar{x}$ = mean value of windspeeds

N = total number of observations

x_i = windspeed for i^{th} year

σ = standard deviation of windspeeds

(b) Determine design windspeed for each direction. Use the Gumbel distribution (see Appendix A of DM-26.5 for description) to determine design windspeeds for each direction:

$$V_R = u - \frac{\ln \{- \ln [1 - P(X \geq x)]\}}{\alpha} \tag{4-6}$$

WHERE: V_R = windspeed associated with return period (return period = 1/[P(X>/=x)])

$$[\alpha] = \frac{1.282}{[\sigma]} \qquad (4\text{-}7)$$

$$u = \bar{x} - \frac{0.577}{[\alpha]} \qquad (4\text{-}8)$$

P(X>/=x) = probability of exceedence associated with desired return period (see Table 4)

The easiest way to use Equation (4-6) is to compute the windspeed, V_R, for each of the return periods given in Table 4. The results will plot as a straight line on Gumbel paper. (A blank sheet of Gumbel probability paper which can be photocopied for design use is provided in DM-26.5, Appendix A, Figure A-2.)

TABLE 4
Return Period for Various P(X>/=x)

Return Period	P(X>/=x)
1,000	0.001
100	0.01
50	0.02
25	0.04
20	0.05
15	0.0667
10	0.1
5	0.2
2	0.5

Note: The return period is the reciprocal of the probability of exceedence.

(c) Determine directional probability. The directional probability can be determined if directional wind data are available. Usually, available data consist of one extreme windspeed and its direction for each year of record. Data which provide extreme windspeed for each year of record from each direction (say, eight compass points) are needed to accurately determine directional probability. Nondirectional windspeed data collected for 50 years would consist of 50 data points (that is, 50 values of windspeed and the direction of each), whereas 400 data points (50 extreme-windspeed values from each of the eight compass points) would be required to determine directional probability accurately. When a complete data set consisting of the yearly extreme windspeed from each of the eight compass-point directions is available, directional probability is determined using the above steps given in (a) and (b) for each direction. When the data set consists of the yearly extreme windspeed and direction of that windspeed, the directional probability is approximated. Steps (a) and (b) are used to develop a plot of probability of exceedence versus windspeed for all directions combined (Figure 18). Approximate the directional probability using the following:

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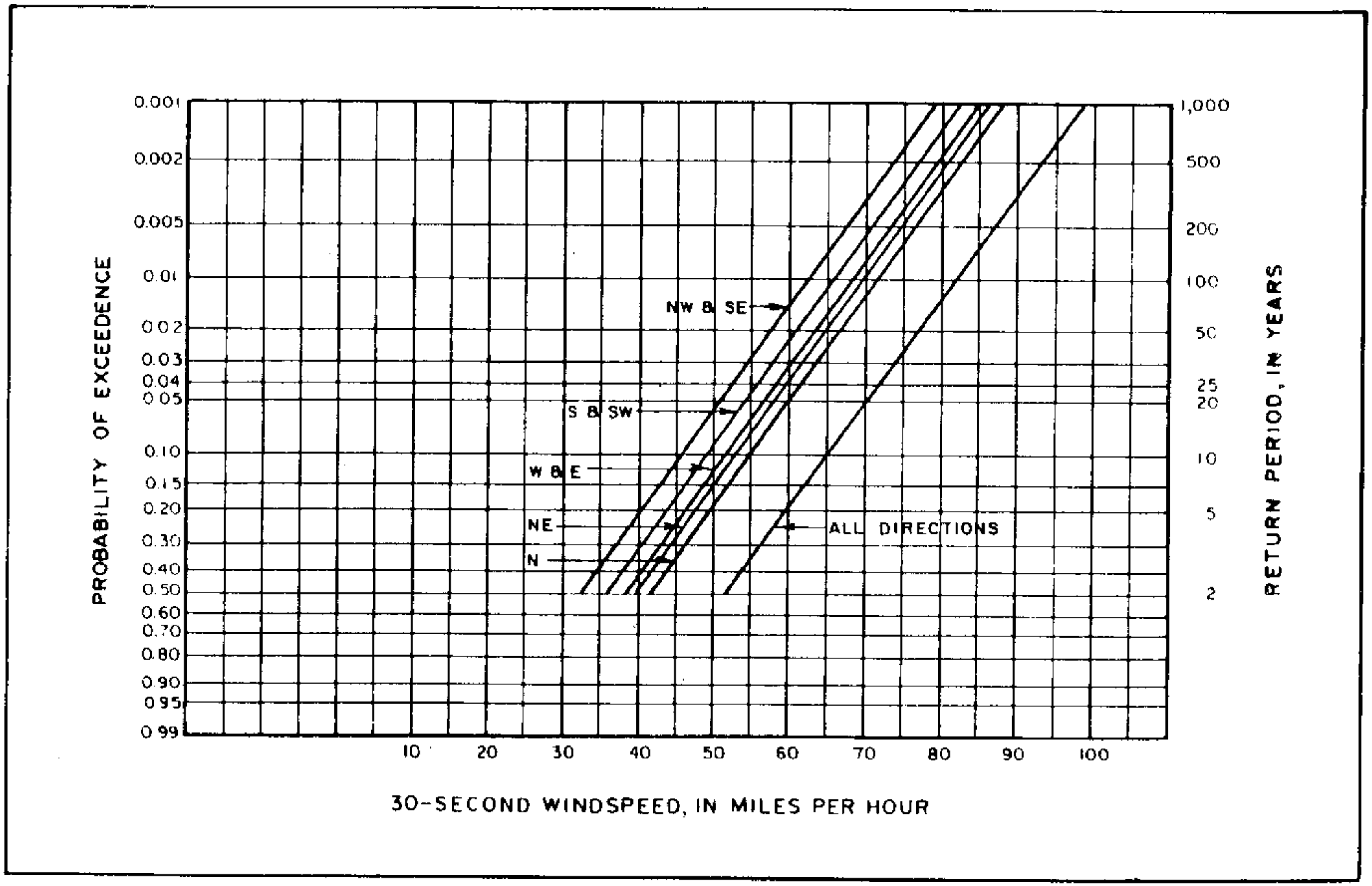


FIGURE 18
Probability of Exceedence and Return Period Versus Windspeed

$$P(X \geq x)\big|_{\theta} = P(X \geq x)\,\frac{N_{\theta}}{N} \qquad (4\text{-}9)$$

WHERE: $P(X \geq x)\big|_{\theta}$ = probability of exceedence for a windspeed from direction θ

$P(X \geq x)$ = probability of exceedence for windspeeds from all directions combined

N_{θ} = number of times extreme windspeed came from direction θ

N = total number of extreme windspeeds

The above equation can be used to construct lines for the probability of exceedence versus windspeed for each direction (Figure 18). The design windspeeds are then determined from the constructed lines. Examples illustrating this procedure are provided in Section 5.

(d) Check accuracy of Gumbel distribution. The designer may want to determine how well the Gumbel distribution fits the data. This is done by first ranking windspeed data from highest to lowest. The number 1 is assigned to the highest windspeed on record, the number 2 to the second highest windspeed, and so on. The lowest windspeed will be assigned the number N, which is the number of extreme windspeeds on record.

Compute the probability of exceedence for each windspeed using the following equation:

$$P(X \geq x) = \frac{m}{N + 1} \qquad (4\text{-}10)$$

WHERE: $P(X \geq x)$ = probability that a variable, X (windspeed), is equal to or greater than a specified value, x, with rank m

m = rank of windspeed x

N = total number of windspeeds in the record

Plot the probability of exceedence, $P(X \geq x)$, versus windspeed on Gumbel probability paper. Compare the plotted data to the straight lines for the Gumbel distribution determined above. If the data do not fit the Gumbel distribution well, the designer should investigate other statistical distributions described in Simiu and Scanlon (1978).

d. Design Current. In the determination of probabilistic design current, a conservative procedure is recommended where tidal current governs the design. A peak flood- or ebb-current velocity should be used, in conjunction with the 50-year design wind. Values of peak ebb and flood currents for the Atlantic and Pacific coasts of North America and the Pacific coast of Asia may be obtained from tidal current tables published by National Ocean Survey (NOS), Rockville, MD 20852. These tables present the average speeds and directions of the maximum floods and maximum ebbs. Directions are given in degrees, reading clockwise from 0 to 359 degrees, and are in the directions toward which the currents flow. If there are no current data, then

measurements of currents should be made. Tidal currents reverse; therefore, in the determination of maximum loads, both flood and ebb tidal currents should be investigated.

Moorings located in rivers may be subjected to high currents during floods. River-discharge statistics may be analyzed using the above methods for wind probability. A 50-year river velocity is recommended for design. A 50-year wind-induced current should be used in designs where wind-induced currents are important.

4. ENVIRONMENTAL LOADS ON SINGLE MOORED VESSELS. This section describes methods for determining static wind and current loads on single moored vessels. The lateral force, longitudinal force, and yarn moment are evaluated. Figure 19 defines the coordinate system and nomenclature for describing these loads. The wind angle, θ_w, and current angle, θ_c, are defined as positive in clockwise direction. A discussion of the various physical phenomena involved in these procedures is provided in Section 3.

a. Wind Load. Determining wind load on single moored vessels differs for ship-shaped vessels and floating drydocks.

(1) Ship-Shaped Vessels. The procedure for determining static wind loads on ship-shaped, single moored vessels is taken from Owens and Palo (1982).

(a) Lateral wind load. Lateral wind load is determined using the following equation:

$$F_{yw} = \frac{1}{2} \rho_a V_w^2 A_y C_{yw} f_{yw}(\theta_w) \qquad (4\text{-}11)$$

WHERE: F_{yw} = lateral wind load, in pounds

ρ_a = a mass density of air - 0.00237 slugs per cubic foot at 68deg.F

V_w = wind velocity, in feet per second

A_y = lateral projected area of ship, in square feet

C_{yw} = lateral wind-force drag coefficient

$f_{yw}(\theta_w)$ = shape function for lateral load

θ_w = wind angle

The lateral wind-force drag coefficient depends upon the hull and superstructure of the vessel:

$$C_{yw} = 0.92 \left[\left[\frac{V_S}{V_R} \right]^2 A_S + \left[\frac{V_H}{V_R} \right]^2 A_H \right] / A_y \qquad (4\text{-}12)$$

WHERE: C_{yw} = lateral wind-force drag coefficient

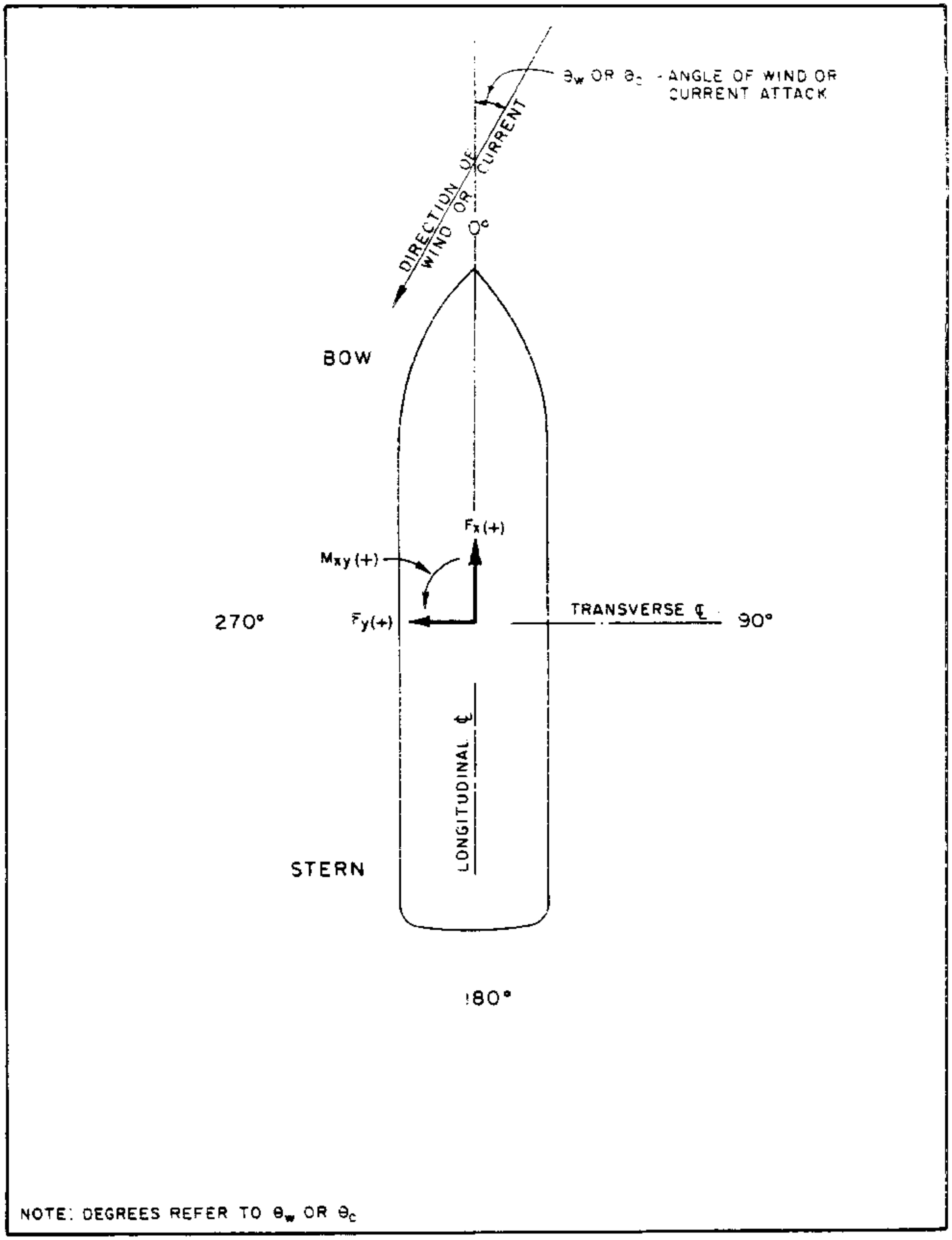


FIGURE 19
Coordinate System and Nomenclature for Wind and Current Loads

V_S/V_R = average normalized wind velocity over superstructure

V_R = reference wind velocity at 33.33 feet above sea level

A_S = lateral projected area of superstructure only, in square feet

V_H/V_R = average normalized wind velocity over hull

A_H = lateral projected area of hull only, in square feet

A_y = lateral projected area of ship, in square feet

The values of V_S/V_R and V_H/V_R are determined using the following equations:

$$\frac{V_S}{V_R} = \left[\frac{h_S}{h_R}\right]^{1/7} \tag{4-13}$$

$$\frac{V_H}{V_R} = \left[\frac{h_H}{h_R}\right]^{1/7} \tag{4-14}$$

WHERE: V_S/V_R = average normalized wind velocity over superstructure

h_S = average height of superstructure, in feet

h_R = reference height of windspeed (33.33 feet)

V_H/V_R = average normalized wind velocity over hull

h_H = average height of hull, in feet

Details of the hull and superstructure areas of vessels can be determined from the book of general plans for the vessel or from Jane's Fighting Ships (1976).

The shape function for lateral load, $f_{yw}(\theta_w)$, is given as:

$$f_{yw}(\theta_w) = \frac{+\left(\sin\theta_w - \frac{\sin 5\theta_w}{20}\right)}{1 - \frac{1}{20}} \tag{4-15}$$

WHERE: $f_{yw}(\theta_w)$ = shape function for lateral load

θ_w = wind angle

Vessels secured to fixed moorings are often sheltered by the fixed mooring itself or by landside buildings or similar structures. The designer should account for sheltering when determining the lateral projected areas of the vessel.

(b) Longitudinal wind load. Longitudinal wind load is determined using the following equation:

$$F_{xw} = \frac{1}{2} \rho_a V_w^2 A_x C_{xw} f_{xw}(\theta_w) \qquad (4\text{-}16)$$

WHERE: F_{xw} = longitudinal wind load, in pounds

ρ_a = mass density of air = 0.00237 slugs per cubic foot at 68deg.F

V_w = wind velocity, in feet per second

A_x = longitudinal projected area of ship, in square feet

C_{xw} = longitudinal wind-force drag coefficient

$f_{xw}(\theta_w)$ = shape function for longitudinal load

The longitudinal wind-force drag coefficient varies according to vessel type and characteristics. Additionally, a separate wind-force drag coefficient is provided for headwind (over the bow: θ_w = 0 degrees) and tailwind (over the stern: θ_w - 180 degrees) conditions. The headwind (bow) wind-force drag coefficient is designated C_{xwB} and the tailwind (stern) wind-force drag coefficient is designated C_{xwS}. The following longitudinal wind-force drag coefficients are recommended for hull-dominated vessels, such as aircraft carriers, submarines, and passenger liners:

$$C_{xwB} = 0.40 \qquad (4\text{-}17)$$

$$C_{xwS} = 0.40 \qquad (4\text{-}18)$$

For all remaining types of vessels, except for specific deviations, the following are recommended:

$$C_{xwB} = 0.70 \qquad (4\text{-}19)$$

$$C_{xwS} = 0.60 \qquad (4\text{-}20)$$

An increased headwind wind-force drag coefficient is recommended for center-island tankers:

$$C_{xwB} = 0.80 \qquad (4\text{-}21)$$

For ships with an excessive amount of superstructure, such as destroyers and cruisers, the recommended tailwind wind-force drag coefficient is:

$$C_{xwS} = 0.80 \qquad (4\text{-}22)$$

An adjustment consisting of adding 0.08 to C_{xwB} and C_{xwS} is recommended for all cargo ships and tankers with cluttered decks.

Longitudinal shape function, $f_{xw}(\theta_w)$, differs over the headwind and tailwind regions. The incident wind angle that produces no net longitudinal force, designated θ_{wz} for zero crossing, separates these two regions.

Selection of θ_{wz} is determined by the mean location of the superstructure relative to midships. (See Table 5.)

TABLE 5
Selection of θ_{wz}

Location of Superstructure	θ_{wz}
Just forward of midships	80deg.
On midships	90deg.
Aft of midships	100deg.
Hull-dominated	120deg.

For many ships, including center-island tankers, $\theta_{wz} \simeq 100$ degrees is typical; $\theta_{wz} \simeq 110$ degrees is recommended for warships.

The shape function for longitudinal load for ships with single, distinct superstructures and hull-dominated ships is given below. (Examples of ships in this category are aircraft carriers, EC-2, and cargo vessels.)

$$f_{xw}(\theta_w) = -\cos\phi \tag{4-23}$$

WHERE:

$$\phi_{(-)} = \left(\frac{90°}{\theta_{wz}}\right)\theta_w \text{ for } \theta_w < \theta_{wz} \tag{4-24}$$

$$\phi_{(+)} = \left(\frac{90°}{180° - \theta_{wz}}\right)(\theta_w - \theta_{wz}) + 90° \text{ for } \theta_w > \theta_{wz} \tag{4-25}$$

θ_{wz} = incident wind angle that produces no net longitudinal force

θ_w = wind angle

The value of $f_{xw}(\theta_w)$ is symmetrical about the longitudinal axis of the vessel. Therefore, when $\theta_w > 180$deg., use 360deg. - θ_w as θ_w in determining the shape function. For example, if θ_w = 330deg., use 360deg. - θ_w = 360deg. - 330deg. = 30deg. for θ_w.

Ships with distributed super Structures are characterized by a "humped" cosine wave. The shape function for longitudinal load is:

$$f_{xw}(\theta_w) = \frac{-\left(\sin\gamma - \frac{\sin 5\gamma}{10}\right)}{1 - \frac{1}{10}} \tag{4-26}$$

WHERE:

$$\gamma_{(-)} = \left(\frac{90°}{\theta_{wz}}\right)\theta_w + 90° \text{ for } \theta_w < \theta_{wz} \tag{4-27}$$

$$\gamma_{(+)} = \left(\frac{90°}{180° - \theta_{wz}}\right)\theta_w + \left(180° - \frac{90°\,\theta_{wz}}{180° - \theta_{wz}}\right) \text{ for } \theta_w > \theta_{wz} \tag{4-28}$$

As explained above, use 360deg. - θ_w for θ_w when θ_w>180deg..

(c) Wind yaw moment. Wind yaw moment is calculated using the following equation:

$$M_{xyw} = \frac{1}{2} \rho_a V_w^2 A_y L C_{xyw}(\theta_w) \qquad (4\text{-}29)$$

WHERE: M_{xyw} = wind yaw moment, in foot-pounds

ρ_a = mass density of air = 0.00237 slugs per cubic foot at 68deg.F

V_w = wind velocity, in feet per second

A_y = lateral projected area of ship, in square feet

L = length of ship

$C_{xyw}(\theta_w)$ = normalized yaw-moment coefficient

Figures 20 through 23 provide yaw-moment coefficients for various vessel types.

(2) Wind Load on Floating Drydocks.

(a) Lateral wind load. lateral wind load on floating drydocks (without the maximum vessel on the blocks) is determined using the following:

$$F_{yw} = \frac{1}{2} \rho_a V_w^2 A_y C_{DW} \sin\theta_w \qquad (4\text{-}30)$$

WHERE: F_{yw} = lateral wind load, in pounds

ρ_a = mass density of air = 0.00237 slugs per cubic foot at 68deg.F

V_w = wind velocity, in feet per second

A_y = lateral projected area of drydock, in square feet

C_{DW} = wind-force drag coefficient

θ_w = wind angle

When a vessel within the dock protrudes above the profile of the dock, the dock should be treated as a normal, "ship-shaped" vessel. (See Subsection 5.3.a.(1).) Table 3 of DM-26.6 provides characteristics of floating drydocks and gives broadside wind areas for the drydocks with the maximum vessel on the blocks.

The wind-force drag coefficient, C_{DW}, for various drydocks in various loading conditions is presented in Table 6. The values of C_{DW} in Table 6 are given for floating drydocks without a vessel on the blocks.

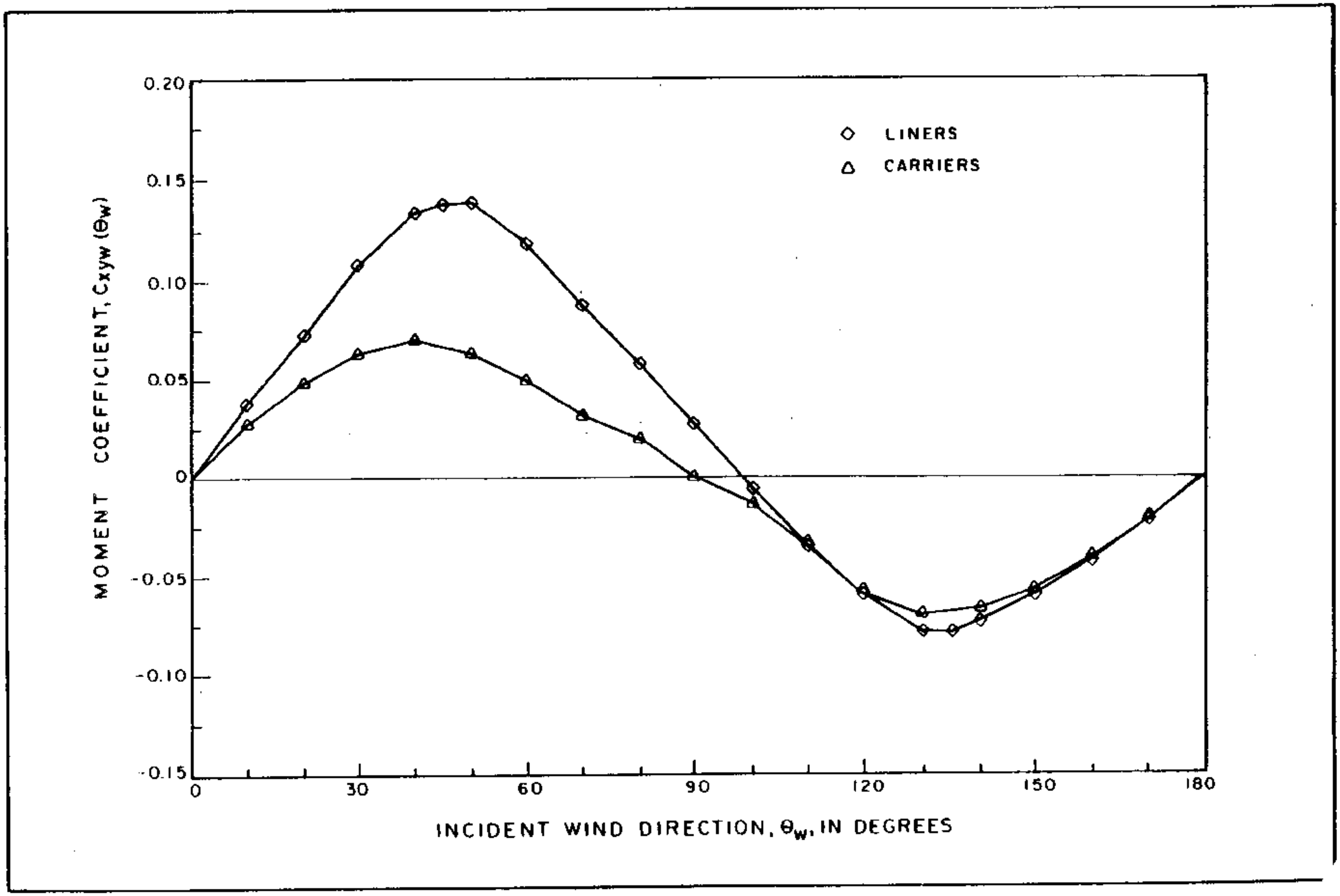


FIGURE 20
Recommended Yaw-Moment Coefficient for Hull-Dominated Vessels

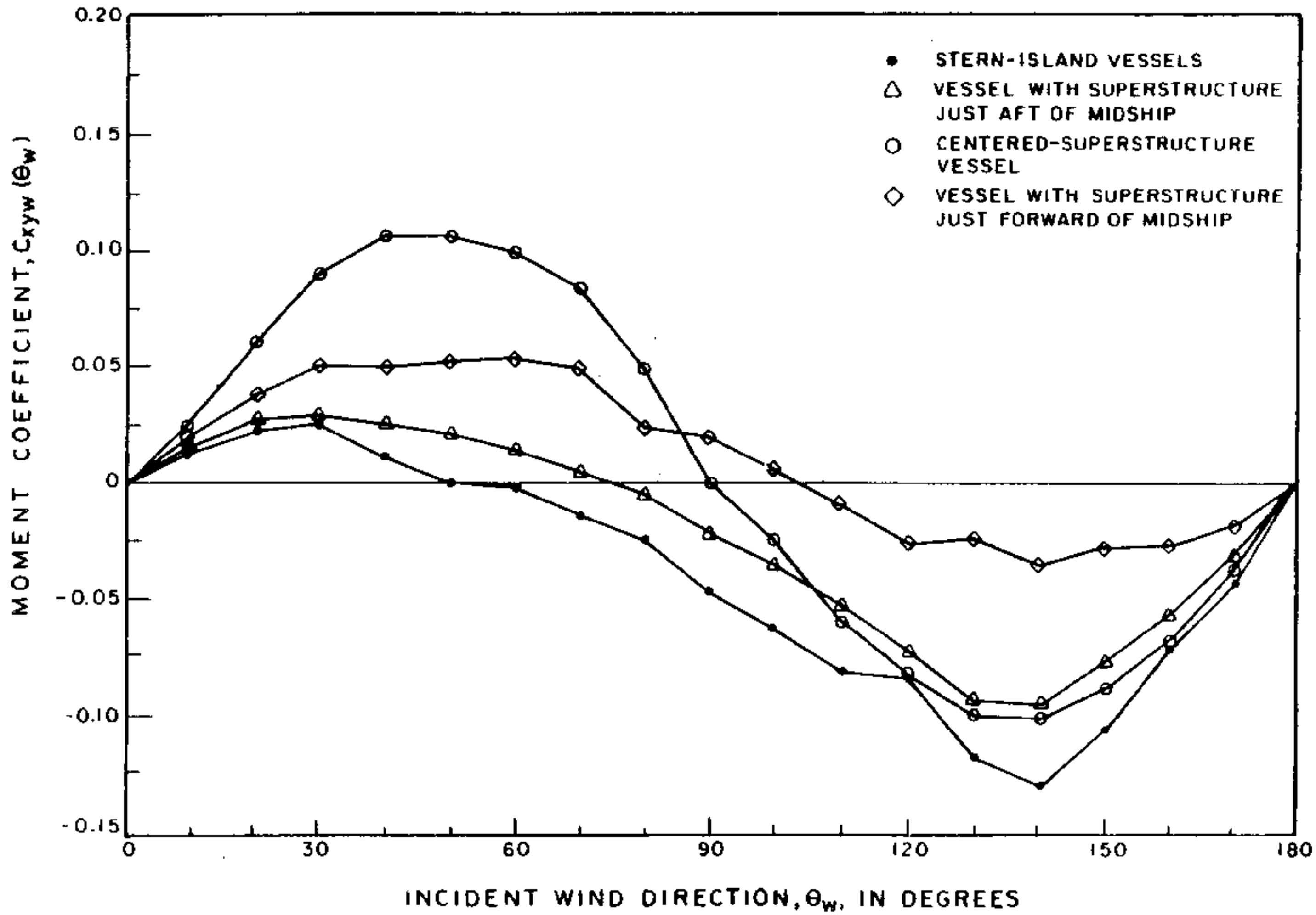


FIGURE 21
Recommended Yaw-Moment Coefficient for Various Vessels According to Superstructure Location

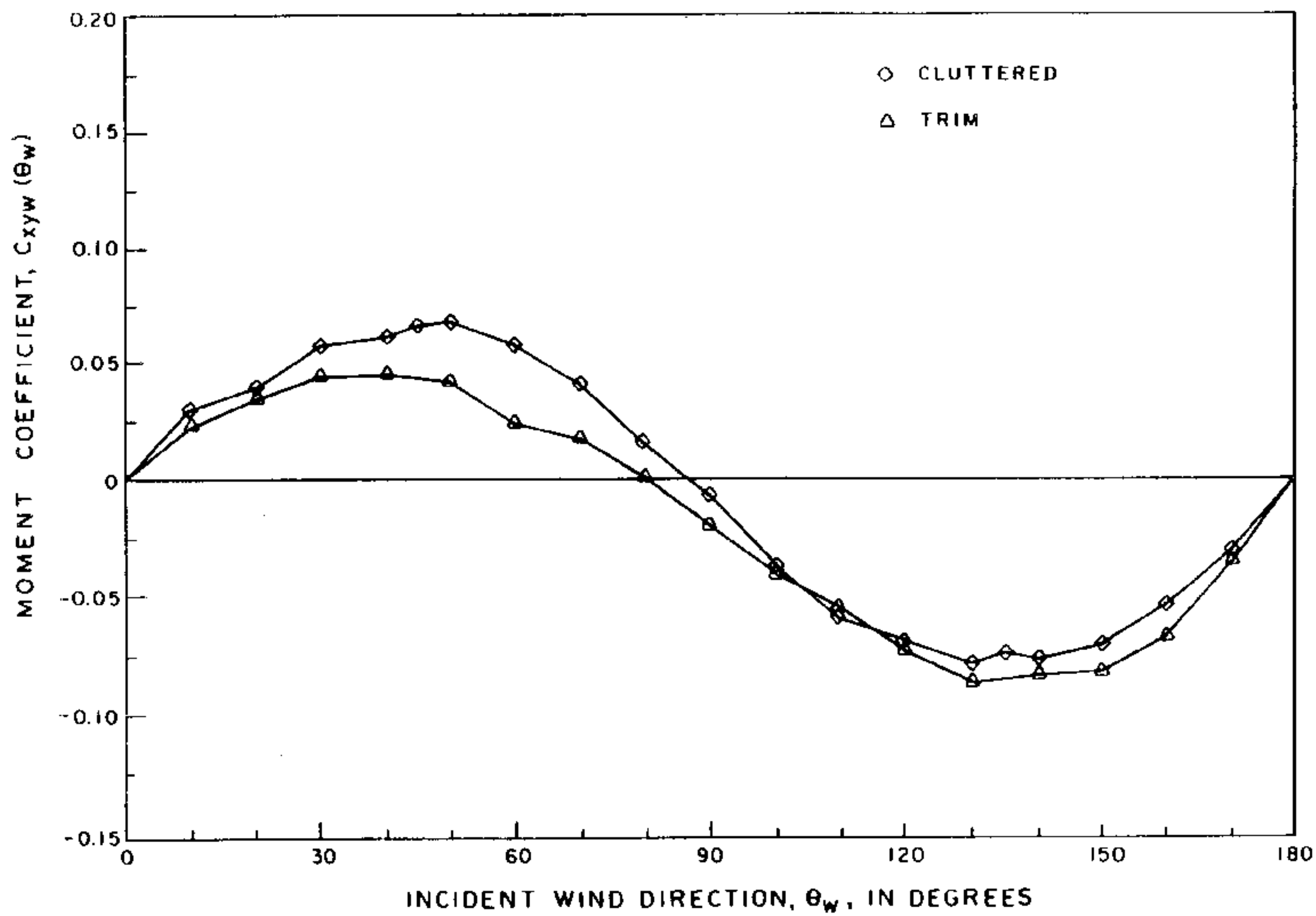


FIGURE 22
Recommended Yaw-Moment Coefficient for Center-Island Tankers

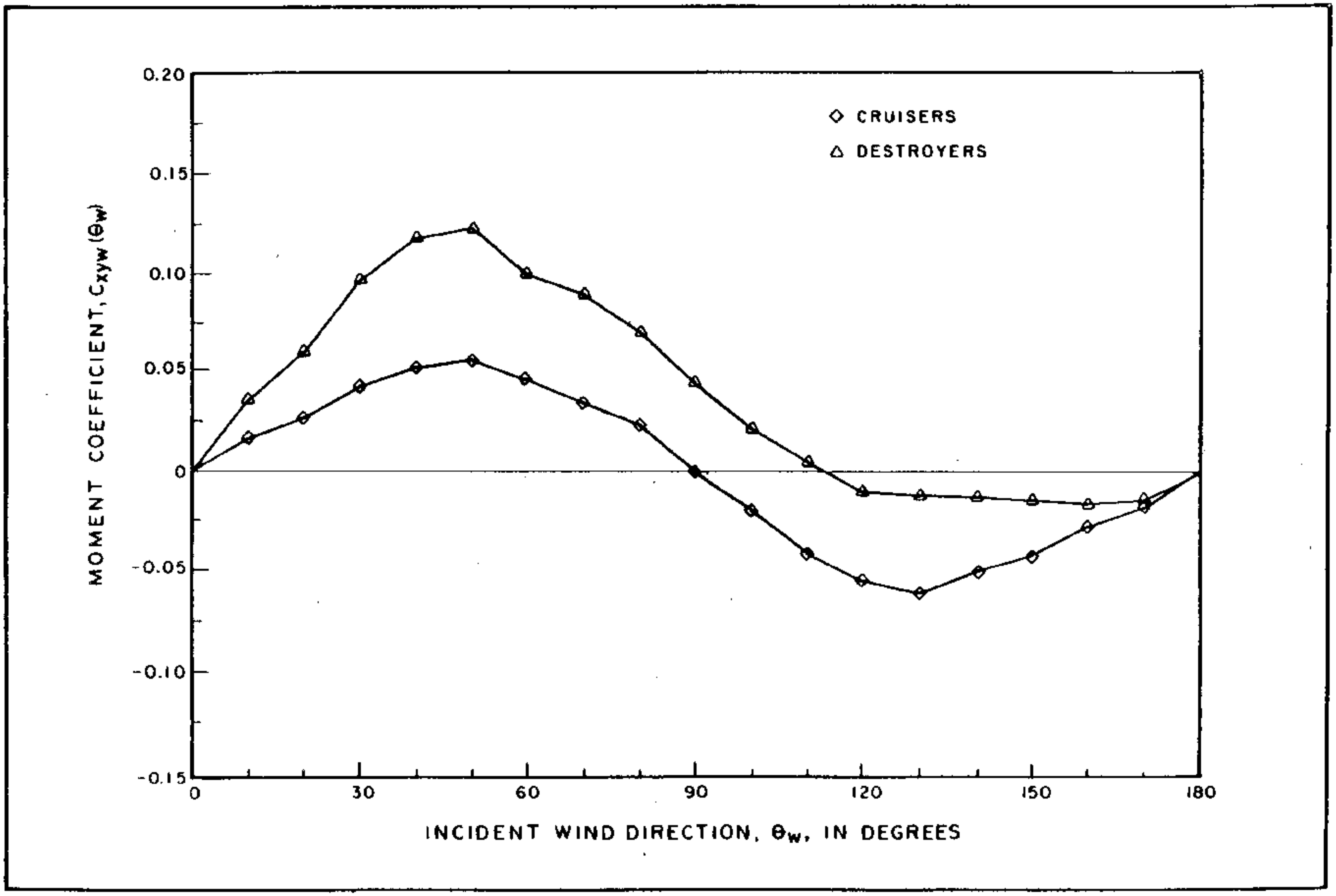


FIGURE 23
Recommended Yaw-Moment Coefficient for Typical Naval Warships

TABLE 6
Wind-Force Drag Coefficient, C_{DW}, for Floating Drydocks

Vessel	C_{DW}	Condition
ARD-12	0.909	Loaded draft but no ship
ARD-12	0.914	Minimum draft
AFDL-1	0.788	Minimum draft
AFDL-1	0.815	Loaded draft but no ship
AFDB-4	0.936	Minimum draft
AFDB-4	0.893	Loaded draft but no ship
AFDB-4	0.859	Drydock folded wing walls

(b) Longitudinal wind load. Longitudinal wind load on floating drydocks (without a vessel within the dock) is determined using the following:

$$F_{xw} = \frac{1}{2} \rho_a V_w^2 A_x C_{DW} \cos\theta_w \qquad (4\text{-}31)$$

WHERE: F_{xw} = longitudinal wind load, in pounds

ρ_a = mass density of air = 0.00237 slugs per cubic foot at 68deg.F

V_w = wind velocity, in feet per second

A_x = longitudinal projected area of dock, in square feet

C_{DW} = wind-force drag coefficient

The frontal wind areas for floating drydocks are provided in Table 3 of DM-26.6. As in the case of lateral load, when the maximum vessel on the blocks protrudes above the dock profile, then the dock should be treated as a "ship-shaped" vessel. (See Subsection 5.3.a.(1).)

The longitudinal wind load on a floating drydock is computed in the same manner as is the lateral wind load. Therefore, the wind-force drag coefficients, C_{DW}, for the lateral and longitudinal wind loads are the same and are those given in Table 6.

(c) Wind yarn moment. Wind yarn moment is computed using the following equation for the ARD-12 taken from Altmann (1971):

$$M_{xyw} = F_{yw} e_w \qquad (4\text{-}32)$$

WHERE: M_{xyw} = wind yarn moment, in foot-pounds

F_{yw} = lateral wind load, in pounds

e_w = eccentricity of F_{yw}, in feet

$$e_w = L \left[\frac{3.125}{100} - 0.0014\,(\theta_w - 90deg.)\right] \text{ for } 0deg. \leq \theta_w \leq 180deg. \qquad (4\text{-}33)$$

$$e_w = L \left[\frac{3.125}{100} + 0.0014\,(\theta_w - 270deg.)\right] \text{ for } 180deg. \leq \theta_w \leq 360deg. \qquad (4\text{-}34)$$

L = length of drydock

Unlike the ARD-12, which is asymmetrically shaped, the AFDL-1 and AFDB-4 are symmetrically shaped drydocks. Therefore, from an analytical standpoint, the wind yaw moment on the AFDL-1 and AFDB-4 drydocks is zero when there is no vessel within the dock. When the vessel within the dock protrudes above the drydock profile, the wind yaw moment is computed using the procedures for "ship-shaped" vessels. (See Subsection 5.3.a.(1).)

b. Current load.

(1) Lateral Current load. lateral current load is determined from the following equation:

$$F_{yc} = \frac{1}{2}\,\rho_w\, V_c^{\,2}\, L_{wL}\, T\, C_{yc} \sin\theta_c \qquad (4\text{-}35)$$

WHERE: F_{yc} = lateral current load, in pounds

ρ_w = mass density of water = 2 slugs per cubic foot for sea water

V_c = current velocity, in feet per second

L_{wL} = vessel waterline length, in feet

T = vessel draft, in feet

C_{yc} = lateral current-force drag coefficient

θ_c = current angle

The lateral current-force drag coefficient is given by:

$$C_{yc} = C_{yc}\big|_{\infty} + \left(C_{yc}\big|_1 - C_{yc}\big|_{\infty}\right) e^{-k\left(\frac{wd}{T} - 1\right)} \qquad (4\text{-}36)$$

WHERE: C_{yc} = lateral current-force drag coefficient

$C_{yc}\big|_{\infty}$ = limiting value of lateral current-force drag coefficient for large values of $\frac{wd}{T}$

$C_{yc}\big|_1$ = limiting value of lateral current-force drag coefficient for $\frac{wd}{T} = 1$

e = 2.718

k = coefficient

wd = water depth, in feet

T = vessel draft, in feet

Values of $C_{yc}|_{\infty}$ are given in Figure 24 as a function of L_{wL}/B (the ratio of vessel waterline length to vessel beam) (ordinate) and vessel block coefficient, ϕ, (abscissa). The block coefficient is defined as:

$$\phi = \frac{35\ D}{L_{wL}\ B\ T} \tag{4-37}$$

WHERE: ϕ = vessel block coefficient

D = vessel displacement, in long tons

L_{wL} = vessel waterline length, in feet

B = vessel beam, in feet

T = vessel draft, in feet

Values of $C_{yc}|_{1}$ are given in Figure 25 as a function of $C_{p}L_{wL}/\sqrt{T}$. C_{p}, the prismatic coefficient of the vessel, is defined as:

$$C_{p} = \frac{\phi}{C_{m}} \tag{4-38}$$

WHERE: C_{p} = prismatic coefficient of vessel

ϕ = vessel block coefficient

C_{m} = midship section coefficient

$$= \frac{\text{immersed area of midship section}}{B\ T} \tag{4-39}$$

B = vessel beam, in feet

T = vessel draft, in feet

The value of the coefficient, k, is given in Figure 26 as a function of the vessel block coefficient, ϕ, and vessel hull shape (block-shaped or normal ship-shaped).

The values of the coefficients $C_{yc}|_{\infty}$, $C_{yc}|_{1}$, and k are presented in Table 7 for each vessel originally tested by the David Taylor Model Basin, Dimensional properties of each vessel are also given in this table.

(2) Longitudinal Current Load. Longitudinal current load procedures are taken from Cox (1982). Longitudinal current load is determined using the following equation:

$$F_{xc} = F_{x\ form} + F_{x\ friction} + F_{x\ prop} \qquad (4\text{-}40)$$

WHERE: F_{xc} = total longitudinal current load

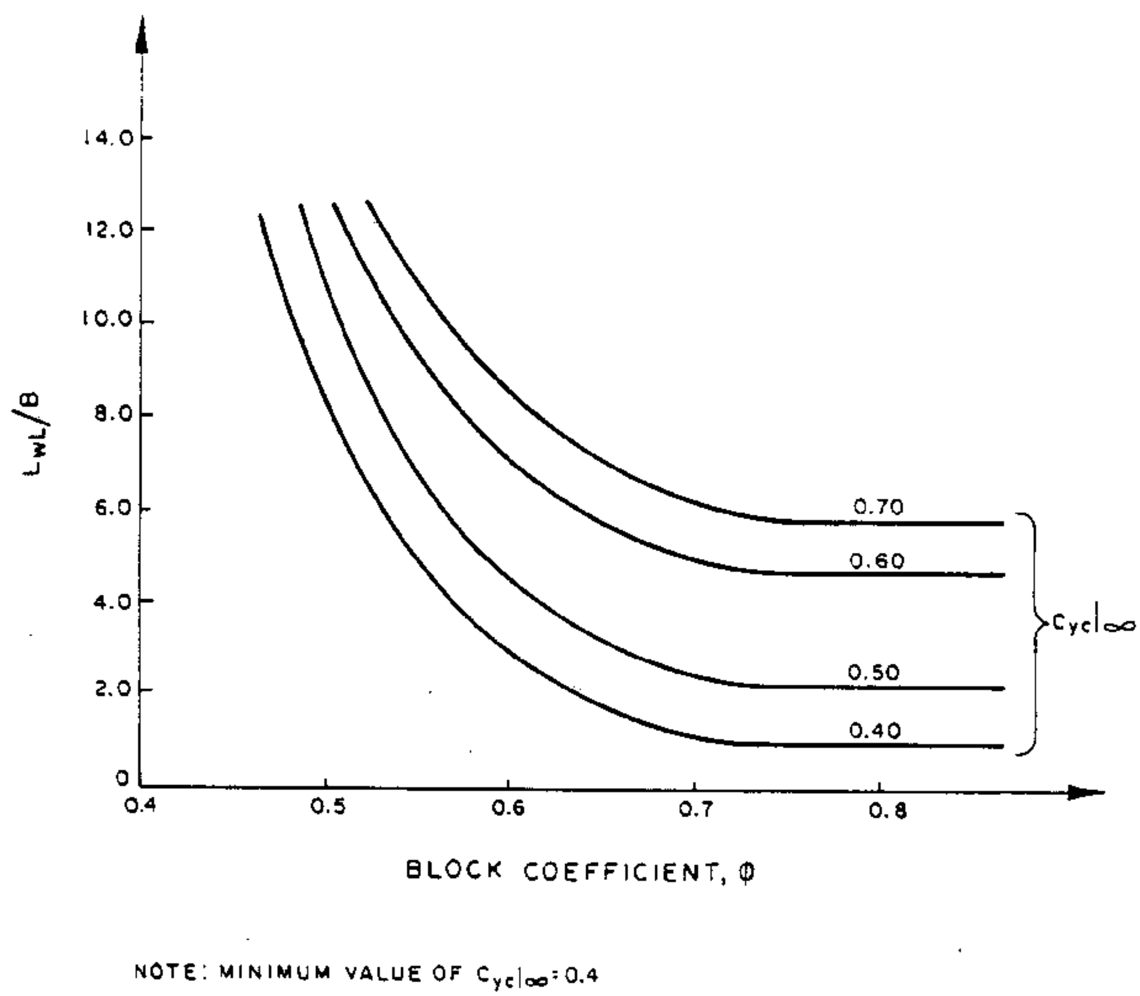


FIGURE 24

$C_{yc}|_{\infty}$ as a Function of L_{wL}/B and ϕ

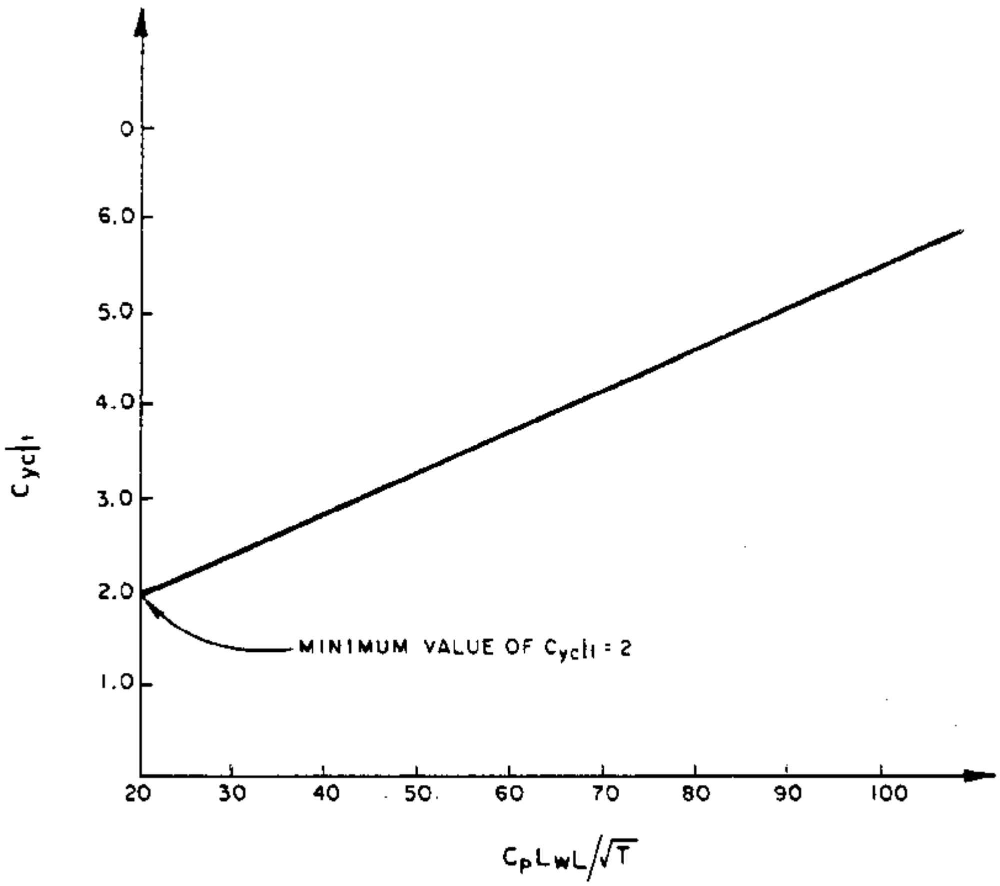


FIGURE 25

$C_{yc}\big|_1$ as a Function of $C_p L_{wL}/\sqrt{T}$

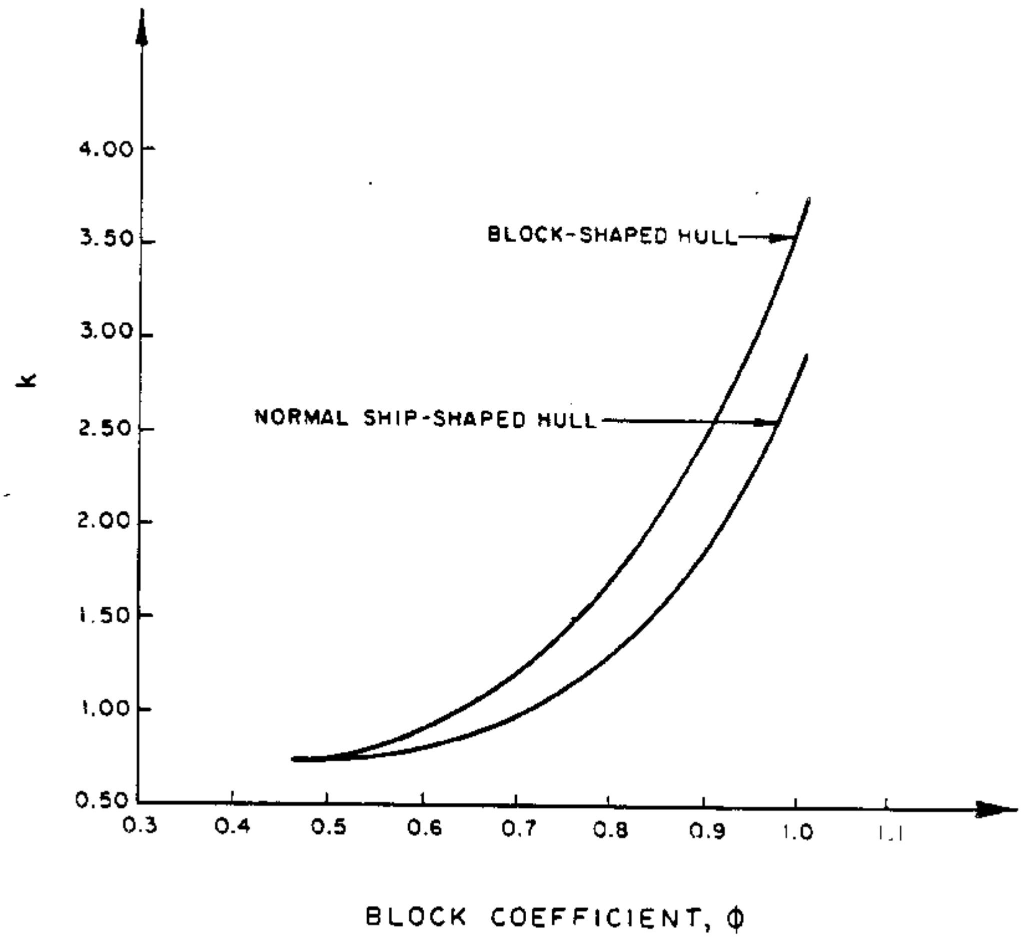


FIGURE 26
k as a Function of ϕ and Vessel Hull Shape

TABLE 7

ϕ, $C_{yc}|_{\infty}$, $C_{yc}|_{1}$, C_p, $C_pL_{wL}/\sqrt{T}$, k, and Dimensional Properties for DTMB Models

Ship Type	L_{wL} (feet)	B (feet)	T (feet)	Block Coefficient, ϕ	$C_{yc}|_{\infty}$ (deep water)	$C_{yc}|_{1}$ (shallow water)	C_p (estimated)	$\frac{C_pL_{wL}}{\sqrt{T}}$	k
AFDB-4	725	240	10.0	0.721	0.50	5.00	*		5.00
			20.0	0.785-0.820			*		
			67.0	0.855			1	88	
AFDL-1	200	64	4.5	0.675	0.55	2.55	*		3.00
			8.0	0.728			*		
			28.5	0.776			1	37	
ARD-12	489	81	6.0	0.805	0.70	4.25	*		1.80
			10.5	0.828			*		
			32.0	0.864			1	86	
AO-143(T-5)	655	86	16.6	0.636	0.75	4.00	0.684	82	0.75
			35.1	0.672					
EC-2	410	57	10.0	0.626	0.60	4.60	0.758	98	0.80
CVE-55	490	65	16.64	0.547	0.60	4.60	0.567	68	0.80
SS-212	307	27	14.25	0.479	0.40	2.80	0.479	39	0.75
DD-692	369	41	10.62	0.472	0.40	3.30	0.539	61	0.75

*Not computed for smaller draft; assume that drydock is moored to accommodate maximum draft

$F_{x\ form}$ = longitudinal current load due to form drag

$F_{x\ friction}$ = longitudinal current load due to skin friction drag

$F_{x\ prop}$ = longitudinal current load due to propeller drag

Form drag is given by the following equation:

$$F_{x\ form} = -\frac{1}{2} \rho_w V_c^{2} B T C_{xcb} \cos\theta_c \qquad (4\text{-}41)$$

WHERE: $F_{x\ form}$ = longitudinal current load due to form drag

ρ_w = mass density of water = 2 slugs per cubic foot for sea water

V_c = average current speed, in feet per second

B = vessel beam, in feet

T = vessel draft, in feet

C_{xcb} = longitudinal current form-drag coefficient = 0.1

θ_c = current angle

Friction drag is given by the folowing equation:

$$F_{x\ friction} = -\frac{1}{2} \rho_w V_c^{2} S C_{xca} \cos\theta_c \qquad (4\text{-}42)$$

WHERE: $F_{x\ friction}$ = longitudinal current load due to skin friction

ρ_w = mass density of water = 2 slugs per cubic foot for sea water

V_c = average current speed, in feet per second

S = wetted surface area, in square feet

$$= (1.7\ T\ L_{wL}) + \left(\frac{35\ D}{T}\right) \qquad (4\text{-}43)$$

T = vessel draft, in feet

L_{wL} = waterline length of vessel, in feet

D = displacement of ship, in long tons

C_{xca} = longitudinal skin-friction coefficient

$$= 0.075/(\log R_n - 2)^{2} \qquad (4\text{-}44)$$

R_n = Reynolds number = $V_c\ L_{wL}$

cos[theta]┌c┐/[upsilon] (4-45)

$[\upsilon]$ = kinematic viscosity of water (1.4×10^{-5} square feet per second)

$[\theta]_c$ = current angle

Propeller drag is the form drag of the vessel's propeller with a locked shaft. Propeller drag is given by the following equation:

$$F_{x\,prop} = -\frac{1}{2} [\rho]_w V_c^2 A_p C_{prop} \cos[\theta]_c \qquad (4\text{-}46)$$

WHERE: $F_{x\,prop}$ = longitudinal current load due to propeller drag

$[\rho]_w$ = mass density of water = 2 slugs per cubic foot for sea water

V_c = average current speed, in feet per second

A_p = propeller expanded (or developed) blade area, in square feet

C_{prop} = propeller-drag coefficient (assumed to be 1)

$[\theta]_c$ = current angle

A_p is given by:

$$A_p = \frac{A_{Tpp}}{1.067 - 0.229\ p/d} = \frac{A_{Tpp}}{0.838} \qquad (4\text{-}47)$$

WHERE: A_p = propeller expanded (or developed) blade area, in square feet

A_{Tpp} = total projected propeller area, in square feet

p/d = propeller pitch to diameter ratio (assumed to be 1)

Table 8 shows the area ratio, A_R, for six major vessel groups. (The area ratio is defined as the ratio of the waterline length times the beam to the total projected propeller area.) Then, the total projected propeller area, A_{Tpp}, can be given in terms of the area ratio as follows:

$$A_{Tpp} = \frac{L_{wL}\ B}{A_R} \qquad (4\text{-}48)$$

WHERE: A_{Tpp} = total projected propeller area, in square feet

L_{wL} = waterline length of vessel, in feet

B = vessel beam, in feet

A_R = area ratio, found in Table 8

TABLE 8
A_R for Propeller Drag

Vessel Type	Area Ratio, A_R
Destroyer	100
Cruiser	160
Carrier	125
Cargo	240
Tanker	270
Submarine	125

(3) Current Yaw Moment. Procedures for determining current yaw moment are taken from Altmann (1971). Current yarn moment is determined using the following equation:

$$M_{xyc} - F_{yc}\left[\frac{e_c}{L_{wL}}\right] L_{wL} \qquad (4\text{-}49)$$

WHERE: M_{xyc} = current yarn moment, in foot-pounds

F_{yc} = lateral current load, in pounds

$\left[\frac{e_c}{L_{wL}}\right]$ = ratio of eccentricity of lateral current load measured along the longitudinal axis of the vessel from amidships to vessel waterline length

e_c = eccentricity of F_{yc}

L_{wL} = vessel waterline length, in feet

The value of (e_c/L_{wL}) is given in Figure 27 as a function of current angle, [theta]$_c$, and vessel type.

5. ENVIRONMENTAL LOADS ON MULTIPLE MOORED VESSELS. This section describes methods for determining static wind and current loads on multiple moored vessels. The longitudinal force, lateral force, and yaw moment are evaluated. Figure 19 defines the coordinate system and nomenclature for describing these loads. A discussion of the various physical phenomena involved in these procedures is provided in Section 3. Procedures vary depending upon whether the multiple-vessel mooring consists of identical or nonidentical vessels.

a. Identical Vessels. Altmann (1971) has formulated a procedure for estimating wind and current loads induced on nests of identical moored vessels. The procedures provide conservative estimates of lateral loads, longitudinal loads, and yaw moment.

(1) Wind Load.

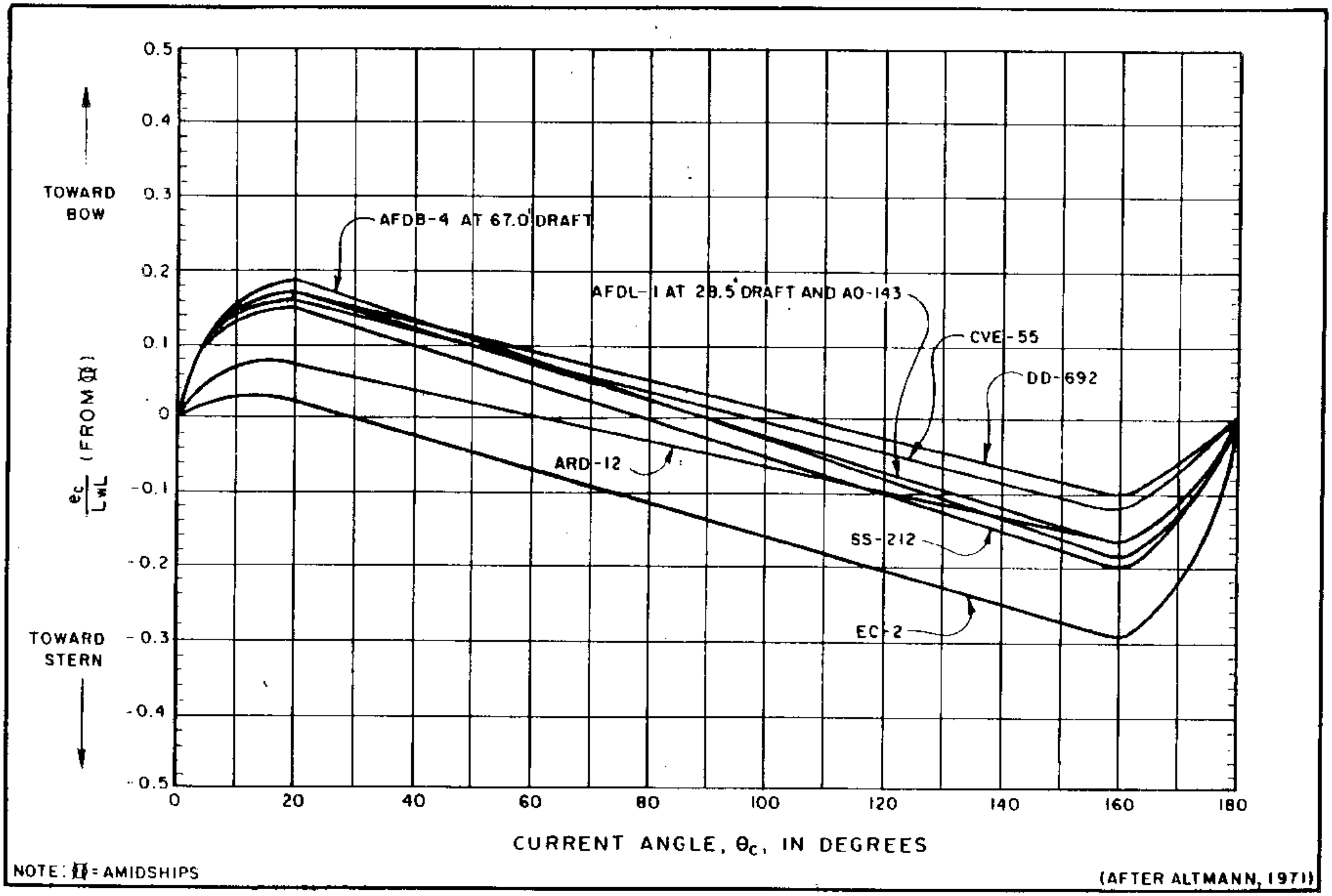


FIGURE 27
(e_c/L_{wL}) as a Function of Vessel Type and Current Angle

(a) Lateral wind load. The lateral wind load on a single vessel within a group of identical vessels depends upon the position of that vessel within the group. For example, the wind load is larger on the first (most windward) vessel in a group than on the interior vessels. The following empirical equation gives lateral wind load on a group of identical vessels:

$$F_{ywg} = F_{yws}\ (K_1 \sin\theta_w + K_2 \sin3\theta_w + K_3 \sin3\theta_w + K_4\ (1 - \cos4\theta_w) + \ldots K_5\ (1 - \cos4\theta_w)) \tag{4-50}$$

WHERE: F_{ywg} = total lateral wind load on a group of identical vessels (g refers to "group")

F_{yws} = lateral wind load on a single vessel (Equation (4-11)) at θ_w = 90° (s refers to "single")

$K_1 \ldots K_5$ = dimensionless wind-force coefficients

θ_w = wind angle (assumes values between 0 and 180 degrees; beyond 180 degrees, the relative positions of the vessels become reversed)

The dimensionless wind-force coefficients, K_1, K_2 ... K_5, are presented in Table 9 as a function of ship type (normal or hull-dominated) and position of the vessel in the mooring. The number of K terms used in Equation (4-50) is a function of the number of ships in the mooring. If the load on only one of the vessels in the mooring is desired, then only the term of interest is is needed. For example, if the load on the second vessel in a group of three is needed, then only K_2 is used in Equation (4-50). The load on the entire mooring is the summation indicated by Equation (4-50). The terms K_1 and K_5, which represent the most windward and leeward vessels in a mooring, respectively, are always used. K_2 is used for the second vessel in a group of three or more. K_4 is used for the second-from-last vessel in a group of four or more vessels. The K_3 coefficient is used for the third vessel in moorings of five or more vessels. The K_4 coefficient is used for each additional vessel in moorings of six or more vessels. Figure 28 shows how to assign the various K coefficients for vessel groups consisting of two to six vessels.

TABLE 9
Lateral Wind-Force Coefficients for Multiple-Vessel Moorings

Ship Model	Ship Type	K_1	K_2	K_3	K_4	K_5
CVE-55 SS-212	Hull-dominant; little superstructure	1.00	0.20	0.16[1]	0.35	0.44
EC-2 DD-692	Standard profile; considerable superstructure	1.00	0.14	0.11	0.13	0.30

[1]No data; suggested value

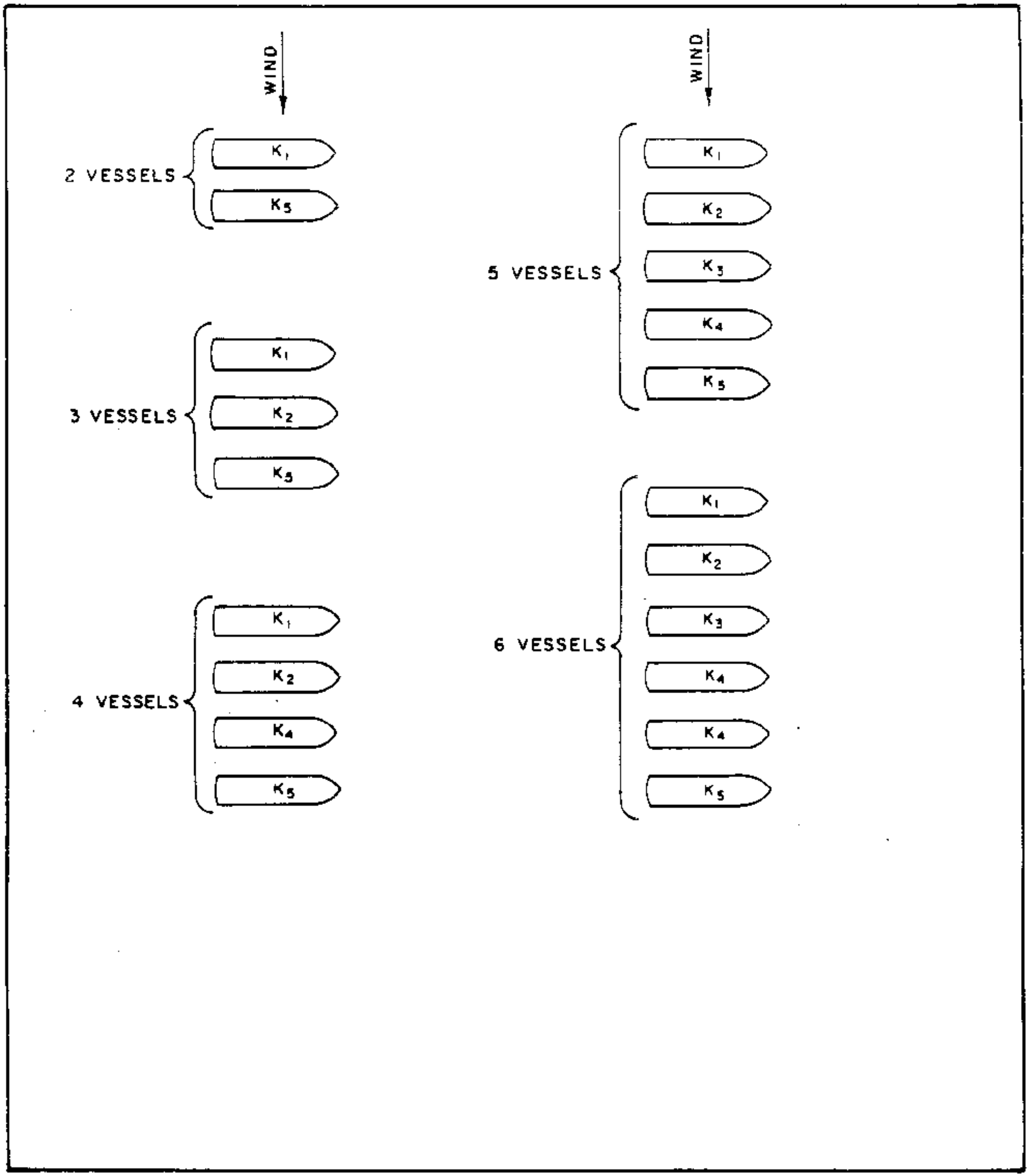


FIGURE 28
Assignment of K Coefficients for Vessel Groups of Two to Six Vessels

(b) Longitudinal wind load. The total longitudinal wind load on a group of identical vessels is determined as follows:

$$F_{xwg} = F_{xws}\ n \qquad (4\text{-}51)$$

WHERE: F_{xwg} = total longitudinal wind load an a group of identical vessels

F_{xws} = longitudinal wind load on a single vessel (Equation (4-16))

n = number of vessels in the group

(c) Wind yaw moment. The wind yaw moment on a Single vessel within a group of identical vessels is a function of the position of that vessel and the number of vessels in the mooring. First, the yaw moment on a single vessel, M_{xyws}, at a specified wind angle, θ_w, is calculated. Then, the appropriate coefficients from Figure 29 are used to determine the moment on individual vessels in the mooring. The coefficients, k_{Nw}, from Figure 29 are summed and multiplied by M_{xyws} to determine the total moment on the vessel group:

$$M_{xywg} = M_{xyws}\ (k_{Nw1} + K_{Nw2} + K_{Nw3} + \ldots) \qquad (4\text{-}52)$$

WHERE: M_{xywg} = total wind yaw moment on a group of identical vessels

M_{xyws} = wind yaw moment on a single, vessel (Equation (4-29))

K_{Nw1}, K_{Nw2} ... = wind yaw-moment coefficient which accounts for the number and location of vessels in the mooring; given in Figure 29

(2) Current load.

(a) Lateral current load. The lateral current load on a single vessel within a group of identical vessels depends upon the spacing of the vessels and the position of the vessel within the group. The effect of vessel spacing is shown in Figure 30, which provides the ratio (K_6) of the load on the first vessel in the mooring to that on a single vessel for several values of dimensionless spacing and for vessel types. (The first vessel is the one which is subjected to the full current load, analogous to the most windward vessel discussed previously.) Dimensionless spacing is defined as the ratio of distance between vessel centerlines, d_{cL}, to vessel beam, B. The effect of vessel position in a multiple-vessel mooring is shown in Figure 31, which presents the ratio, K_7, of lateral current load on a vessel within a mooring to that on the first vessel as a function of the position and total number of vessels in the mooring.

The following equations can be used to determine lateral current loads on a group of identical vessels. The lateral current load on the first vessel in the mooring is given by:

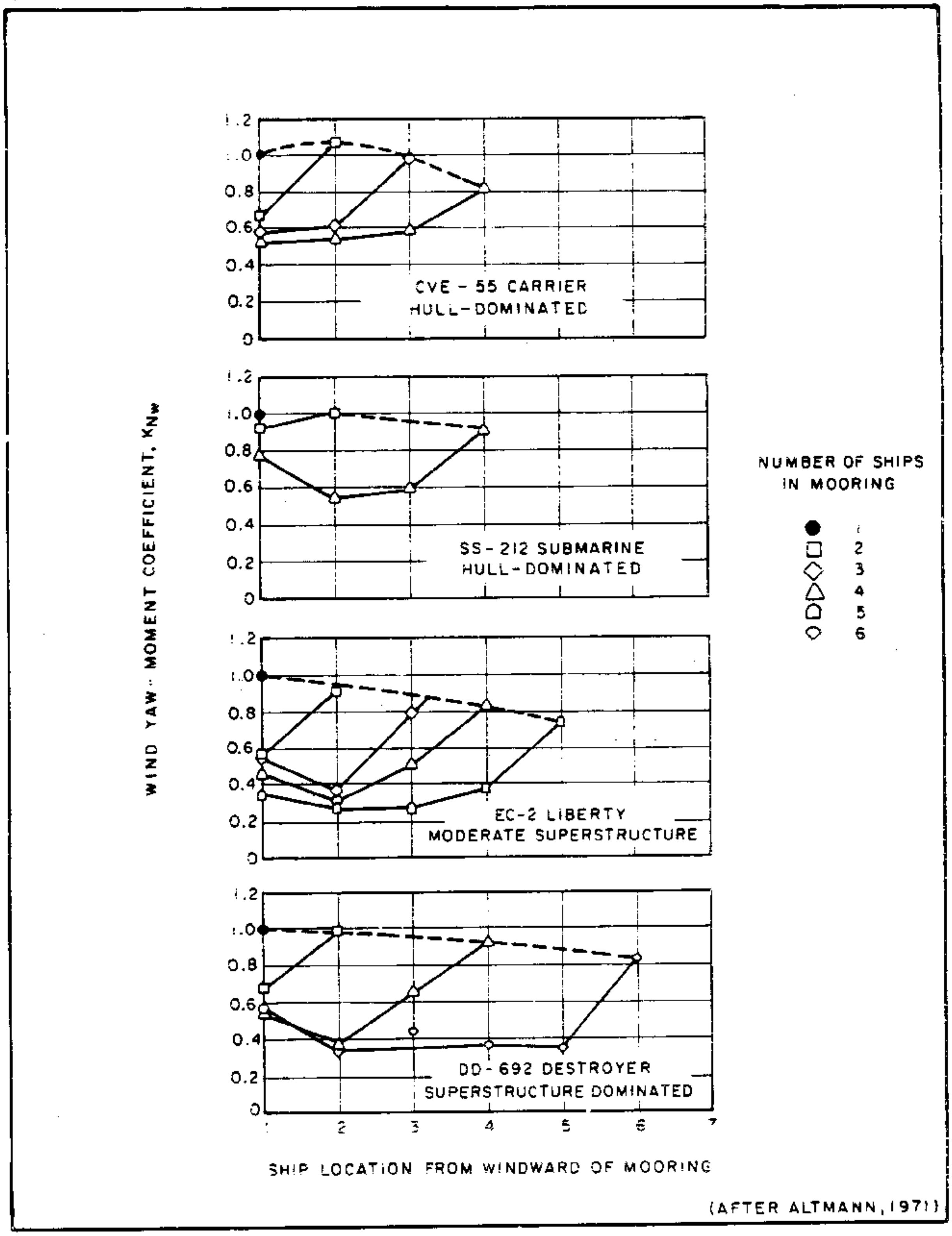


FIGURE 29

Wind Yaw-Moment Coefficient, K_{Nw}, for Multiple-Vessel Moorings

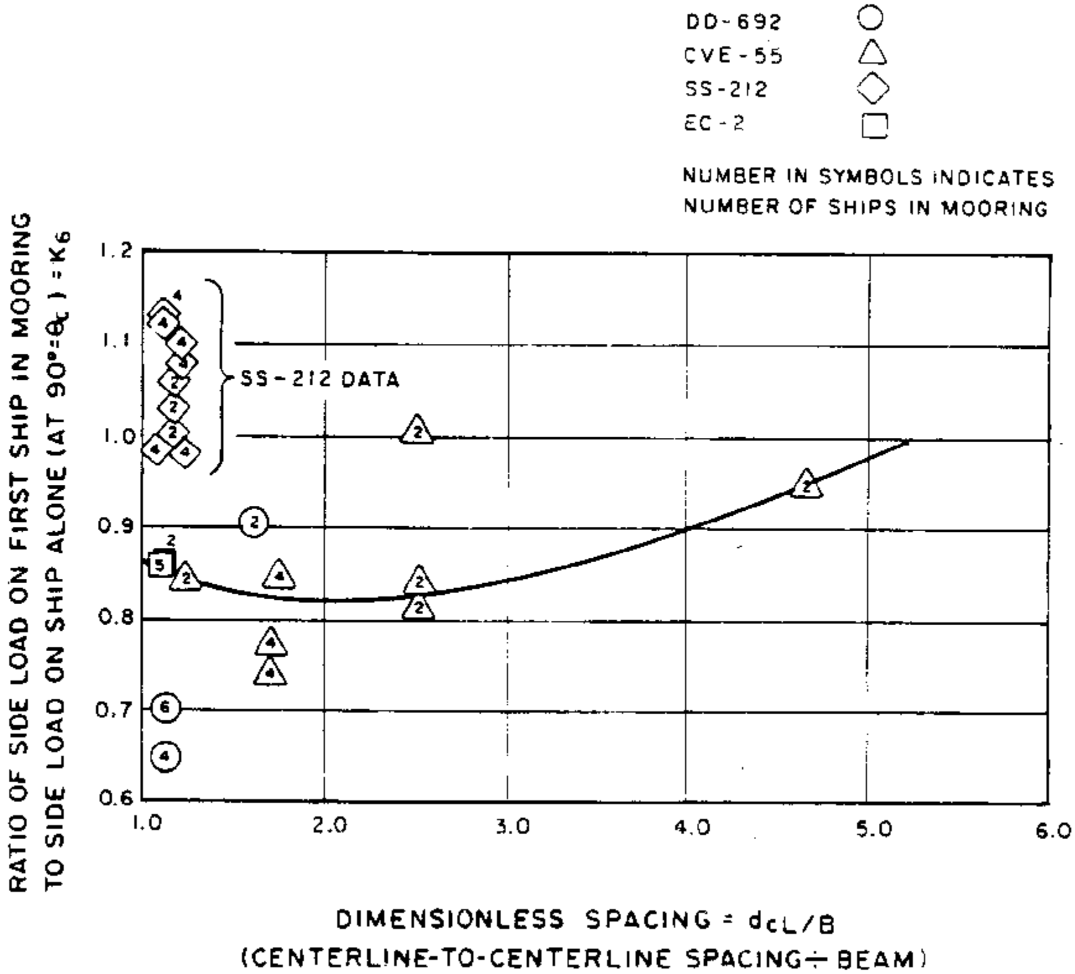


FIGURE 30
K_6 as a Function of Dimensionless Spacing

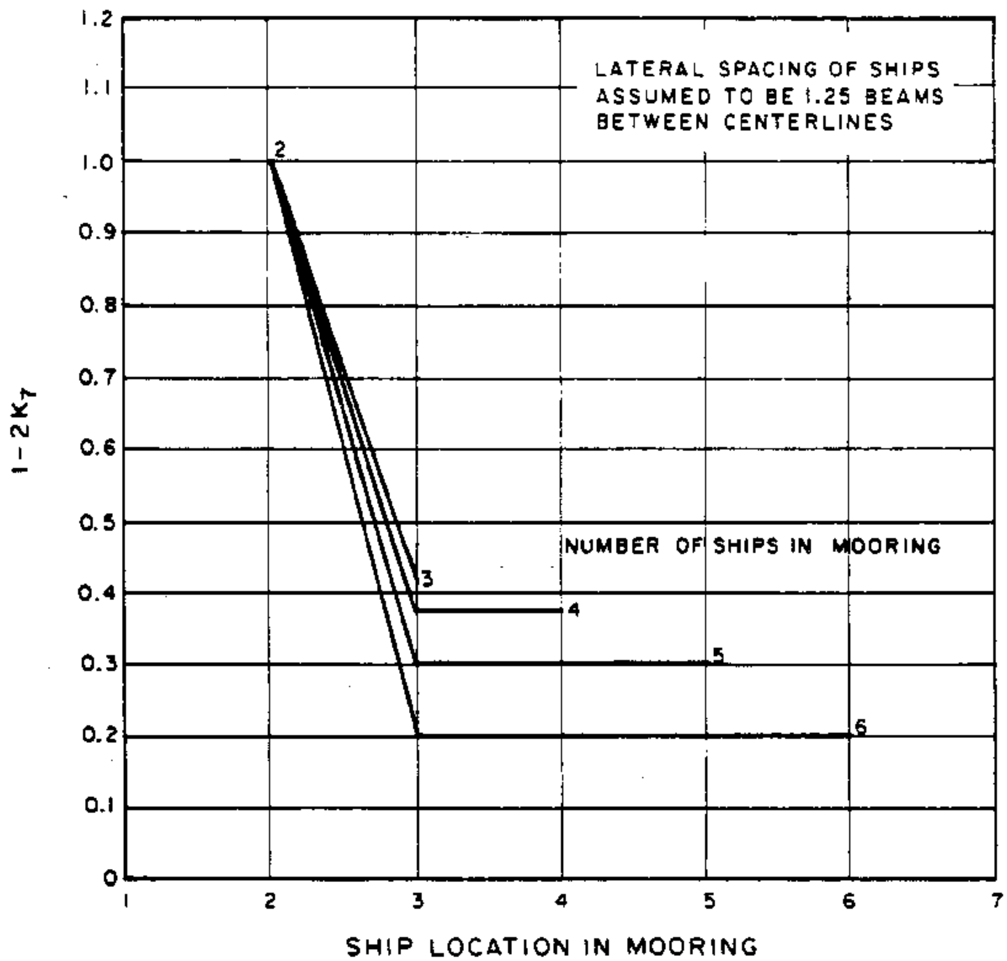


FIGURE 31

K_7 as a Function of Vessel Position and Number of Vessels in Mooring

$$F_{yc1} = 1/2\ F_{ycs}\ K_6\ (1- \cos 2\theta_c) \qquad (4\text{-}53)$$

The lateral current load on the second vessel of a mooring with three or more vessels is given by:

$$F_{yc2} = (F_{yc1} \text{ @ } 90\text{deg.})\ [\sin\theta_c - K_7\ (1 - \cos 2\theta_c)] \qquad (4\text{-}54)$$

The lateral current load on each remaining vessel in a mooring, or on the second vessel if there are only two vessels in the mooring, is given by:

$$F_{ycz} = (F_{yc1} \text{ @ } 90\text{deg.})\ [\sin\theta_c - K_7\ (1 - 0.5 \cos 2\theta_c - 0.5 \cos 6\theta_c)] \qquad (4\text{-}55)$$

WHERE:

- F_{yc1} = lateral current load on the first vessel in a group
- F_{ycs} = lateral current load on a single vessel at θ_c = 90deg. (Equation (4-35))
- K_6 = spacing factor, given in Figure 30
- θ_c = current angle
- F_{yc2} = lateral current load on the second vessel in a group of three or more
- F_{yc1} @ 90deg. = lateral current load on the first vessel in a group at θ_c = 90deg.
- K_7 = a factor for position and number of vessels in a mooring, given by Figure 31
- F_{ycz} = lateral current load on the z^{th} vessel in a mooring, or on the second vessel if there are only two vessels in the mooring
- z = a position of vessel

The above equations can be used to determine the loads on each individual vessel or, when summed, to determine the total load on the group of identical vessels.

(b) Longitudinal current load. The total longitudinal current load on a group of identical vessels is determined by the following equation:

$$F_{xcg} = F_{xcs}\ ^{n} \qquad (4\text{-}56)$$

WHERE:

- F_{xcg} = total longitudinal current load on a group of identical vessels
- F_{xcs} = longitudinal current load on a single vessel (Equation (4-40))
- n = number of vessels in the group

(c) Current yaw moment. The current yaw moment on a single vessel within a group of identical vessels is a function of the position of that vessel and the number of vessels in the mooring. First, the yaw moment on a single vessel, M_{xycs}, at a specified current angle, θ_c, is calculated. Then, the appropriate coefficients from Figure 32 are used to determine the moment on individual vessels in the mooring. The coefficients, K_{Nc}, from Figure 32 are summed and multiplied by M_{xycs} to determine the total moment on the vessel group:

$$M_{xycg} = M_{xycs} (K_{Nc1} + K_{Nc2} + K_{Nc3} + ...) \qquad (4\text{-}57)$$

WHERE: M_{xycg} = total current yaw moment on a group of identical vessels

M_{xycs} = current yaw moment on a single vessel (Equation (4-49))

K_{Nc1}, K_{Nc2}... = current yaw-moment coefficient which accounts for the number and location of vessels in the mooring, given in Figure 32

b. Nonidentical Vessels. Typical present-day multiple-vessel mooring arrangements consist of a tender with a number of identical vessels moored alongside in parallel fashion. In these moorings, the separation distance between the nested vessels and the tender is small. Frequently, the nested vessels are moored to each other and then to the tender. In this case, the mooring must be able to sustain the entire loading pattern induced on all vessels. This situation requires special treatment and additional model testing. In the absence of proper data, or until such data become available, the following approximate procedure for estimating wind loads on multiple moored vessels is suggested:

(1) Estimate the wind loads on the nest of identical vessels moored alongside the tender following the approach outlined above.
(2) Estimate the wind loads induced on the tender as a single vessel.
(3) Add the longitudinal loads linearly, since there is minimum interference between projected areas for streamlined objects in head-on winds. These additive loads constitute the longitudinal loads for the vessel group in wind.
(4) Compare the projected broadside areas exposed to wind for the nested group and the tender and compare the respective lateral forces, as determined from (1) and (2), above. Compare the beam of the tender with the composite beam of the nested group. The following cases are possible:

   (a) The beam of the tender is greater than half the composite beam of the nested group.
   (b) The beam of the tender is less than half the composite beam of the nested group.

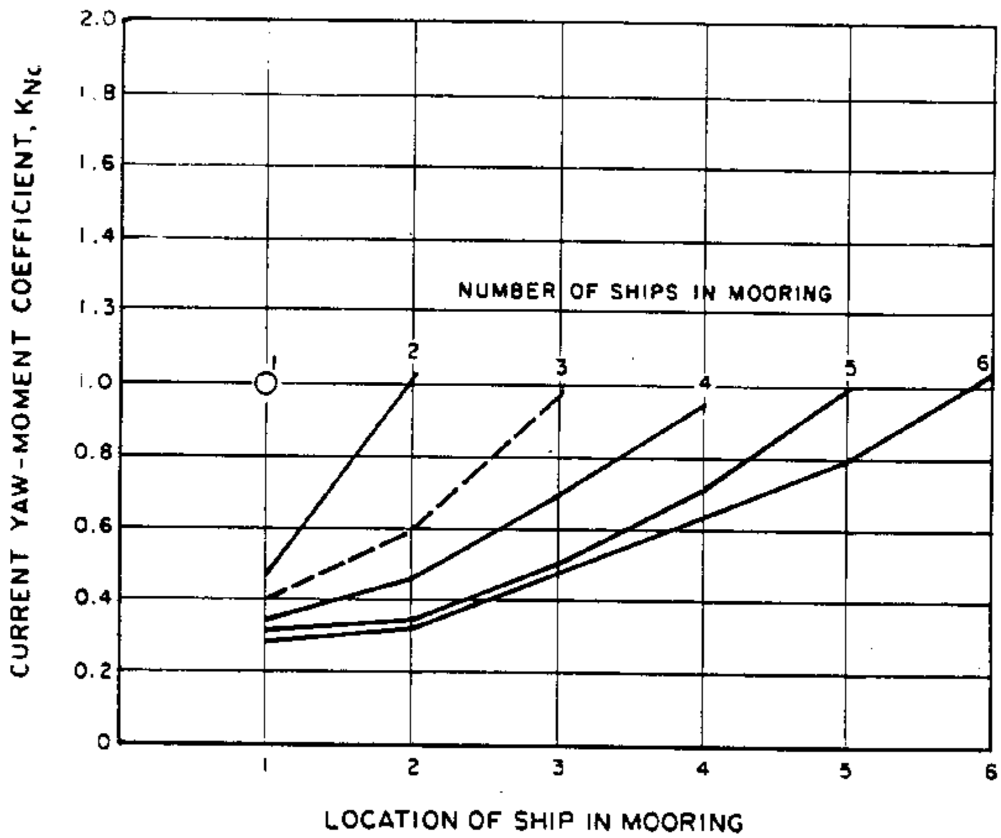


FIGURE 32
Current Yaw-Moment Coefficient, K_{Nc}, for Multiple-Vessel Moorings

(c) The projected broadside area of the tender exposed to wind is greater than twice the projected broadside area of the nested group (or single vessel).
(d) The projected broadside area of the tender exposed to wind is less than twice the projected broadside area of the nested group (or single vessel).

If (a) and (c) occur, then there is essentially complete sheltering and the lateral load for the group should be taken as the greater of the loads computed under (1) or (2) above. If (a) and (d) or (b) and (c) occur, then there is some sheltering, but it is not complete. Therefore, increase the maximum lateral load determined under (1) or (2) above by 10 percent for standard-profile vessels and by 15 percent for hull-dominated vessels. If (b) and (d) occur, then the sheltering that occurs is minimal and is not very effective. Under this circumstance, the maximum lateral load as determined under (1) or (2) above should be increased by 20 percent for standard-profile vessels and by 30 percent for hull-dominated vessels. The percentage increments indicated above are compatible with, but not the same as, the K factors defined for identical vessels.

(5) With the maximum lateral and longitudinal loads as determined in steps (1) through (4) above the following equation is used to determine loads acting at angles other than head-on and beam-on:

$$F_{xwg} = (F_{xwg} \text{ @ } 0\text{deg.}) \cos\theta_w \qquad (4\text{-}58)$$

$$F_{ywg} = (F_{ywg} \text{ @ } 90\text{deg.}) \sin\theta_w \qquad (4\text{-}59)$$

WHERE: F_{xwg} = longitudinal wind load acting on vessel group from wind with angle θ_w

F_{xwg} @ 0deg. = longitudinal wind load on vessel group at θ = 0deg.

θ_w = wind angle

F_{ywg} = lateral wind load acting on vessel group from wind with angle θ_w

F_{ywg} @ 90deg. = lateral wind load on vessel group at θ_w = 90deg.

(6) The yaw moments should be taken as the maximum of either the individual values determined in (1) or (2) above or the algebraic sum if the signs are the same.

In order to estimate current loads on multiple moored vessels, a similar procedure to that outlined in steps (1) through (6) above is used. There are differences in the procedure. First, instead of broadside projected area, the product of the waterline length (L_{wL}) and the draft (T) (that is,

L_{wL} times T) is used. Secondly, the effect of sheltering seems to be more effective over longer beam distances in the case of current than in the case of wind. The following change in procedure as outlined in Steps (4) and (5) above is recommended:

(4) (Changed) Compare the product L_{wL} T for the tender and for the nested group, and compare the respective lateral loads as determined from (1) and (2) above. Compare the beam of the tender with the composite beam of the nested group (including separation distances). The following cases are possible:

(a) The beam of the tender is greater than one-fourth of the beam of the composite group.
(b) The beam of the tender is less than one-fourth of the beam of the composite group.
(c) The L_{wL} T area of the tender exposed to current is greater than the L_{wL} T of the nested group.
(d) The L_{wL} T area of the tender exposed to current is less than the L_{wL} T of the nested group.

If (a) and (c) occur, then there is essentially complete sheltering and the lateral load for the group should be taken as the greater of the loads computed under (1) and (2) above. If (a) and (d) or (b) and (c) occur, then there is some sheltering, but it is not complete. Therefore, increase the maximum lateral load determined under (1) or (2) above by 10 percent for all vessels. If (b) and (d) occur, then the sheltering that occurs is minimal and equivalent to that of an additional vessel in the group. Increase the maximum lateral load as determined under (1) and (2) above by 20 percent. These percentage increments are compatible with the analysis for identical vessels. These increments are not the same as, but represent, both the effect of ship spacing (K_6) and the cumulative effect of the number of ships (K_7).

(5) (Changed) With the maximum lateral and longitudinal loads as determined above, the following equations are used to determine loads acting at angles other than head-on and beam-on:

$$F_{xcg} = (F_{xcg} \text{ @ } 0\text{deg.}) \cos\theta_c \tag{4-60}$$

$$F_{ycg} = (F_{ycg} \text{ @ } 90\text{deg.}) \sin\theta_c \tag{4-61}$$

WHERE: F_{xcg} = longitudinal current load acting on vessel group from current with angle θ_c

F_{xcg} @ 0deg. = longitudinal current load on vessel group at θ_c = 0deg.

θ_c = current angle

F_{ycg} = lateral current load acting on vessel group from current with angle θ_c

F_{ycg} @ 90deg. = lateral current load on vessel group at θ_c = 90deg.

As the dimensions of the tender vessel approach those of the vessel moored alongside, then the analysis should be the same as that obtained by considering a group of identical vessels (including the tender). On the other hand, as the dimensions of the tender vessel increase relative to those of the vessels moored alongside, the forces on the tender vessel dominate the loading pattern, and the forces induced on the nested group of vessels are inconsequential.

Often, in fixed moorings, the separation between the nested vessels and the tender is such that the vessels and tender act independently of each other. In fact, it is often desirable that the moorings be independent. This is an important consideration in exposed locations. Because the tender may not always be present, a conservative approach is one that emphasizes analysis and design of the mooring for the nested vessels separately from that of the tender mooring. In this case, the procedures for predicting loads (and moments) on the group of identical vessels should be used.

6. LOADS ON MOORING ELEMENTS. Wind and current loads on mooring lines, mooring structures, and breasting structures must be determined. Simplified procedures for determining loads on mooring elements are presented below. These simplified solutions are useful for preliminary design. The computer program presented in Appendix B of DM-26.5 is recommended for final design.

Mooring-line load analysis is presented so that mooring loads on mooring and breasting structures can be determined. Mooring lines are generally provided by the vessel, and selection of mooring lines is not normally part of the design process. However, the designer should check to see that the mooring-line factors of safety are maintained. Recommendations for working loads and factors of safety, which are given in DM-26.6, are summarized in Table 10. The minimum breaking strengths of various types of synthetic fiber, natural fiber, and wire rope are presented in DM-26.6, Tables 5 through 9. When the factors of safety of mooring lines are too low, the designer should recommend stronger lines or investigate another mooring geometry.

a. Total Loads. The first step in analyzing loads on mooring elements is to determine the total lateral load, total longitudinal load, and total yaw moment on the moored vessel using the following equations:

$$F_{yT} = F_{yw} + F_{yc} \qquad (4\text{-}62)$$

$$F_{xT} = F_{xw} + F_{xc} \qquad (4\text{-}63)$$

$$M_{xyT} = M_{xyw} + M_{xyc} \qquad (4\text{-}64)$$

WHERE: F_{yT} = total lateral load

F_{yw} = lateral wind load

F_{yc} = lateral current load

TABLE 10
Recommended Working Load and Factor of Safety
for Various Mooring-Line Types[1]

Mooring-Line Diameter	>/= 3/4 inch		< 3/4 inch	
Mooring-Line Material	Working Load[2] (percent)	Factor of Safety[3]	Working Load[2] (percent)	Factor of Safety[3]
Nylon	11	9	8.3	12
Kelvar	11	9	8.3	12
Polyester	17	6	10	10
Polypropylene	17	6	10	10
Polyethylene	17	6	10	10
Manila	17	6	10	10
Sisal	17	6	10	10
Wire	20	5	20	5

[1]Working loads and factors of safety are as recommended by the Cordage Institute and from manufacturers' minimum catalog breaking strength values. These values are based upon a percentage of the minimum breaking test of new and unused rope of current manufacturers. These values are based upon normal service conditions and do not cover exceptional conditions, such as shock loads and sustained loads, nor do they cover conditions where life, limb, or valuable property are involved. In these cases, a lower working load or higher factor of safety may be advisable. A higher working load or lower factor of safety should be used only with an expert knowledge of conditions or professional estimates of risk.

[2]Percent of minimum breaking strength of mooring line.

[3]Based upon minimum breaking strength of mooring line.

F_{xT} = total longitudinal load

F_{xw} = longitudinal wind load

F_{xc} = longitudinal current load

M_{xyT} = total yaw moment

M_{xyw} = wind yaw moment

M_{xyc} = current yaw moment

The yaw moment is resolved into lateral loads at the bow and stern of the vessel using the following equations (see Figure 33):

$$F_{yB} = \frac{F_{yT}}{2} + \frac{M_{xyT}}{L_{MP}} \tag{4-65}$$

$$F_{yS} = \frac{F_{yT}}{2} - \frac{M_{xyT}}{L_{MP}} \tag{4-66}$$

WHERE: F_{yB} = lateral load at vessel bow

F_{yT} = total lateral load

M_{xyT} = total yaw moment

L_{MP} = length between mooring points

F_{yS} = lateral load at vessel stern

b. Lateral Load and Yaw Moment. Lateral load and yaw moment are restrained either by mooring lines (bow, stern, or breast lines), by breasting structures, or by a combination of mooring lines and breasting structures. First, the signs of the lateral loads, F_{yB} and F_{yS}, at the bow and stern of the vessel, respectively, are compared. Case 1 is used if F_{yB} and F_{yS} are both negative; Case 2 is used if both are positive; and Case 3 is used if their signs are opposite. The sign convention used to determine the appropriate case must be consistent with that given in Figure 33. Note that the total mooring-line load is the sum of the applied load and the mooring-line pretension.

(1) Case 1. When F_{yB} and F_{yS} are both negative, the lateral load is restrained entirely by mooring lines. (See Figure 12.) The procedure for evaluating lateral load in bow, stern, and breast lines is shown in Figure 34.

(2) Case 2. When F_{yB} and F_{yS} are both positive, the lateral load is restrained entirely by the breasting structures. Figure 35 presents a simple analysis for determining loads on a fixed mooring consisting of two breasting structures separated by a distanced L_F. A more sophisticated analysis may be required for more complicated breasting-structure arrangements. However, Figure 35 outlines the basic principles involved.

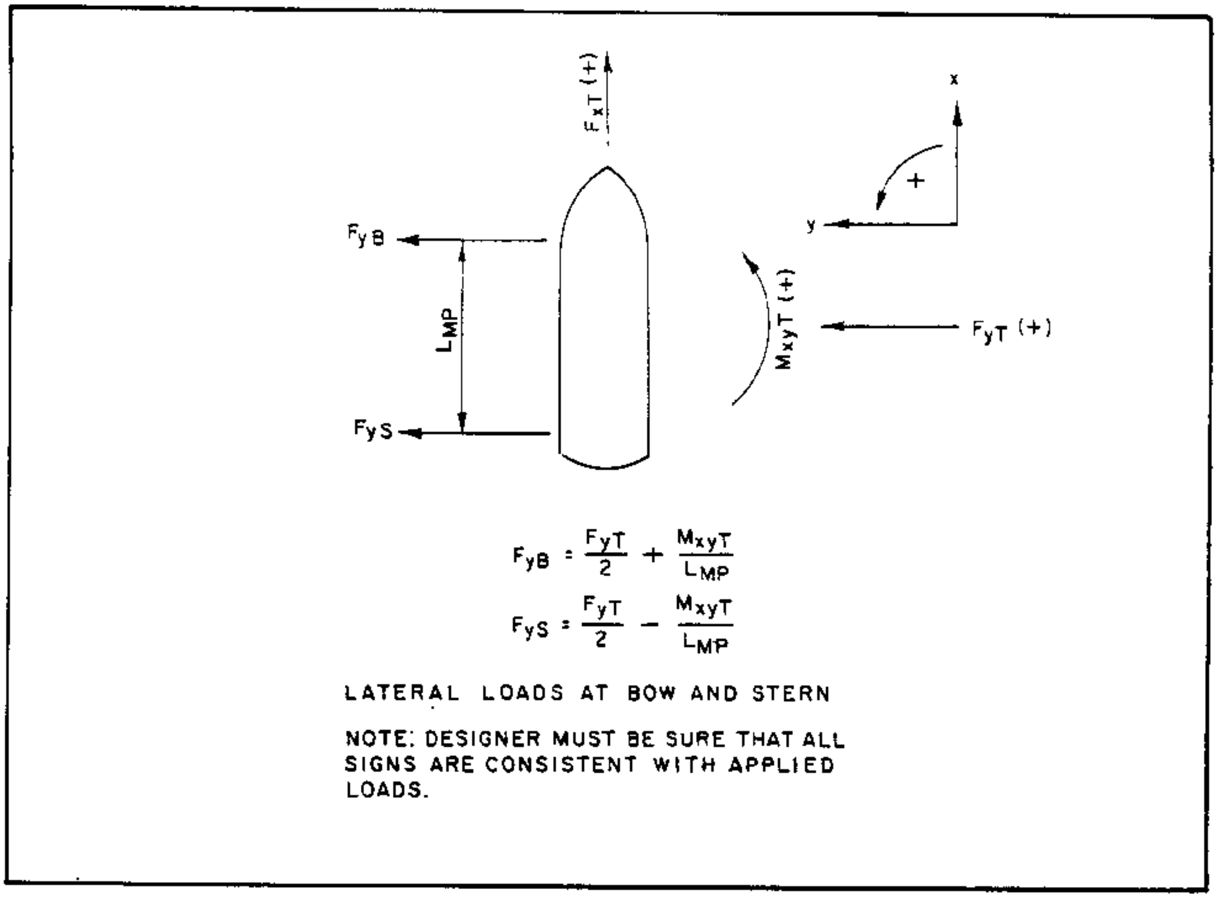


FIGURE 33
Method for Resolving Yaw Moment Into Lateral Loads at Bow and Stern of Vessel

(3) Case 3. When F_{yB} and F_{yS} are opposite in sign, part of the lateral load is restrained by the mooring lines in tension, while the remainder of the lateral load is restrained by a breasting structure in compression at the opposite end of the vessel. Figure 36 outlines the procedure for analyzing Case 3. This procedure assumes that the positive lateral load is taken by one breasting structure. This is true for fixed moorings with two breasting structures, and provides a conservative estimate of load on the outside breasting structure for moorings with more than two breasting structures. The computer program presented in Appendix B of DM-26.5 should be used for situations involving more than two breasting structures.

c. Longitudinal Load. Longitudinal loads are taken by spring lines. Figure 37 outlines the procedure for determining the load in spring lines. Note that the total mooring-line load is the sum of the applied load and the mooring-line pretension.

d. Maximum Mooring Loads. Fixed-mooring elements must be designed for maximum loads. This involves determining the combinations of current load,

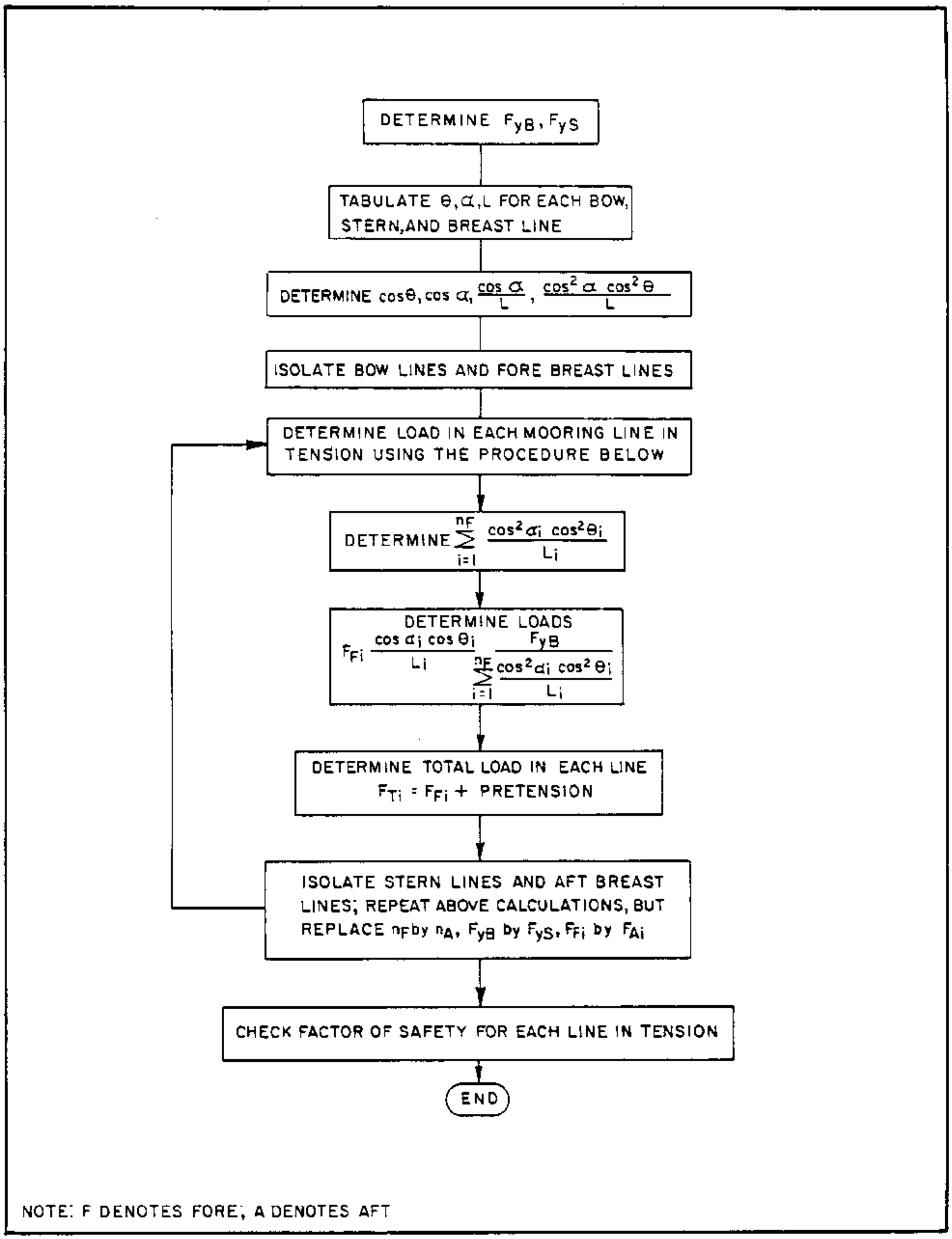


FIGURE 34
Case 1

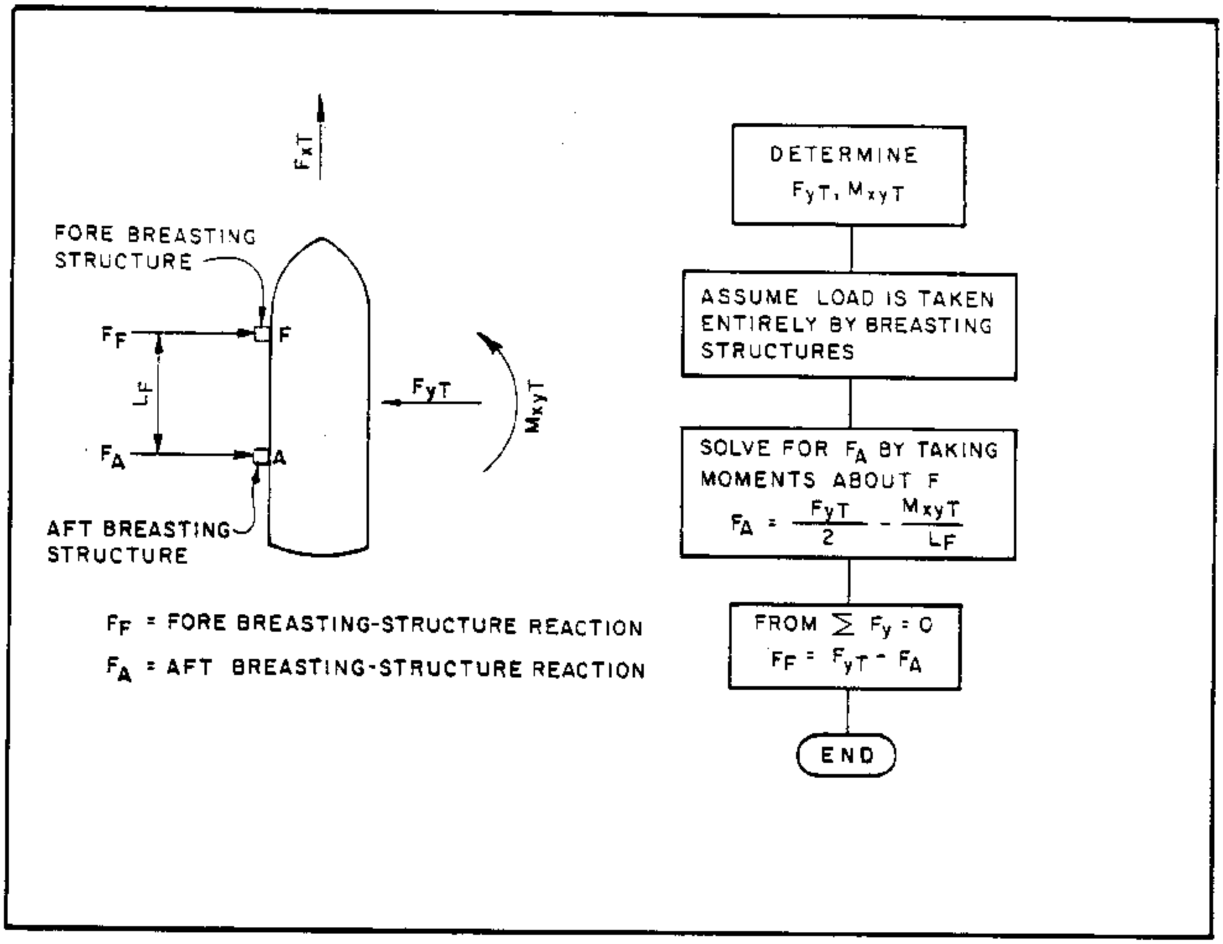


FIGURE 35
Case 2

wind load, tide level, and vessel loading (that is, light loaded or fully loaded) which produce the maximum load on each mooring element. Obviously, certain combinations of these variables which produce maximum loads on some mooring elements (for example, spring lines) may not produce maximum loads on other mooring elements (for example, breast lines). Therefore, a variety of combinations of current load, wind load, tide level, and vessel loading must be analyzed. Note that the mooring-line preload must be considered.

Tidal currents are the most important type of current at most fixed moorings; therefore, usually the designer only needs to investigate two current directions (flood and ebb). Furthermore, wherever possible, the fixed mooring should be oriented so that the longitudinal axis of the vessel is roughly parallel with the direction of the flood and ebb currents.

Wind can generally blow from any direction at most, fixed moorings; moreover, the design windspeed may not be the same from each direction. (See Section 3.) Also, the vessel may be partially sheltered from offshore winds by landside structures.

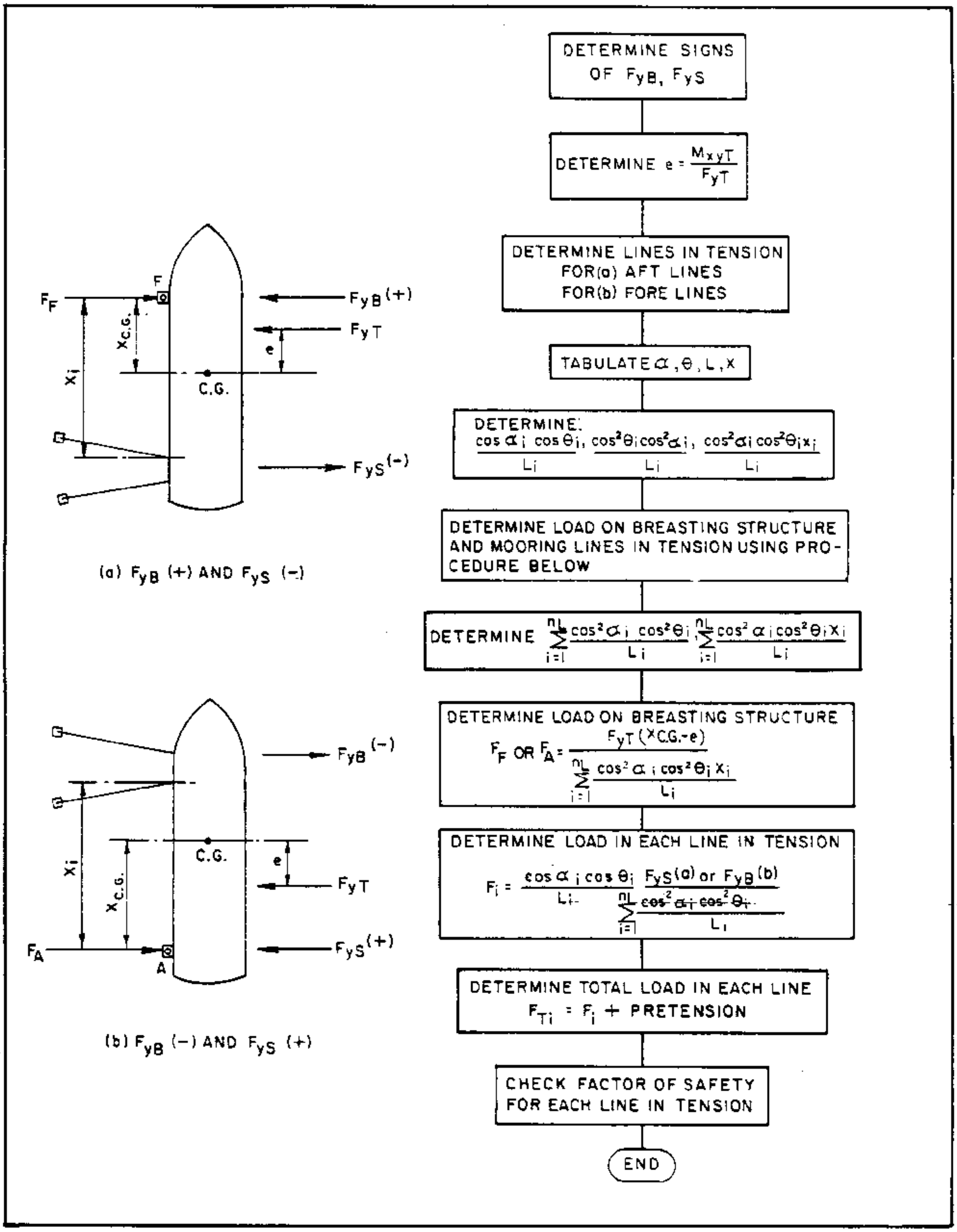


FIGURE 36
Case 3

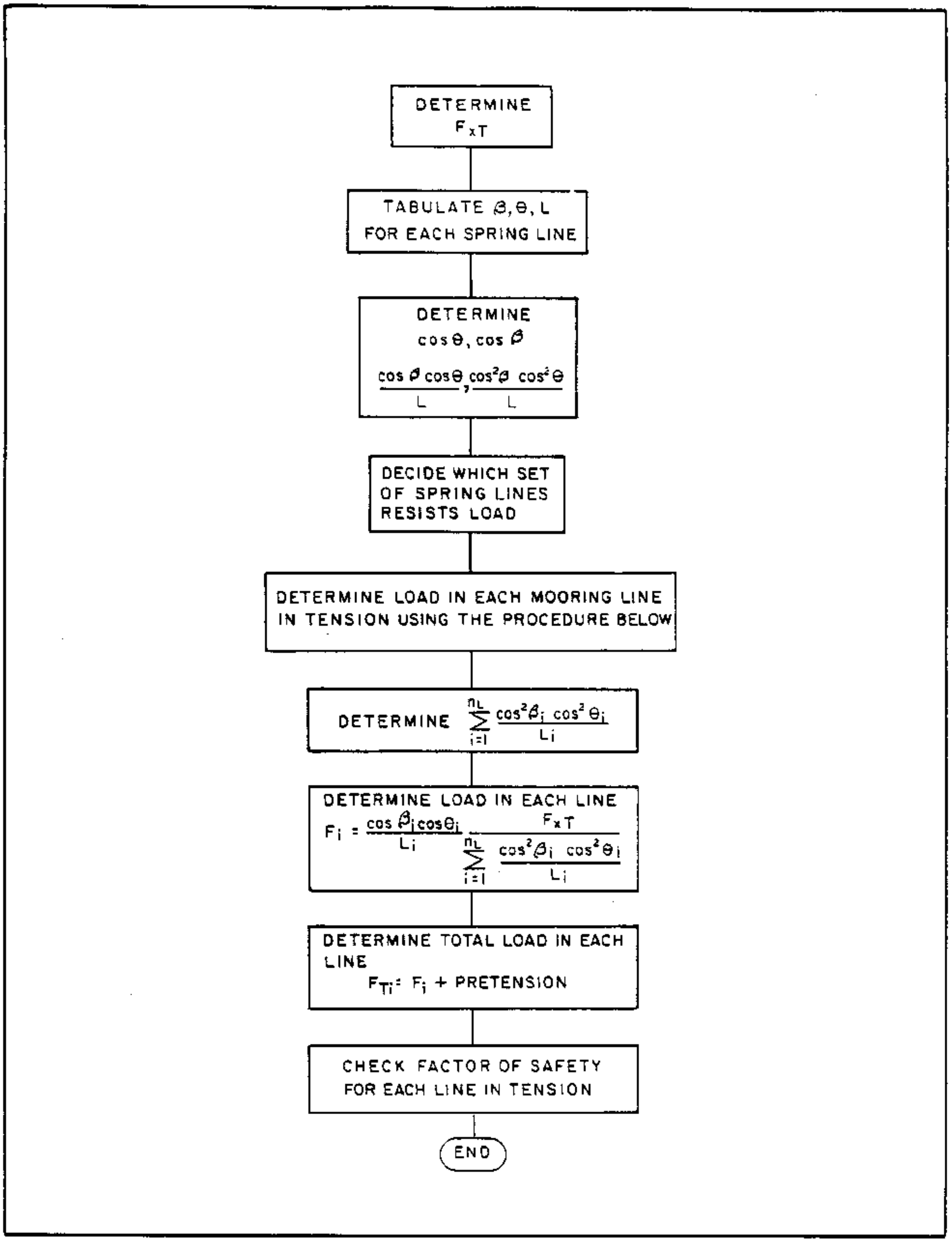


FIGURE 37
Mooring Analysis for Spring Lines

Tide level and vessel loading have important effects upon mooring loads which must be considered. Mooring calculations must be determined for both light-loaded and fully loaded conditions. For each of these conditions, the combined loading due to wind load from each direction and to the flood and ebb current loads at low tide is determined. Then, the procedure outlined in Figure 38 is used to determine line loads at high tide for each of the above conditions.

e. Computer Solution. Appendix B of DM-26.5 provides a computer program for fixed-mooring analysis.

f. Spud Moorings. Spud moorings are a specialized type of fixed mooring used to secure floating drydocks. The procedure for distributing mooring loads to the spuds is outlined in Figure 39.

g. Berthing Loads. Breasting structures must be designed to withstand berthing and mooring loads. The procedure for determining berthing loads, taken from DM-25.1, is outlined in Figure 40. The energy equation for determining the berthing or kinetic energy of a docking vessel is given as follows:

$$KE_B = \frac{1}{2}\frac{W}{g} V_N^2 \, C_B \, C_H \tag{4-67}$$

WHERE: KE_B = berthing energy (kinetic energy of docking vessel), in foot-pounds

W = weight of vessel, in pounds (displacement tonnage, in long tons, times 2,240 pounds)

g = gravitational acceleration (32.2 feet per second^2)

V_N = normal component of approach velocity, in feet per second

C_B = berthing coefficient

C_H = hydrodynamic mass coefficient

(1) Vessel Weight. The weight, W, used in Equation (4-67) is the displacement tonnage of the largest vessel expected to use the fixed-mooring facility. Values of displacement tonnage for various vessel types are presented in DM-26 6, Tables 2 through 4.

(2) Vessel Berthing Velocity and Angle of Approach. The velocity of a docking vessel depends upon environmental conditions at the mooring and upon whether or not tug assistance is provided. The component of velocity normal to the breasting structure depends upon the angle of approach of the vessel. For unassisted vessels, this angle is generally between 5 degrees and 15 degrees. Large vessels, assisted by tugs, generally have approach angles of less than 10 degrees. The approach velocity normal to the breasting structure is determined as follows:

$$V_N = V_A \sin A \tag{4-68}$$

WHERE: V_N = normal component of approach velocity, in feet per second

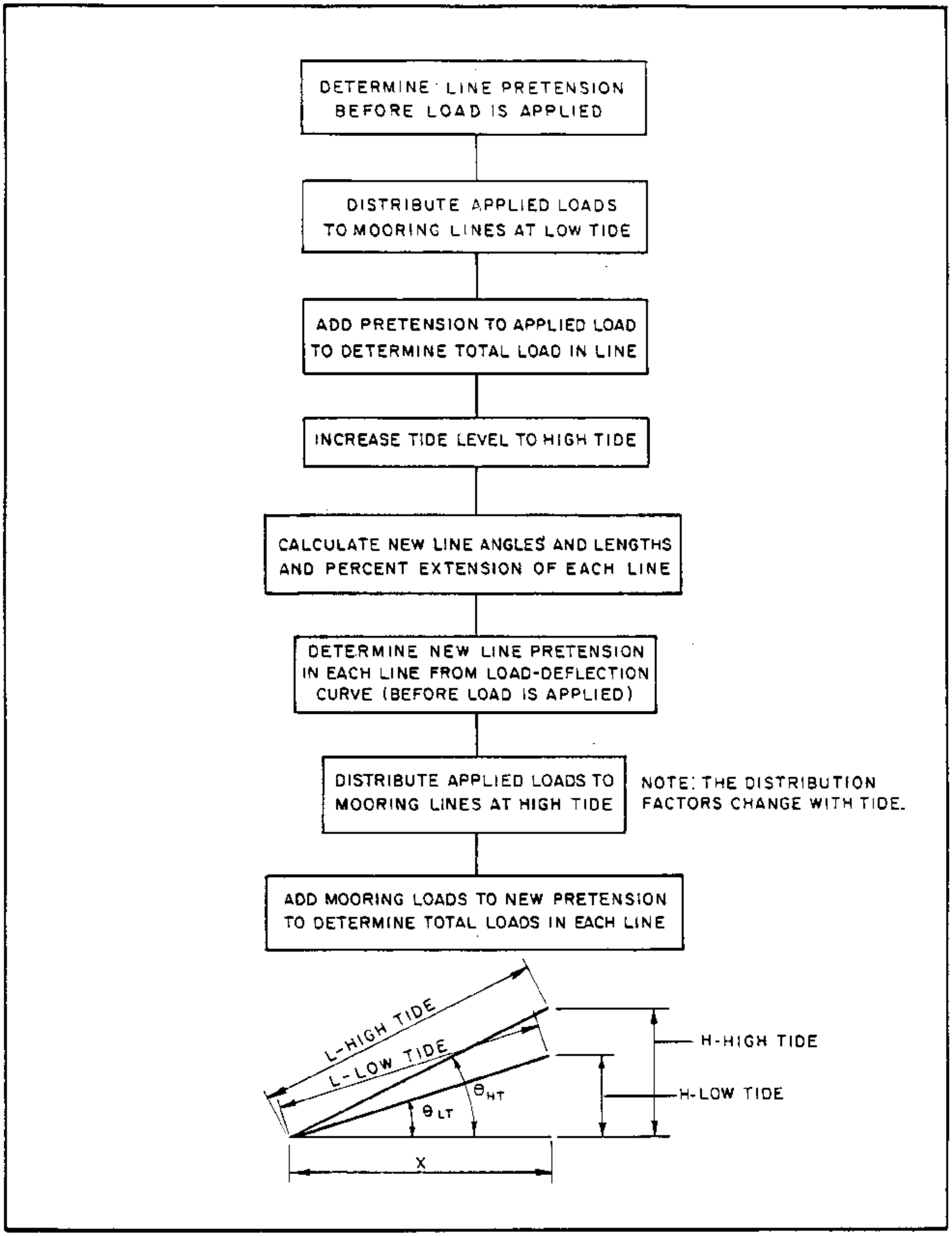


FIGURE 38
Effect of Tide

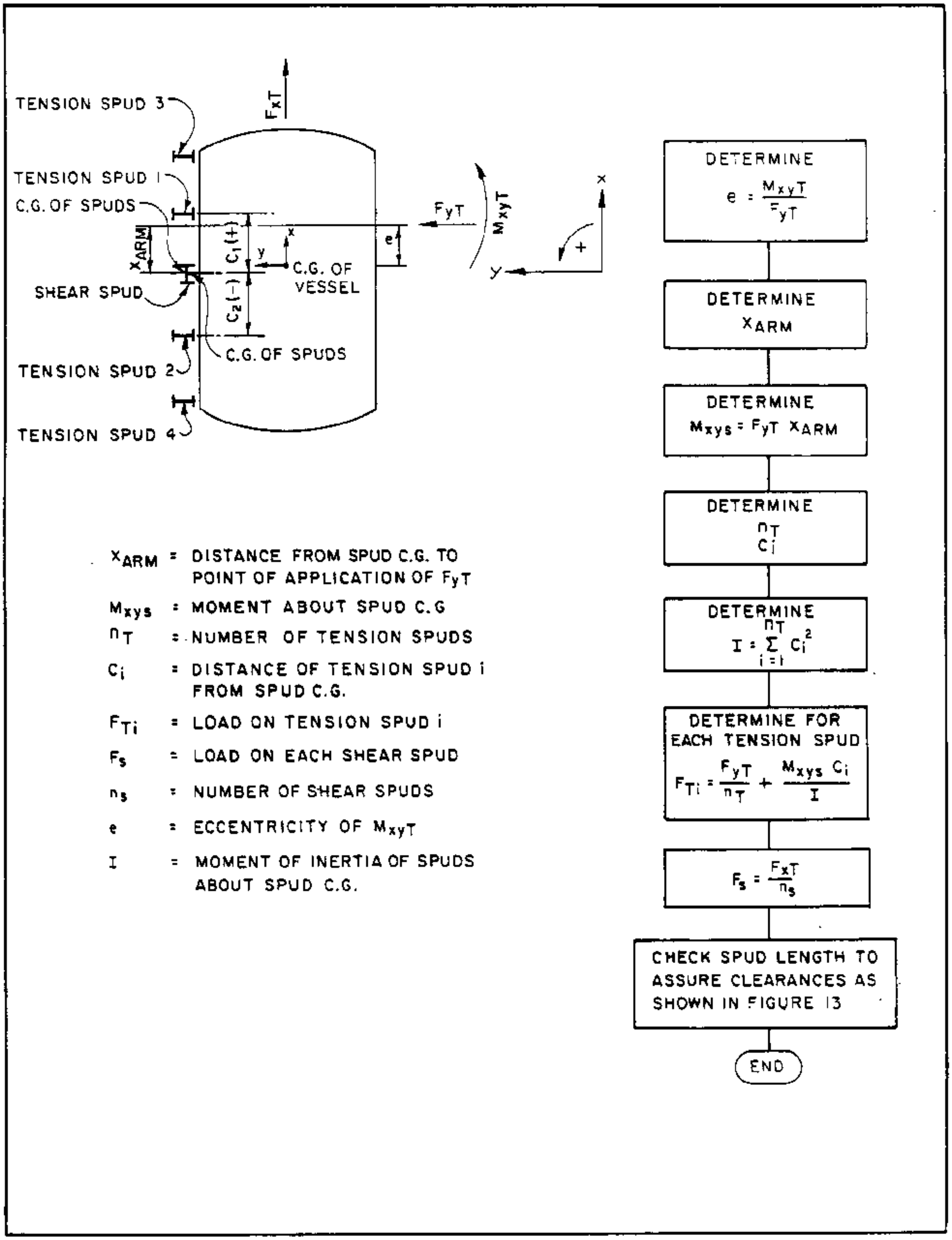


FIGURE 39
Spud-Mooring Analysis

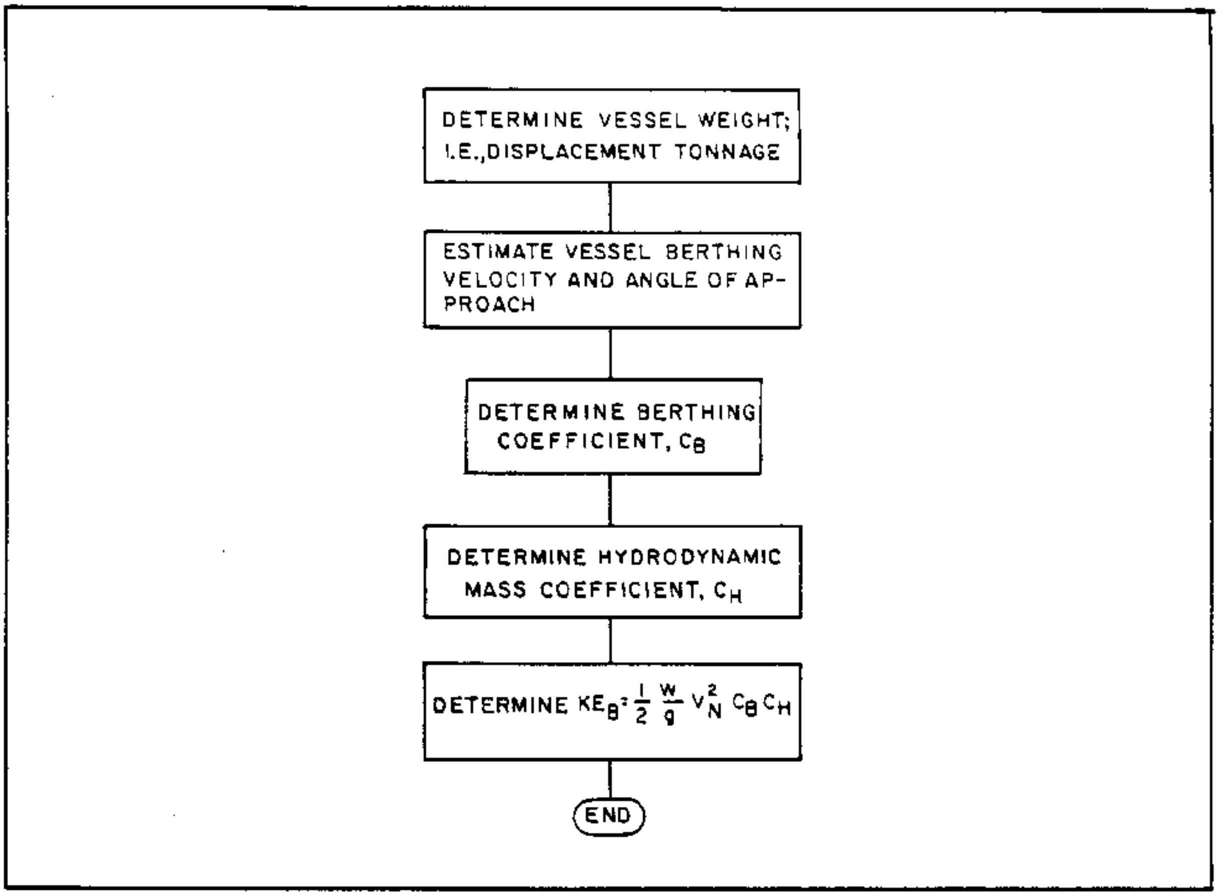


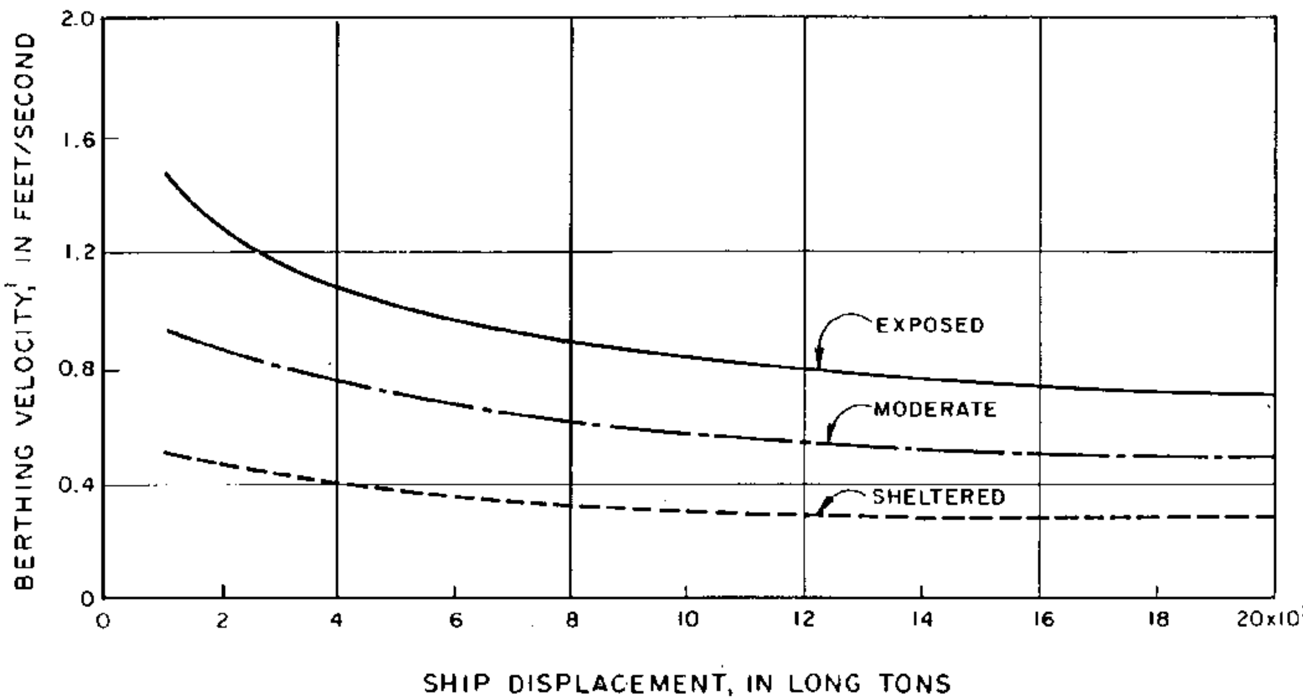
FIGURE 40
Procedure for Determining Berthing Energy

V_A = approach velocity, in feet per second

A = angle of approach

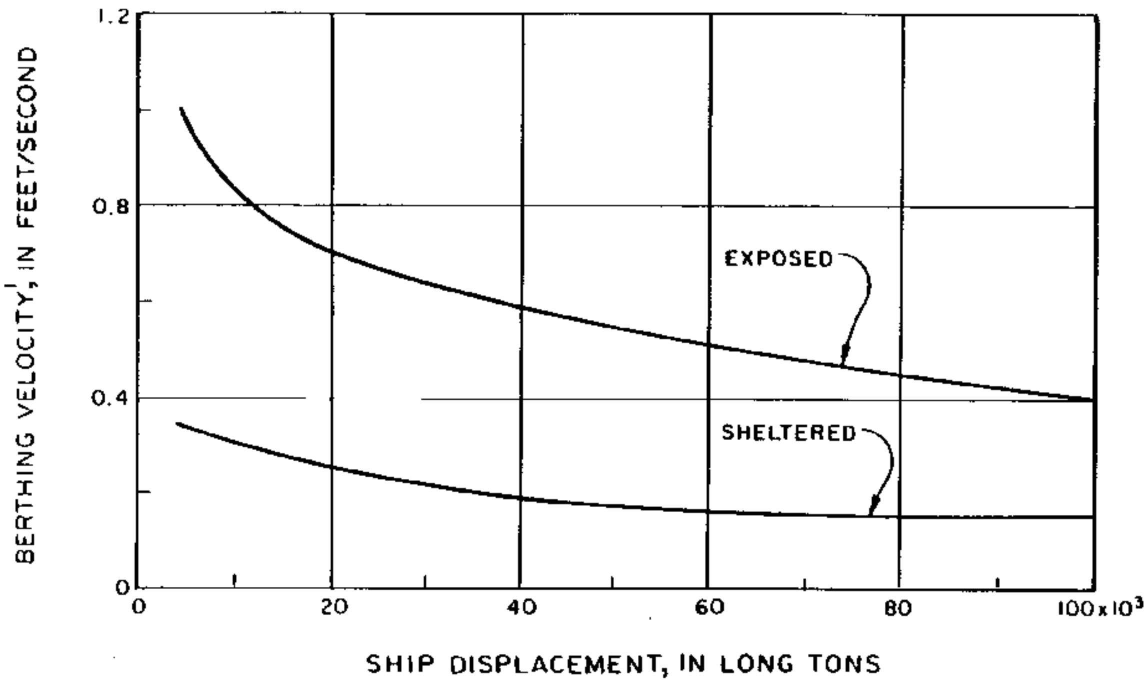
Figures 41 and 42 provide berthing velocity normal to the breasting structure, V_N, as a function of vessel displacement and relative environmental condition. Both figures include the effect of approach angle. Figure 41 is used for vessels with displacements less than or equal to 20,000 long tons, while Figure 42 is used for vessels with displacements greater than 20,000 long tons.

(3) Berthing Coefficient. When a vessel approaches a fixed mooring, the bow or stern of the vessel will generally impinge upon one of the breasting structures first. The reaction of this structure will cause the vessel to rotate. This rotation acts to dissipate a portion of the kinetic energy of the vessel. The berthing coefficient, C_B, accounts for this reduction in kinetic energy. For typical designs, the berthing coefficient is 0.5.



[1]NORMAL TO DOCK

FIGURE 41
Berthing Velocity, V_N, Versus Ship Displacement and Relative Environmental Condition



[1]NORMAL TO DOCK

FIGURE 42
Berthing Velocity, V_N, Versus Ship Displacement and Relative Environmental Condition

(4) Hydrodynamic Mass Coefficient. As a vessel approaches a fixed mooring, the water surrounding the vessel moves along with the vessel; this effectively increases the mass of the vessel. This increased mass, known as the hydrodynamic mass of the vessel, is accounted for by the hydrodynamic mass coefficient, C_H. C_H may be determined from Figure 43.

7. DESIGN OF FIXED-MOORING STRUCTURES. Mooring structures can be designed for static wind and current loads without concern for their ability to absorb energy. Breasting structures, on the other hand, are subjected to berthing loads, and their energy-absorbing capability must be investigated as discussed below.

a. Breasting Structures. Figure 44 presents a design procedure for breasting structures. This procedure involves selecting a preliminary structure and evaluating its ability to absorb berthing energy. This process is repeated until the structure has the desired energy-absorption characteristics.

(1) Maximum Mooring Load and Berthing Energy. The first step is to determine the maximum mooring load, F_M and the berthing energy, KE_B, on the breasting structure under investigation.

(2) Rigid or Flexible Design. Breasting structures may be designed to be flexible or rigid. Examples of flexible structures are timber and steel pipe-pile dolphins. For flexible structures, berthing energy is absorbed by both the structure and its fendering system. Examples of rigid structures are mooring cells and braced concrete mooring platforms. For rigid structures, berthing energy is absorbed almost entirely by the fendering system. A flexible design may be more cost-efficient than a rigid one if structural and foundation considerations permit its use.

(3) Design of Preliminary Structure. In this step, the breasting structure is designed for the maximum mooring load and a suitable fender is chosen. For details on the selection of fendering systems, see DM-25.1.

(4) Load-Deflection Curve. A load-deflection curve is constructed for the breasting structure and its fender for a flexible design, or for the fender alone for a rigid design. In principle, the structure and the fender behave as two springs in series. A composite load-deflection curve can be constructed by adding the deflections of the structure and of the fender together. Load-deflection curves for flexible breasting structures must account for deflection of both the structure itself and the surrounding soil. Load-deflection curves for fenders are available from manufacturers. Also, load-deflection curves for several types of fenders are given in Section 5 of DM-25.1.

Next, the area under the load-deflection curve equal to the berthing energy is determined. (See Figure 14.) The berthing load, F_B, associated with the area under the curve (that is, berthing energy) should equal the maximum mooring load, F_M, for an economical structure. If F_B is greater than F_M, then the fender and/or the structure is stiffer than it needs to be, and a softer breasting structure and/or fender should be designed. This can be done by using a smaller pile, a less elastic material for the structure, or a softer fender.

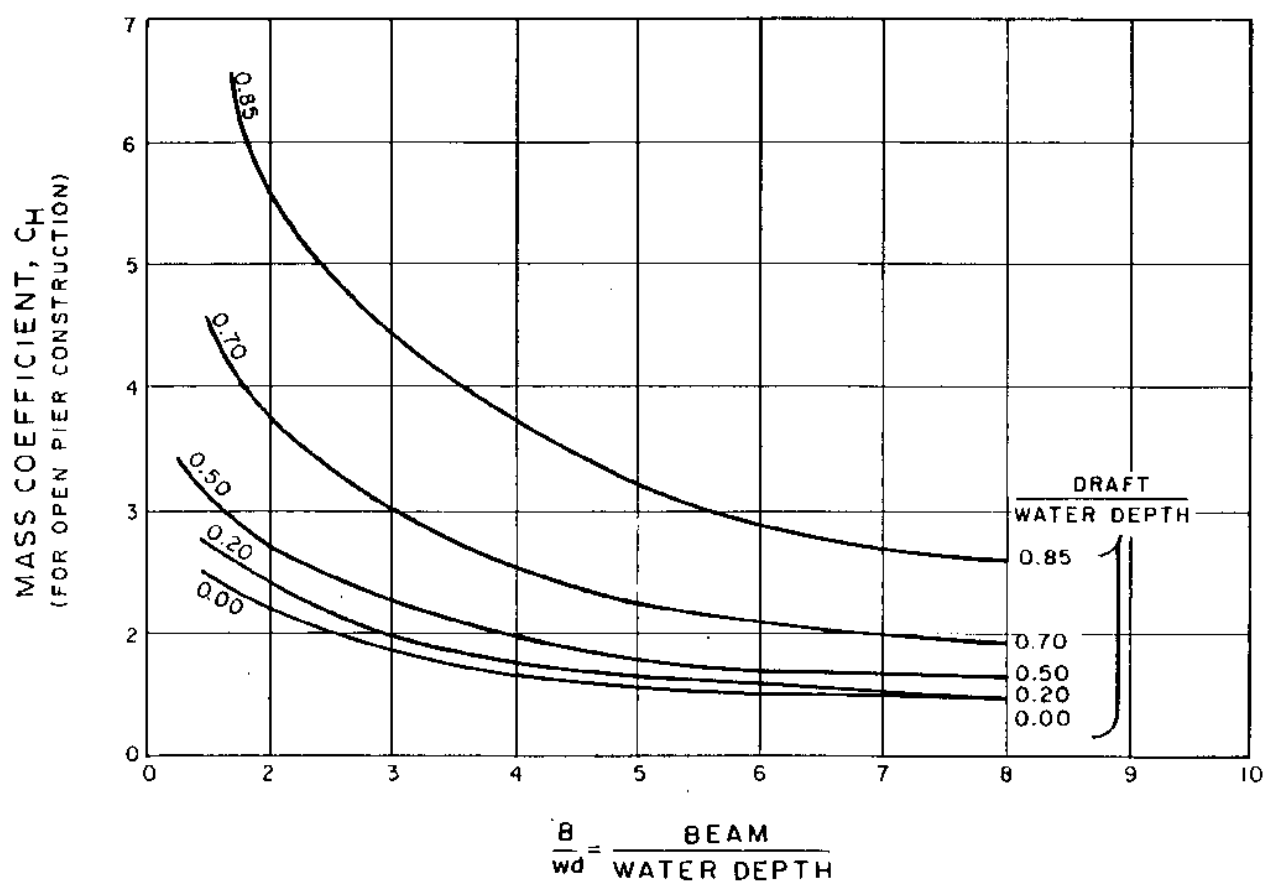


FIGURE 43
Hydrodynamic Mass Coefficient, C_H

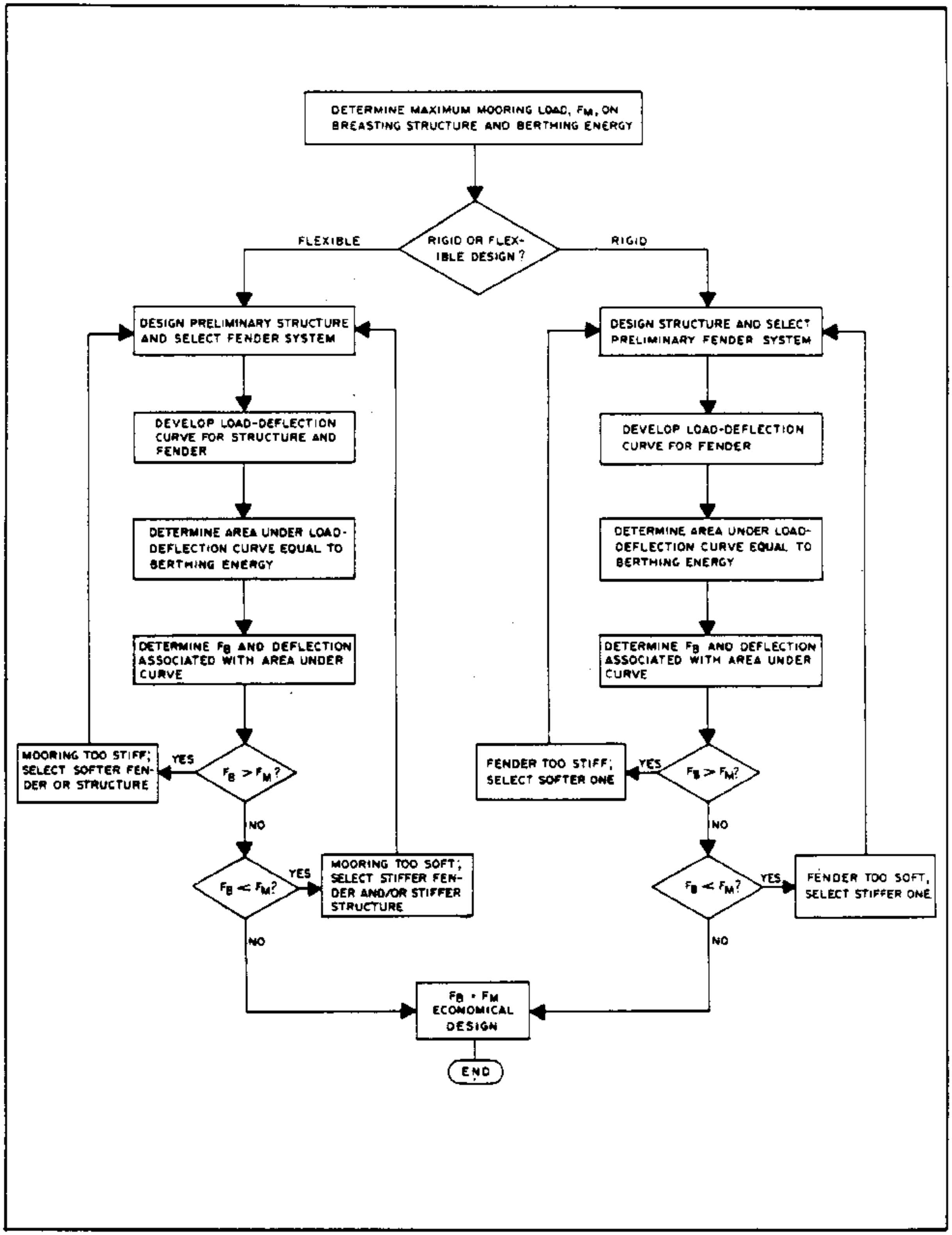


FIGURE 44
Design of Breasting Structures

If the berthing load, F_B, is less than the maximum mooring load, F_M, then the fender and/or structure is softer than it needs to be. As a result, larger deflections of the structure are required to develop the maximum mooring load. Larger deflections may not be desirable; if so, a stiffer structure and/or fender should be designed. However, if the location is relatively exposed and uncertainties exist concerning the berthing energy and design mooring loads, a softer system may be desirable.

b. Structural Design. DM-25.1 and DM-25.6 provide general criteria for the structural design of mooring and breasting structures. See DM-25.1, Section 4, Part 4, for methods describing how to distribute horizontal berthing and mooring forces to the decks of mooring and breasting structures.

8. METRIC EQUIVALENCE CHART. The following metric equivalents were developed in accordance with ASTM E-621. These units are listed in the sequence in which they appear in the text of Section 4. Conversions are approximate.

33.33 feet = 10 meters
1 mile = 1.61 kilometers
60 miles per hour = 96.6 kilometers per hour
10 miles = 16.1 kilometers
0.00237 slugs per cubic foot = 0.00122 gram per cubic centimeter
2 slugs per cubic foot = 1.031 grabs per cubic centimeter
1.4×10^{-5} square feet per second = 1.3×10^{-6} square meters per second
2,240 pounds = 1 long ton = 1 016.1 kilograms
32.2 feet per second^2 = 9.81 meters per second^2
20,000 long tons = 20 320 metric tons

Section 5. EXAMPLE PROBLEMS

EXAMPLE PROBLEM 1: FIXED MOORING

Given:
a. Fixed mooring for an AOE-1. (Mooring configuration is shown in Figure 45.)
b. The water depth at the site is 65 feet mean lower low water (MLLW).
c. The tide range from MLLW to mean higher high water (MHHW) is 6 feet.
d. Wind data for the site are given in Table 11.
e. Currents are due to tides. The maximum flood-current speed, V_c, is 1 knot (θ = 15deg.) and the maximum ebb-current speed, V_c, is 1 knot (θ = 195deg.).
f. Mooring lines are polypropylene (diameter >3/4 inch and breaking strength = 300,000 pounds) with an initial (low tide) pretension of 5,000 pounds.
g. The vertical distance from vessel chock to deck elevation of mooring structures, H, is 36 feet for the light-loaded condition at low tide and 12 feet for the fully loaded condition at low tide.

Find: Design the mooring for wind, current, and berthing loads.

Solution: 1. Determine Vessel Characteristics for AOE-1 from DM-26.6, Table 2:

Overall length, L = 796 feet
Waterline length L_{wL} = 770 feet
Beam, B = 107 feet
Fully loaded draft, T = 41 feet
Light-loaded draft, T = 18.4 feet
Fully loaded displacement, D = 53,600 long tons
Light-loaded displacement, D = 18,870 long tons
Fully loaded broadside wind area, A_y = 36,650 square feet
Light-loaded broadside wind area, A_y = 54,600 square feet
Fully loaded frontal wind area, A_x = 6,400 square feet
Light-loaded frontal wind area, A_x = 8,850 square feet

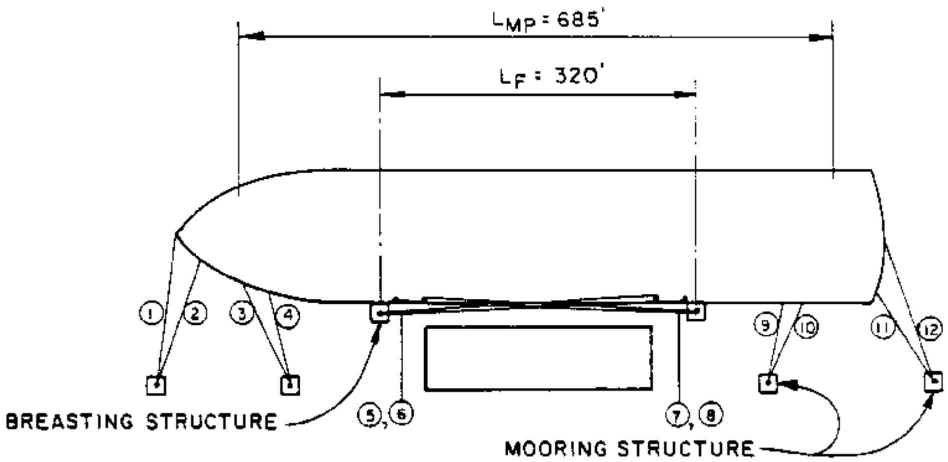
2. Mooring Configuration:

a. The mooring configuration is shown in Figure 45.

b. Check vertical mooring-line angle, θ:

The shortest line will have the maximum vertical angle; this will occur at high tide for a light-loaded condition (H = 36 + 6 = 42 feet). From Figure 45, the shortest line is line number 9: L_H = 95 feet.

$$\theta = \arctan\left(\frac{H}{L_H}\right) = \arctan\left(\frac{42}{95}\right) = 23.9\text{deg.} < 25\text{deg.};\ \text{ok}$$



Mooring Line	α (degrees)	β (degrees)	L_H (feet)
1	18	-	150
2	28	-	140
3	20	-	100
4	13	-	95
5	-	3.5	300
6	-	3.2	260
7	-	3.2	260
8	-	3.5	300
9	13	-	95
10	20	-	100
11	28	-	140
12	18	-	150

FIGURE 45
Mooring Configuration (Example Problem 1)

EXAMPLE PROBLEM 1 (Continued)

TABLE 11
Wind Data for Site

Year	Windspeed[1] (miles per hour)							
	N	NE	E	SE	S	SW	W	NW
1950	38.4	41.6	57.6	30.4	48	39.2	28.8	22.4
1951	25.6	33.6	22.4	27.2	32.8	31.2	30.4	24
1952	44.8	32	26.4	36.8	31.2	31.2	32.8	33.6
1953	36	35.2	33.6	25.6	36.8	41.6	25.6	24
1954	28	28	29.6	21.6	36.8	28	35.2	25.6
1955	25.6	36.8	28.8	24.8	24.8	28.8	33.6	25.6
1956	29.6	29.6	30.4	35.2	39.2	28	26.4	28.8
1957	24.8	28	28.8	32	36.8	21.6	27.2	22.4
1958	22.4	31.2	24.8	25.6	23.2	26.4	33.6	25.6
1959	27.2	28.8	21.6	25.6	30.4	29.6	27.2	23.2
1960	28	36.8	32.8	24	26.4	32.8	31.2	27.2
1961	32.8	28	27.2	31.2	26.4	38.4	35.2	25.6
1962	28	33.6	43.2	31.2	22.4	33.6	32	28.8
1963	49.6	41.6	36	32	22.4	24.8	40	41.6
1964	65.6	38.4	62.4	36	38.4	32.8	34.4	30.4
1965	28.8	36	45.6	28.8	31.2	33.6	38.4	36
1966	24	32	38.4	28.8	29.6	31.2	29.6	28
1967	22.4	60.8	28	23.2	24	31.2	27.2	37.6
1968	41.6	32.8	25.6	31.2	26.4	36.8	27.2	25.6
1969	46.4	41.6	24.8	22.4	28	29.6	28	32
1970	28	28	31.2	35.2	31.2	27.2	29.6	28.8
1971	21.6	29.7	19.8	31.5	25.2	39.6	30.6	42.3
1972	22.5	27	35.1	28.8	27.9	34.2	27.9	39.6
1973	24.3	38.7	36.9	24.3	23.4	31.5	43.2	30.6
1974	22.5	31.5	21.6	39.6	30.6	30.6	30.6	30.6
1975	55.8	24.3	21.6	24.3	24.3	48.6	31.5	30.6
1976	23.4	26.1	18	24.3	26.1	36	37.8	37.8
1977	23.4	23.4	19.8	23.4	18.9	27.9	29.7	25.2
1978	22.5	22.5	17.1	21.6	26.1	35.1	30.6	34.2
1979	28.8	31.5	22.5	26.1	24.3	27.9	28.8	28.8

[1]Windspeeds were collected over water at an elevation of 43 feet. Windspeeds are peak-gust values.

EXAMPLE PROBLEM 1 (Continued)

3. Evaluate Environmental Conditions:

a. Seafloor Soil Conditions: This example problem illustrates the procedures for determining loads on fixed-mooring structures, but does not include structural-design calculations. Consequently, although they are important in structural design, soil conditions are not needed for this example problem.

b. Design Water Depth:

(1) Water depth at low tide, $wd_{low\ tide}$ = 65 feet

(2) Water depth at high tide, $wd_{high\ tide}$ = 65 + 6 = 71 feet

c. Design Wind:

(1) Obtain Wind Data: Wind data obtained for the site are presented in Table 11. Note that directional data are available and directional probability may be determined accurately.

(2) Correct for Elevation:

EQ. (4-1) $$V_{33.33} = V_h \left(\frac{33.33}{h}\right)^{1/7}$$

$$V_{33.33} = V_{43} \left(\frac{33.33}{43}\right)^{1/7} = 0.964\ V_{43};\ \text{use } 0.96\ V_{43}$$

Therefore, elevation correction factor = 0.96

(3) Correct for Duration: The recorded windspeeds are peak-gust values; reduce the windspeeds by 10 percent to obtain the 30-second windspeeds. Therefore, duration correction factor = 0.90.

(4) Correct for Overland-Overwater Effects: Data were collected over water; therefore, no correction is necessary.

THEREFORE: Total correction factor = (0.9) (0.96) = 0.864

Multiply each value in Table 11 by 0.864 to obtain the 30-second windspeed at 33.33 feet above the water surface. The results are shown in Table 12.

(5) Determine Windspeed Probability:

(a) Determine mean value, $\bar{x}$, and standard deviation, [sigma], for each windspeed direction:

EXAMPLE PROBLEM 1 (Continued)

TABLE 12
Adjusted Wind Data for Site

Year	Windspeed (miles per hour)							
	N	NE	E	SE	S	SW	W	NW
1950	33.2	35.9	49.8	26.3	41.5	33.9	24.9	19.4
1951	22.1	29	19.4	23.5	28.3	27	26.3	20.7
1952	38.7	27.7	22.8	31.8	27	27	28.3	29
1953	31.1	30.4	29	22.1	31.8	35.9	22.1	20.7
1954	24.2	24.2	25.6	18.7	31.8	24.2	30.4	22.1
1955	22.1	31.8	24.9	21.4	21.4	24.9	29	22.1
1956	25.6	25.6	26.3	30.4	33.9	24.2	22.8	24.9
1957	21.4	24.2	24.9	27.7	31.8	18.7	23.5	19.4
1958	19.4	27	21.4	22.1	20	22.8	29	22.1
1959	23.5	24.9	18.7	22.1	26.3	25.6	23.5	20
1960	24.2	31.8	28.3	20.7	22.8	28.3	27	23.5
1961	28.3	24.2	23.5	27	22.8	33.2	30.4	22.1
1962	24.2	29	37.3	27	19.4	29	27.7	24.9
1963	42.9	35.9	31.1	27.7	19.4	21.4	34.6	35.9
1964	56.7	33.2	53.9	31.1	33.2	28.3	29.7	26.3
1965	24.9	31.1	39.4	24.9	27	29	33.2	31.1
1966	20.7	27.7	33.2	24.9	25.6	27	25.6	24.2
1967	19.4	52.5	24.2	20	20.7	27	23.5	32.5
1968	35.9	28.3	22.1	27	22.8	31.8	23.5	22.1
1969	40.1	35.9	21.4	19.4	24.2	25.6	24.2	27.6
1970	24.2	24.2	27	30.4	27	23.5	25.6	24.9
1971	18.7	25.7	17.1	27.2	21.8	34.2	26.4	36.5
1972	19.4	23.3	30.3	24.9	24.1	29.6	24.1	34.2
1973	21	33.4	31.9	21	20.2	27.2	37.3	26.4
1974	19.4	27.2	18.7	34.2	26.4	26.4	26.4	26.4
1975	48.2	21	18.7	21	21	42	27.2	26.4
1976	20.2	22.6	15.6	21	22.6	31.1	32.7	32.7
1977	20.2	20.2	17.1	20.2	16.3	24.1	25.7	21.8
1978	19.4	19.4	14.8	18.7	22.6	30.3	26.4	29.5
1979	24.9	27.2	19.4	22.6	21	24.1	24.9	24.9
$\bar{x}$	27.14	28.48	26.26	24.57	25.16	27.91	27.2	25.81
[sigma]	9.63	6.32	9.31	4.26	5.48	4.76	3.7	4.91
[alpha]	0.133	0.2028	0.138	0.301	0.234	0.2693	0.347	0.261
u	22.8	25.63	22.08	22.65	22.69	25.77	25.5	23.6

EXAMPLE PROBLEM 1 (Continued)

EQ. (4-4)

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$$

EQ. (4-5)

$$\sigma = \frac{1}{N - 1} \sum_{i=1}^{N} (x_i - \bar{x})^2$$

These values are tabulated in Table 12. Note that $\bar{x}$ and [sigma] can be calculated with most handheld calculators.

(b) Use Gumbel distribution to determine design windspeed for each direction:

(i) Compute Gumbel parameters [alpha] and u for each direction:

EQ. (4-7)

$$[\alpha] = \frac{1.282}{[\sigma]}$$

EQ. (4-8)

$$u = \bar{x} - \frac{0.577}{[\alpha]}$$

For example, for north:

$$[\alpha] = \frac{1.282}{9.63} = 0.133$$

$$u = 27.14 - \frac{0.577}{0.133} = 22.8$$

These values are presented in Table 12 for each direction.

(ii) Compute V_R for 25- and 50-year return periods for each direction. Plot results on Gumbel paper. (Note: 50-year return period is used for design.) Use Equation (4-6):

EQ. (4-6)

$$V_R = u - \frac{\ln \{- \ln [1 - P(X \geq x)]\}}{\quad}$$

[alpha]

For example, for north:

From Table 4, for a return period of 25 years, P(X >/= x) = 0.04, and, for a return period of 50 years, P(X >/= x) = 0.02.

THEN:

$$V_{25} = 22.8 - \frac{1N\ [- 1N\ (1 - 0.04)]}{0.133}$$

$$V_{25} = 22.8 + \frac{3.2}{0.133}$$

V_{25} = 46.9 miles per hour

AND:

$$V_{50} = 22.8 - \frac{1n\ [- 1n\ (1 - 0.02)]}{0.133}$$

$$V_{50} = 22.8 + \frac{3.9}{0.133}$$

V_{50} = 52.1 miles per hour

EXAMPLE PROBLEM 1 (Continued)

These values are presented in Table 13 and are plotted in Figure 46.

TABLE 13
V_{25} and V_{50}

Direction	V_{25} (miles per hour)	V_{50} (miles per hour)	V_{50} (feet per second)
N	46.9	52.1	76.4
NE	41.4	44.9	65.8
E	45.3	50.3	73.7
SE	33.3	35.6	52.2
S	36.4	39.4	57.8
SW	37.7	40.2	58.9
W	26.6	36.7	53.8
NW	35.9	38.5	56.4

Note: 1.467 feet per second = 1 mile per hour

d. Design Current: The design currents are due to tides.

(1) Flood current = 1 knot toward 195deg. true north (θ_c = = 15deg.)

(2) Ebb current = 1 knot toward 15deg. true north (θ_c = 195deg.)

e. A summary of design wind and current conditions is shown in Figure 47.

4. Evaluate Environmental Loads:

a. Wind Load:

(1) Lateral Wind Load: Find F_{yw}:

EQ. (4-11)
$$F_{yw} = 1/2\ \rho_a V_w^2\ A_y\ C_{yw}\ f_{yw}(\theta)$$

ρ_a = 0.00237 slugs per cubic foot

EQ. (4-12)
$$C_{yw} = .092 \left[\left(\frac{V_S}{V_R} \right)^2 A_S \left(\frac{V_H}{V_R} \right)^2 A_H \right] / A_y$$

EQ. (4-13)
$$\frac{V_S}{\quad} = \left(\frac{h_S}{\quad} \right)^{1/7}$$

$$V_{\lceil R \rceil} \qquad \left\lfloor h_{\lceil R \rceil} \right\rfloor$$

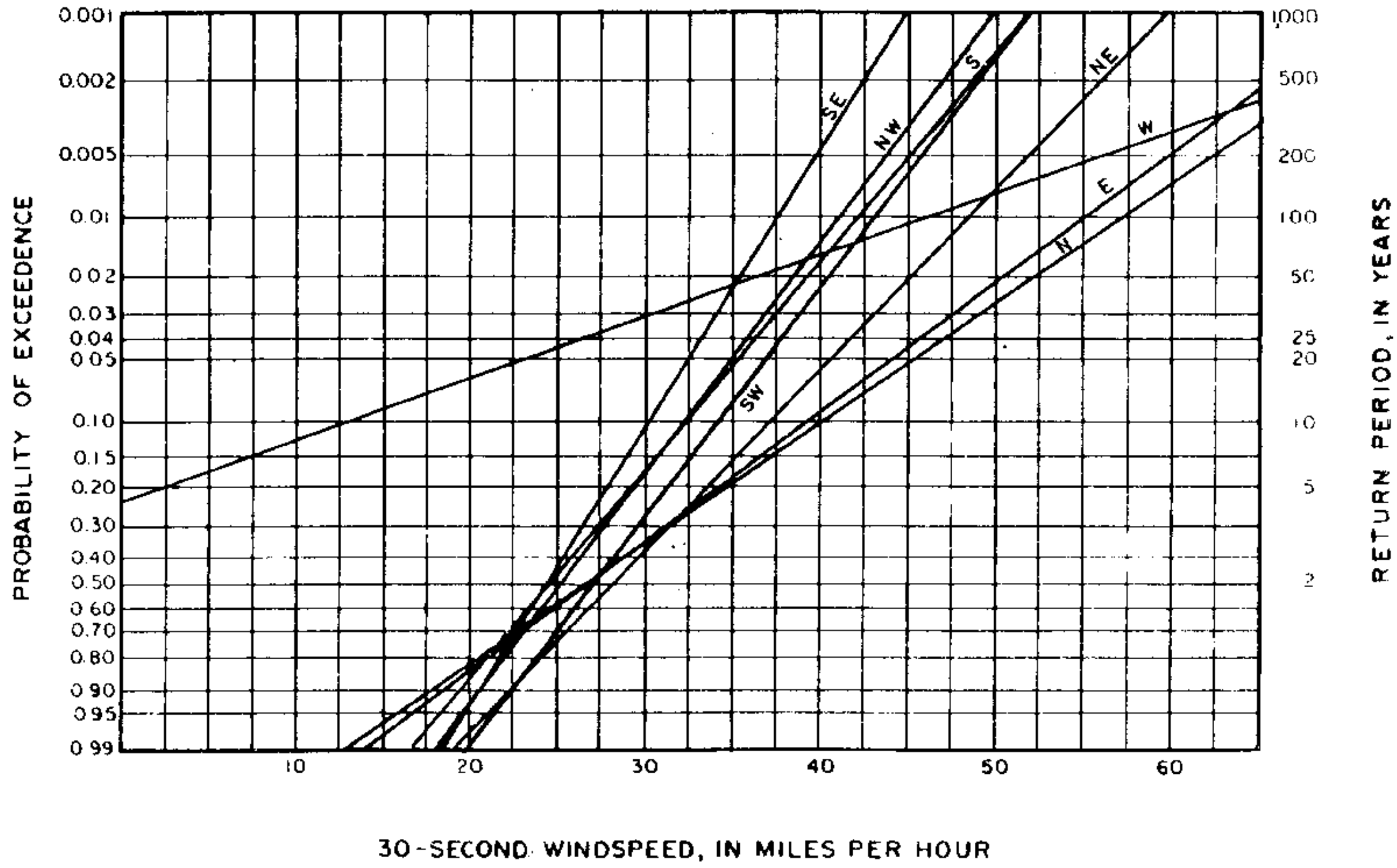


FIGURE 46
Plot of V_R for Each Direction (Example Problem 1)

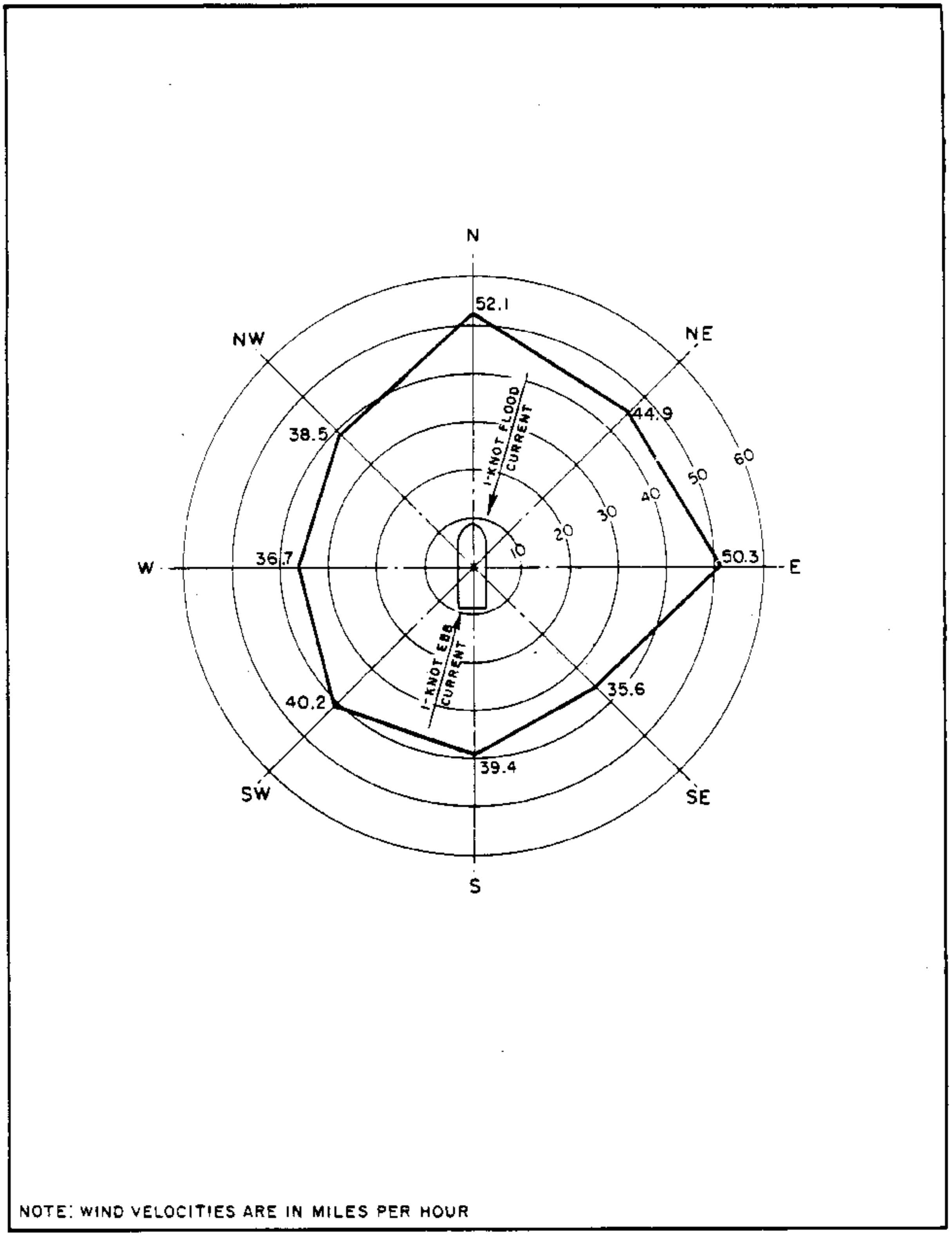


FIGURE 47
Summary of Design Wind and Current Conditions (Example Problem 1)

EXAMPLE PROBLEM 1 (Continued)

EQ. (4-14)

$$\frac{V_H}{V_R} = \left(\frac{h_H}{h_R}\right)^{1/7}$$

$$h_R = 33.33 \text{ feet}$$

EQ. (4-15)

$$f_{yw}(\theta_w) = \frac{+\left(\sin\theta_w - \frac{\sin 5\theta_w}{20}\right)}{1 - \frac{1}{20}}$$

(a) Light-Loaded Condition: Find F_{yw} for the light-loaded condition:

Assume h_S = 45 feet and h_H = 15 feet:

THEN:

$$\frac{V_S}{V_R} = \left[\frac{45}{33.33}\right]^{1/7} = 1.04$$

AND:

$$\frac{V_H}{V_R} = \left[\frac{15}{33.33}\right]^{1/7} = 0.89$$

A_y = 54,600 square feet

Assume:

$A_S = 0.30\ A_y = (0.3)(54,600) = 16,380$ square feet

$A_H = 0.70\ A_y = (0.7)(54,600) = 38,220$ square feet

THEN:

$C_{yw} = 0.92\ [(1.04)^2(16,380) + (0.89)^2(38,220)]/54,600$

$C_{yw} = 0.81$

AND:

$F_{yw} = 1/2\ (0.00237)\ V_w^2\ (54,600)(0.81)\ f_{yw}(\theta_w)$

$F_{yw} = 52.4\ V_w^2\ f_{yw}(\theta_w)$

This equation is used to determine F_{yw} for V_w and θ_w for the light-loaded condition. The results are given in Table 14.

(b) Fully Loaded Condition: Find F_{yw} for the fully loaded condition:

Assume h_S = 40 feet and h_H = 12 feet:

$$\frac{V_S}{V_R} = \left[\frac{40}{33.33}\right]^{1/7} = 1.03$$

EXAMPLE PROBLEM 1 (Continued)

TABLE 14
Lateral Wind Load: Light-Loaded Condition

Direction	θ_w (degrees)	V_w (feet per second)	$f_{yw}(\theta_w)$	F_{yw} (pounds)
N	0	76.4	0	0
NE	45	65.8	0.782	177,415
E	90	73.7	1	284,621
SE	135	52.2	0.782	111,655
S	180	57.8	O	0
SW	225	58.9	-0.782	-142,157
W	270	53.8	-1	-151,669
NW	315	56.4	-0.782	-130,346

$$\frac{V_H}{V_R} = \left[\frac{12}{33.33}\right]^{1/7} = 0.86$$

A_y = 36,650 square feet

From step (a), A_S = 16,380 square feet

$A_H = A_y - A_S$ = 36,650 - 16,380 = 20,270 square feet

THEN: $C_{yw} = 0.92\ [(1.03)^2(16,380)+(0.86)^2(20,270)]/36,650$

$C_{yw} = 0.81$

AND: $F_{yw} = 1/2\ (0.00237)\ V_w^2\ (36,650)(0.81)\ f_{yw}(\theta_w)$

$F_{yw} = 35.2\ V_w^2\ f_{yw}\ (\theta_w)$

This equation is used to determine F_{yw} for V_w and θ_w for the fully loaded condition. Results are given in Table 15.

(2) Longitudinal Wind Load: Find F_{xw}:

EQ. (4-16) $F_{xw} = 1/2\ \rho_a\ V_w^2\ A_x\ C_{xw}\ f_{xw}(\theta_w)$

ρ = 0.00237 slugs per cubic foot

EQ. (4-19) For an AOE-1 $C_{xwB} = 0.70$

EQ. (4-20) $C_{xwS} = 0.60$

For vessels with distributed superstructures:

EXAMPLE PROBLEM 1 (Continued)

TABLE 15
Lateral Wind Load: Fully Loaded Condition

Direction	θ_w (degrees)	V_w (feet per second)	$f_{yw}[\theta_w]$	F_{yw} (pounds)
N	0	76.4	0	0
NE	45	65.8	0.782	119,179
E	90	73.7	1	191,196
SE	135	52.2	0.782	75,005
S	180	57.8	O	0
SW	225	58.9	-0.782	-95,495
W	270	53.8	-1	-101,884
NW	315	56.4	-0.782	-87,560

EQ. (4-26)

$$f_{xw}(\theta_w) = \frac{-\left[\sin\delta - \dfrac{\sin 5\delta}{10}\right]}{1 - \dfrac{1}{10}}$$

EQ. (4-27)

$$\delta_{(-)} = \left[\frac{90\text{deg.}}{\theta_{wz}}\right]\theta_w + 90\text{deg. for}$$

$$\theta_w < \theta_{wz}$$

EQ. (4-28)

$$\delta_{(+)} = \left[\frac{90\text{deg.}}{180\text{deg.} - \theta_{wz}}\right]\theta_w +$$

$$\left[180\text{deg.} - \frac{90\text{deg. } \theta_{wz}}{180\text{deg.} - \theta_{wz}}\right]$$

$$\text{for } \theta_w > \theta_{wz}$$

Use θ_{wz} = 90 degrees:

THEN:

$$\delta_{(+)} = \left|\frac{90\text{deg.}}{90\text{deg.}}\right| \theta_w + 90\text{deg.} =$$

$$\left[\quad \right]$$

$[\theta]_w + 90deg.$

AND: $$[\delta]_{(-)} = \left[\frac{90deg.}{180deg. - 90deg.} \right] [\theta]_w + \left[180deg. - \frac{(90deg.)\ (90deg.)}{180deg. - 90deg.} \right]$$

$$= [\theta]_w + 90deg.$$

(a) Light-Loaded Condition: Find F_{xw} for the light-loaded condition:

$A_x = 8{,}850$ square feet

THEN: $F_{xw} = 1/2\ (0.00237)\ V_w^2\ (8{,}850)\ C_{xw}\ f_{xw}([\theta]_w)$

$F_{xw} = 10.49\ V_w^2\ C_{xw}\ f_{xw}\ ([\theta]^w)$

EXAMPLE PROBLEM 1 (Continued)

This equation is used to determine F_{xw} for V_{w}, C_{xw} (C_{xwB} or C_{xws}), and θ_{w} for the light-loaded condition. Results are given in Table 16.

TABLE 16
Longitudinal Wind Load: Light-Loaded Condition

Direction	θ_{w} (degrees)	V_{w} (feet per second)	C_{x}	$f_{yw}(\theta_{w})$	V_{x} (poun
N	0	76.4	0.7	-1	-42,8
NE	45	65.8	0.7	-0.864	-27,4
E	90	73.7	0.6	0	
SE	135	52.2	0.6	0.864	14,8
S	180	57.8	0.6	1	21,0
SW	225	58.9	0.6	0.864[*]	18,8
W	270	53.8	0.7	0	
NW	315	56.4	0.7	-0.864[*]	-20,1

[*] $f_{xw}(\theta_{w})$ is symmetrical about the longitudinal axis of the vessel

(b) Fully Loaded Condition: Find F_{xw} for the fully loaded condition:

A_{x} = 6,400 square feet

THEN: $F_{xw} = 1/2\ (0.00237)\ V_{w}^{2}\ (6,400)\ C_{xw}\ f_{xw}(\theta_{w})$

$F_{xw} = 7.58\ V_{w}^{2}\ C_{xw}\ f_{xw}(\theta_{w})$

This equation is used to determine F_{xw} for V_{w}, C_{xw} (C_{xwB} or C_{xwS}), and θ for the fully loaded condition. Results are given in Table 17.

(3) Wind Yaw Moment: Find M_{xyw}:

EQ. (4-29) $M_{xyw} = 1/2\ \rho_{a}\ V_{w}^{2}\ A_{y}\ L\ C_{xyw}(\theta_{w})$

ρ_{a} = 0.00237 slugs per cubic foot

L = 796 feet

$C_{xyw}(\theta_{w})$ is found in Figure 23.

(a) Light-Loaded Condition: Find M_{xyw} for the light-loaded condition:

EXAMPLE PROBLEM 1 (Continued)

TABLE 17
Longitudinal Wind Load: Fully Loaded Condition

Direction	$[\theta]_w$ (degrees)	V_w (feet per second)	C_x	$f_{yw}[\theta]_w$	F_x (poun
N	0	76.4	0.7	-1	-30,9
NE	45	65.8	0.7	-0.864	-19,8
E	90	73.7	0.6	0	
SE	135	52.2	0.6	0.864	10,7
S	180	57.8	0.6	1	15,1
SW	225	58.9	0.6	0.864[*]	13,6
W	270	53.8	0.7	0	
NW	315	56.4	0.7	-0.864[*]	-14,5

[*] $f_{xw}([\theta]_w)$ is symmetrical about the longitudinal axis of the vessel

A_y = 54,600 square feet

THEN:

$$M_{xyw} = 1/2\ (0.00237)\ V_w^{2}\ (54,600)\ (796)\ C_{xyw}([\theta]_w)$$

$$M_{xyw} = 51,502\ V_w^{2}\ C_{xyw}([\theta]_w)$$

This equation is used to determine M_{xyw} for V_w and $[\theta]_w$ for the light-loaded condition. Results are given in Table 18.

TABLE 18
Wind Yarn Moment: Light-Loaded Condition

Direction	$[\theta]_w$ (degrees)	V_w (feet per second)	$C_{xyw}([\theta]_w)$	M_{xyw} (foot-pounds)
N	0	76.4	0	0
NE	45	65.8	0.105	2.3413 x 1
E	90	73.7	0	0
SE	135	52.2	-0.10	-1.4033 x 1
S	180	57.8	0	0
SW	225	58.9	0.10	1.7867 x 1
W	270	53.8	0	0
NW	315	56.4	-0.105	-1.7202 x 1

(b) Fully Loaded Condition: Find M_{xyw} for the fully loaded condition.

EXAMPLE PROBLEM 1 (Continued)

A_y = 35,650 square feet

THEN: $M_{xyw} = 1/2\ (0.00237)\ V_w^2\ (13,050)\ (418)\ C_{xyw}\ ([\theta]_w)$

$M_{xyw} = 6,464\ V_w^2\ C_{xyw}([\theta]_w)$

This equation is used to determine M_{xyw} for V_w and $[\theta]_w$ for the fully loaded condition. Results are given in Table 19.

TABLE 19
Wind Yaw Moment: Fully Loaded Condition

Direction	$[\theta]_w$ (degrees)	V_w (feet per second)	$C_{xyw}([\theta]_w)$	M_{xyw} (foot-pounds)
N	0	76.4	0	0
NE	45	65.8	0.105	1.5716 x $10^{…}$
E	90	73.7	0	0
SE	135	52.2	-0.10	-9.42 x $10^{…}$
S	180	57.8	O	0
SW	225	58.9	0.10	1.1993 x $10^{…}$
W	270	53.8	0	0
NW	315	56.4	-0.105	-1.1547 x $10^{…}$

b. Current Load: Note that lateral and longitudinal flood-current loads ($[\theta]_c$ = 15deg.) are computed below; lateral and longitudinal ebb-current loads are equal to the flood-current loads, but opposite in sign.

(1) Lateral Current Load: Find F_{yc}:

EQ. (4-35) $$F_{yc} = 1/2\ [\rho]_w\ V_c^2\ L_{wL}\ T\ C_{yc}\ \sin[\theta]_c$$

$[\rho]_w$ = 2 slugs per cubic foot

$$V_c = 1 \text{ knot } (1.69 \frac{\text{feet per second}}{\text{knot}})$$

= 1.69 feet per second

EQ. (4-36) $$C_{yc} = C_{yc}\Big|[\infty] = (C_{yc}\Big|1 - C_{yc}\Big|[\infty])\ e^{-k\ (\frac{wd}{T} - 1)}$$

EQ. (4-37)

$$[phi] = \frac{}{L \lceil wL \rceil \; B \; T}$$

EXAMPLE PROBLEM 1 (Continued)

L_{wL} = 770 feet

B = 107 feet

(a) Light-Loaded Condition at Low Tide: Find F_{yc} for the light-loaded condition at low tide:

T = 18.4 feet

wd = 65 feet

D = 18,870 long tons

Find $C_{yc|\infty}$ from Figure 24 for ϕ and L_{wL}/B:

$$\phi = \frac{(35)\ (18{,}870)}{(770)\ (107)\ (18.4)} = 0.436$$

$L_{wL}/B = 770/107 = 7.2$

$C_{yc|\infty} = 0.4$

Find $C_{yc|1}$ from Figure 25 for $C_p\ L_{wL}/\sqrt{T}$:

From Table 7, use C_p = 0.758 for EC-2

$C_p\ L_{wL}/\sqrt{T} = (0.758)\ (770)/\sqrt{18.4} = 136$

$C_{yc|1} = 7$

Find k from Figure 26 for ϕ = 0.436 for a ship-shaped hull:

k = 0.75

$$\frac{wd}{T} = \frac{65}{18.4} = 3.53$$

THEN: $C_{yc} = 0.4 + (7 - 0.4)\ e^{-(0.75)(3.53 - 1)} = 1.39$

THEREFORE: $F_{yc} = 1/2\ (2)\ (1.69)^2\ (770)\ (18.4)\ (1.39)\ \sin(15) = 14{,}558$ pounds

(b) Fully Loaded Condition at Low Tide: Find F_{yc} for the fully loaded condition at low tide:

$T = 41$ feet

$wd = 65$ feet

$D = 53{,}600$ long tons

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EXAMPLE PROBLEM 1 (Continued)

Find $C_{yc|\infty}$ from Figure 24 for ϕ and L_{wL}/B:

$$\phi = \frac{(35)(53{,}600)}{(770)(107)(41)} = 0.56$$

$L_{wL}/B = 770/107 = 7.2$

$C_{yc|\infty} = 0.55$

Find $C_{yc|1}$ from Figure 25 for $C_p L_{wL}/\sqrt{T}$

From Table 7, use $C_p = 0.758$ for EC-2

$C_p L_{wL}/\sqrt{T} = (0.758)(770)/\sqrt{41} = 91.2$

$C_{yc|1} = 5.1$

Find k from Figure 26 for $\phi = 0.555$ for ship-shaped hull:

$k = 0.76$

$$\frac{wd}{T} = \frac{65}{41} = 1.59$$

THEN:

$$C_{yc} = 0.55 + (5.1 - 0.55)\, e^{-(0.76)(1.59 - 1)} = 3.47$$

THEREFORE:

$$F_{yc} = 1/2\ (2)(1.69)^2\ (770)\ (41)(3.47)\ \sin(15) = 80{,}979 \text{ pounds}$$

(2) Longitudinal Current Load: Find F_{xc}:

EQ. (4-40) $$F_{xc} = F_{x\ form} + F_{x\ friction} + F_{x\ prop}$$

EQ. (4-41) $$F_{x\ form} = -\ 1/2\ \rho_w\ V_c^2\ B\ T\ C_{xcb}\ \cos\theta_c$$

$\rho_w = 2$ slugs per cubic foot

$V_c = 1.69$ feet per second

$B = 41$ feet

$C_{xcb} = 0.1$

EQ. (4-42) $$F_x \text{ friction} = -\ 1/2\ \rho_w\ V_c^2\ S\ C_{xca}\ \cos\theta_c$$

EQ. (4-43) $$S = (1.7\ T\ L_{wL}) + \frac{35\ D}{T}$$

EXAMPLE PROBLEM 1 (Continued)

EQ. (4-44) $C_{xca} = 0.075/(\log R_n - 2)^2$

EQ. (4-45) $R_n = V_c L_{wL} \cos\theta_c/\upsilon$

$L_{wL} = 770$ feet

$\upsilon = 1.4 \times 10^{-5}$ square feet per second

EQ. (4-46) $F_{x\,prop} = -1/2\ \rho_w V_c^2 A_p C_{prop} \cos\theta_c$

EQ. (4-47) $$A_p = \frac{A_{Tpp}}{0.838}$$

EQ. (4-48) $$A_{Tpp} = \frac{L_{wL}\ B}{A_R}$$

From Table 8 for cruisers, $A_R = 160$

THEN: $A_{Tpp} = (770)(107)/160 = 515$ square feet

THEN: $$A_p = \frac{515}{0.838} = 615 \text{ square feet}$$

$C_{prop} = 1$

(a) Light-Loaded Condition at Low Tide: Find F_{xc} for the light-loaded condition at low tide:

$T = 18.4$ feet

$D = 18{,}870$ long tons

THEN: $F_{x\,form} = -1/2\ (2)(1.69)^2(107)(18.4)(0.1) \cos(15\text{deg.})$
$= -543$ pounds

$R_n = (1.69)(770) \cos(15\text{deg.})/1.4 \times 10^{-5} = 8.98 \times 10^7$

$C_{xca} = 0.075/[\log(8.97 \times 10^7) -2]^2 = 0.0021$

$$S = (1.7)(18.4)(770) + \frac{(35)(18{,}770)}{18.4}$$
$= 59{,}789$ square feet

THEN: $F_{x\,friction} = -1/2\ (2)(1.69)^2(59{,}789)\ (0.0021) \cos(15\text{deg.}) = -346$ pounds

THEN: $F_{x\,prop} = -1/2\ (2)(1.69)^2(615)\ (1) \cos(15\text{deg.})$
$= -1{,}697$ pounds

THEREFORE: $F_{xc} = - 543 - 346 - 1,697 = - 2,586$ pounds

EXAMPLE PROBLEM 1 (Continued)

(b) Fully Loaded Condition at Low Tide: Find F_{xc} for the fully loaded condition at low tide:

T = 41 feet
D = 53,600 long tons

THEN:

$$F_{x\ form} = -\ 1/2\ (2)(1.69)^{2}(107)(41)(0.1)\cos(15deg.)$$
$$= -\ 1,210 \text{ pounds}$$

$$S = (1.7)(41)(770) + \frac{(35)(53,600)}{41}$$
$$= 99,425 \text{ square feet}$$

THEN:

$$F_{x\ friction} = -\ 1/2\ (2)(1.69)^{2}(99,425)(0.0021)\cos(15deg.) = -\ 576 \text{ pounds}$$

THEN:

$$F_{x\ prop} = -\ 1,697 \text{ pounds}$$

THEREFORE:

$$F_{xc} = -\ 1,210 - 576 - 1,697 = -\ 3,483 \text{ pounds}$$

(3) Current Yaw Moment: Find M_{xyc}:

EQ. (4-49) $$M_{xyc} = F_{yc} \left[\frac{e_c}{L_{wL}}\right] L_{wL}$$

$\left[\frac{e_c}{L_{wL}}\right]$ is found in Figure 27 as a function of

$[theta]_c$ and vessel type. For an EC-2:

$\left[\frac{e_c}{L_{wL}}\right] = 0.025$ for $[theta]_c = 15deg.$

Note that the moment is symmetrical about the vessel stern; therefore, (e_c/L_{wL}) for $[theta]_c = 195deg.$ is

equal to (e_c/L_{wL}) for $[theta]_c = 360deg. - 195deg. + 165deg.$:

$\left[\frac{e_c}{L_{wL}}\right] = -\ 0.025$ for $[theta]_c = 195deg.$

(a) Light-Loaded Condition at Low Tide: Find M_{xyc} for the light-loaded condition at low tide:

Flood current (θ_c = 15deg.):

M_{xyc} = (14,558)(0.025)(770) = 2.8024 x 10^5 foot-pounds

Ebb current (θ_c = 195deg.):

EXAMPLE PROBLEM 1 (Continued)

M_{xyc} = (-14,558)(-0.265)(770) = 2.9706 x 10^{6} foot-pounds

(b) Fully Loaded Condition at Low Tide: Find M_{xyc} for the fully loaded condition at low tide:

Flood current (θ_c = 15deg.):

M_{xyc} = (80,979)(0.025)(770) = 1.559 x 10^{6} foot-pounds

Ebb current (θ_c = 195deg.):

M_{xyc} = (- 80,979)(- 0.265)(770)
= 1.6524 x 10^{7} foot-pounds

5. Evaluate Loads on Mooring Elements:

a. Factor of Safety. The following analysis provides the loads in each of the mooring lines. Once these loads are known, the factors of safety are checked for each mooring line. The mooring lines used to secure the vessel are polypropylene. Table 10 indicates that the factor of safety for a polypropylene rope is 6 (for a mooring-line diameter greater than 3/4 inch).

b. Load Combinations: There are four cases of load combinations which must be analyzed in order to determine the maximum total mooring loads on the vessel:

Load Case 1: Light-loaded condition and flood current
Load Case 2: Light-loaded condition and ebb current
Load Case 3: Fully loaded condition and flood current
Load Case 4: Fully loaded condition and ebb current

Note that, for each case, the maximum loads on the vessel occur when the directions of the wind and current forces coincide. Therefore, loads due to a flood current are combined with loads due to winds from the N, NE, E, and SE. Similarly, loads due to an ebb current are combined with loads due to winds from the S, SW, W and NW.

The load-combination calculations are summarized in Table 20. The following equations are used:

EQ. (4-62) $F_{xT} = F_{xw} + F_{xc}$

EQ. (4-63) $F_{yT} = F_{yw} + F_{yc}$

EQ. (4-64) $M_{xyT} = M_{xyw} + M_{xyc}$

TABLE 20
Load Combinations

Load Case	Wind Direction	θ_w (degrees)	θ_c (degrees)	F_{xT} (pounds)	F_{yT} (pounds)	M_{xyT} (foot-pounds)	F_{yB} (pounds)	F_{yS} (pounds)
1	N	0	15	-45,447	14,558	2.8×10^5	7,688	6,870
	NE	45	15	-30,055	191,973	2.37×10^7	130,585	61,389
	E	90	15	-2,586	299,179	2.8×10^5	149,998	149,181
	SE	135	15	12,232	126,213	-1.375×10^7	43,034	83,180
2	S	180	195	23,613	-14,558	2.97×10^6	-2,943	-11,615
	SW	225	195	21,452	-156,715	2.08×10^7	-47,993	-108,723
	W	270	195	2,586	-166,227	2.97×10^6	-78,778	-87,449
	NW	315	195	-17,595	-144,904	-1.42×10^7	-93,182	-51,722
3	N	0	15	-34,454	80,979	1.59×10^6	42,811	38,168
	NE	45	15	-23,332	200,158	1.73×10^7	125,334	74,824
	E	90	15	-3,483	272,175	1.59×10^6	138,409	133,766
	SE	135	15	7,224	155,984	-7.83×10^6	66,561	89,423
4	S	180	195	18,677	-80,979	1.65×10^7	-16,402	-64,577
	SW	225	195	17,115	-176,474	2.85×10^7	-46,631	-129,843
	W	270	195	3,483	-182,863	1.65×10^7	-67,344	-115,519
	NW	315	195	-11,100	-168,539	4.98×10^6	-76,999	-91,540

EXAMPLE PROBLEM 1 (Continued)

The yaw moment is resolved into lateral loads at the bow and stern using the following equations:

EQ. (4-65) $$F_{yB} = \frac{F_{yT}}{2} + \frac{M_{xyT}}{L_{MP}}$$

EQ. (4-65) $$F_{yS} = \frac{F_{yT}}{2} - \frac{M_{xyt}}{L_{MP}}$$

These loads are computed assuming L_{MP} = 685 feet. (F_{yB} and F_{yS} are given in Table 20.) For example, for a NE wind; CASE 1:

$$F_{yB} = \frac{191,973}{2} + \frac{2.37 \times 10^{7}}{685} = 130,585 \text{ pounds}$$

$$F_{yS} = \frac{191,973}{2} - \frac{2.37 \times 10^{7}}{685} = 61,389 \text{ pounds}$$

c. Lateral Load and Yaw Moment: Light-Loaded Condition:

(1) Case 1 (F_{yB} and F_{yS} both negative): Determine loads in lines 1, 2, 3, 4, 9, 10, 11 and 12:

(a) Low Tide: Determine vertical line angles and line lengths; H = 36 feet:

For example, for lines 1 and 12:

L_{H} = 150 feet

Determine vertical line angle:

$$[\theta] = \arctan \left(\frac{H}{L_{H}}\right) = \arctan \left(\frac{36}{150}\right) = 13.5\text{deg.}$$

Determine actual line length:

$$L = \frac{L_{H}}{\cos[\theta]} = \frac{150}{\cos(13.5)} = 154.3 \text{ feet}$$

Determine unloaded line length, L_{un1}:

Preload = 5,000 pounds

$$\text{Percent of breaking strength} = \left[\frac{5,000}{300,000}\right] (100)$$

└   ┘
= 1.67 percent

From the load-elongation curve for used polypropylene rope (Figure 7), the percent elongation is 0.75 percent.

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EXAMPLE PROBLEM 1 (Continued)

$$L_{un1} = \frac{154.3}{1.0075} = 153.2 \text{ feet.}$$

Similar calculations performed for each line are summarized in Table 21.

Table 21
Unloaded Line Lengths for Low Tide, Light-Loaded Condition

Line Number	L_H (feet)	[theta] (degrees)	L (feet)	Preload (pounds)	Percent of Breaking Strength	Percent Elongation	L_{un1} (feet)
1,12	150	13.5	154.3	5,000	1.67	0.75	153.2
2,11	140	14.4	144.5	5,000	1.67	0.75	143.4
3,10	100	19.8	106.3	5,000	1.67	0.75	105.5
4, 9	95	20.8	101.6	5,000	1.67	0.75	100.8

Determine Line Loads: According to Table 20, the maximum negative load at the vessel bow and/or stern under the light-loaded condition (Load Cases 1 and 2) results from a SW wind and ebb current $[\theta]_c$ = 195deg.):

F_{yB} = - 47,993 pounds

F_{yS} = - 108,723 pounds

(The negative signs will not be carried throughout the calculations as it is understood that a negative sign means that the line is in tension.)

Table 22 provides the resulting mooring-line loads for the above loading Using the procedure outlined in Figure 34.

Table 22
Mooring-Line Loads for Low Tide, Light-Loaded Condition

Line Number	[theta] (degrees)	[alpha] (degrees)	L (feet)	$\frac{\cos^2[\alpha] \cos^2[\theta]}{L}$	F_i (pounds)	(
1,12	13.5	18	154.3	0.005543	24,937	
2,11	14.4	28	144.5	0.005062	24,625	
3,10	19.8	20	106.3	0.007354	34,606	
4,9	20.8	13	101.6	0.008172	37,314	

EXAMPLE PROBLEM 1 (Continued)

$$\sum_{i=1}^{n_F} \frac{\cos^2\alpha \ \cos^2\theta}{L} = \sum_{i=1}^{4} \frac{\cos^2\alpha \ \cos^2\theta}{L} = 0.026131$$

The fore lines (1, 2, 3, and 4) and the aft lines (9, 10, 11, and 12) are both analyzed for the largest lateral load; that is, F_y = - 108,723 pounds. This provides a conservative estimate of line loads and reduces the required number of calculations.

For example, for line 1 (and line 12):

Determine F_1:

$$F_1 = \frac{\cos\alpha \ \cos\theta}{L} \frac{F_y}{\sum_{i=1}^{4} \frac{\cos^2\alpha \ \cos^2\theta}{L}}$$

$$= \frac{\cos(18)\cos(13.5)(108,723)}{(154.3)(0.026131)}$$

$$F_1 = 24,937 \text{ pounds}$$

Determine F_T:

$F_T = F_1$ + Pretension = 24,937 + 5,000 = 29,937 pounds

Results for all lines are presented in Table 22.

The maximum mooring-line load is 42,314 pounds.

Check factor of safety:

$$\text{Factor of safety} = \frac{\text{breaking strength}}{\text{line load}} = \frac{300{,}000}{42{,}314}$$

$$= 7.1 > 6; \text{ ok}$$

(b) High Tide: Following the procedure outlined in Figure 38, determine the increase in line loads due to an increase in water level (H = 36 + 6 = 42 feet):

Calculate new line angles, line lengths, and pretensions at high tide:

For example, for lines 1 and 12:

L_H = 150 feet

EXAMPLE PROBLEM 1 (Continued)

Determine vertical line angle:

$$[\theta] - \arctan \left(\frac{H}{L_H}\right) = \arctan \left(\frac{42}{150}\right) = 15.6\text{deg.}$$

Determine actual line length:

$$L = \frac{L_H}{\cos[\theta]} = \frac{150}{\cos(15.6)} = 155.7 \text{ feet}$$

Determine percent elongation: L_{un1} is given in Table 21.

$$\text{Percent elongation} = \left[\frac{L - L_{un1}}{L_{un1}}\right](100)$$

$$= \left[\frac{155.7 - 153.2}{153.2}\right](100)$$

Percent elongation = 1.63 percent

Determine percent of breaking strength from Figure 7 for used polypropylene rope:

Percent breaking strength = 6 percent

New pretension = (0.06)(300,000) = 18,000 pounds

Similar calculations performed for each line are summarized in Table 23.

Table 23
Line Lengths and Pretensions for High Tide, Light-Loaded Condition

Line Number	L_H (feet)	[theta] (degrees)	L (feet)	Percent Elongation	Percent of Breaking Strength	New Pretension (pounds)
1,12	150	15.6	155.7	1.63	6	18,000
2,11	140	16.7	146.2	1.95	8	24,000
3,11	100	22.8	108.5	2.84	13	39,000
4, 9	95	23.9	103.9	3.1	15	45,000

Mooring-line loads for a high tide and a light-loaded condition are computed in a manner similar to that used above for low tide. Results for all lines are given in Table 24.

EXAMPLE PROBLEM 1 (Continued)

Table 24
Mooring-Line Loads for High Tide, Light-Loaded Condition

Line Number	θ (degrees)	α (degrees)	L (feet)	$\frac{\cos^2\alpha \cos^2\theta}{L}$	F_i (pounds)	(
1,12	15.6	18	155.7	0.00539	25,751	
2,11	16.7	28	146.2	0.00489	25,319	
3,10	22.8	20	108.5	0.00692	34,946	
4, 9	23.9	13	103.9	0.00764	37,527	

$$\sum_{i=1}^{4} \frac{\cos^2\alpha \cos^2\theta}{L} = 0.02484$$

The maximum mooring-line load is 82,527 pounds.

Check factor of safety:

$$\text{Factor safety} = \frac{\text{breaking strength}}{\text{line load}} = \frac{300{,}000}{82{,}527}$$

$$= 3.6 < 6$$

Therefore, unless the mooring lines are tended, the factor of safety will be less than required, and a stronger line will be required.

(2) Case 2 (F_{yB} and F_{yS} both positive): Determine breasting-structure loads using the procedure outlined in Figure 35. From Table 20, the maximum positive lateral load under the light-loaded condition is due to an E wind with a flood current:

F_{yT} = 299,179 pounds

M_{xyt} = 2.8 x 10^5 foot-pounds

F_{yT} M_{xyT} 299,179 2.8 x 10^5

$$F_A = \frac{\quad}{2} - \frac{\quad}{L_F} = \frac{\quad}{2} - \frac{\quad}{320}$$

F_A = 148,715 pounds

$F_F = F_{yT} - F_A$ = 299,179 - 148,715

F_F = 150,464 pounds

EXAMPLE PROBLEM 1 (Continued)

d. Longitudinal Load: Light-Loaded Condition:

(1) Low Tide: Determine vertical line angles and line lengths; H = 36 feet. The calculations, identical to those above for lateral load and yaw moment, are summarized in Table 25.

Table 25
Unloaded Line Lengths for Low Tide, Light-Loaded Condition

Line Number	L_H (feet)	[theta] (degrees)	L (feet)	Preload (pounds)	Percent of Breaking Strength	Percent Elongation	L_{un1} (feet)
5,8	300	6.8	302.1	5,000	1.67	0.75	299.9
6,7	260	7.9	262.5	5,000	1.67	0.75	260.5

Determine Line Loads: According to Table 20, the maximum longitudinal load on the mooring under the light-loaded condition is F_{xT} = - 45,447 pounds for a N wind and a flood current. Table 26 provides the mooring-line loads obtained using the procedure outlined in Figure 37.

Table 26
Mooring-Line Loads for Low Tide, Light-Loaded Condition

Line Number	[theta] (degrees)	[beta] (degrees)	L (feet)	$\frac{\cos^2[\beta] \cos^2[\theta]}{L}$	F_i (pounds)	F_T (pou
5,8	6.8	3.5	302.1	0.00325	21,361	26,3
6,7	7.9	3.2	262.5	0.00373	24,531	29,5

$$\sum_{i=1}^{2} \frac{\cos^2\beta \cos^2\theta}{L} = 0.00698$$

The maximum mooring-line load is 29,531 pounds.

Check factor of safety:

$$\text{Factor of safety} = \frac{\text{breaking strength}}{\text{line load}} = \frac{300{,}000}{29{,}531}$$

$$= 10.2 > 6;\ \text{ok}$$

EXAMPLE PROBLEM 1 (Continued)

(2) High Tide: Following the procedure outlined in Figure 38, determine the increase in line loads due to an increase in water level (H = 36 + 6 = 42 feet).

New line angles, line lengths, and pretensions at high tide are calculated in a manner similar to that for the lateral load above. The results are given in Table 27.

Table 27
Line Lengths and Pretensions for High Tide, Light-Loaded Condition

Line Number	L_H (feet)	[theta] (degrees)	L (feet)	Percent Elongation	Percent of Breaking Strength	New Pretension (pounds)
5,8	300	8	302.9	1	3.5	10,500
6,7	260	9.2	263.4	1.1	3.75	11,250

Mooring-line loads for a high tide and a light-loaded condition are computed in a manner similar to that used above for low tide. Results are given in Table 28.

Table 28
Mooring-Line Loads for High Tide, Light-Loaded Condition

Line Number	[theta] (degrees)	[beta] (degrees)	L (feet)	$\frac{\cos^2 [\text{beta}] \cos^2 [\text{theta}]}{L}$	F_i (pounds)	F_T (pou
5,8	8	3.5	302.9	0.00323	21,431	31,9
6,7	9.2	3.2	263.4	0.00369	24,574	35,8

$$\sum_{i=1}^{2} \frac{\cos^2\beta \cos^2\theta}{L} = 0.00692$$

The maximum mooring-line load is 35,824 pounds.

Check factor of safety:

$$\text{Factor of safety} = \frac{\text{breaking strength}}{\text{line load}} = \frac{300{,}000}{35{,}824}$$

$$= 8.4 > 6;\ \text{ok}$$

EXAMPLE PROBLEM 1 (Continued)

e. Lateral Load and Yarn Moment: Fully Loaded Condition:

(1) Case 1 (F_{yB} and F_{yS} both negative): Determine load in lines 1, 2, 3, 4, 9, 10, 11 and 12.

(a) Low Tide: Determine vertical line angles and line lengths; H = 12 feet.

For example, for lines 1 and 12:

L_H = 150 feet

Determine vertical line angle:

$$\theta = \arctan\left(\frac{H}{L_H}\right) = \arctan\left(\frac{12}{150}\right) = 4.6\text{deg.}$$

Determine actual line length:

$$L = \frac{L_H}{\cos\theta} = \frac{150}{\cos(4.6)} = 150.5 \text{ feet}$$

Determine unloaded line length, L_{un1}:

Preload = 5,000 pounds

$$\text{Percent of breaking strength} = \left[\frac{5{,}000}{300{,}000}\right](100)$$

$$= 1.67 \text{ percent}$$

From the load-elongation curve for used polypropylene rope (Figure 7), the percent elongation is 0.75 percent.

$$L_{un1} = \frac{150.5}{1.0075} = 149.4 \text{ feet.}$$

Similar calculations performed for each line are summarized in Table 29.

Table 29
Unloaded Line Lengths for Low Tide, Fully Loaded Condition

Line Number	L_H (feet)	[theta] (degrees)	L (feet)	Preload (pounds)	Percent of Breaking Strength	Percent Elongation	L_{un1} (feet)
1,12	150	4.6	150.5	5,000	1.67	0.75	149.4

2,11	140	4.9	140.5	5,000	1.67	0.75	139.5
3,10	100	6.8	100.7	5,000	1.67	0.75	100
4, 9	95	7.2	95.8	5,000	1:67	0.75	95

EXAMPLE PROBLEM 1 (Continued)

Determine Line Loads: According to Table 20, the maximum negative load at the vessel bow and/or stern under the fully loaded condition (Load Cases 3 and 4) results from a SW wind and ebb current (θ_c = 195deg.):

F_{yB} = - 46,631 pounds

F_{yS} = - 129,843 pounds

(The negative signs will not be carried throughout the calculations as it is understood that a negative sign means that the line is in tension.)

Table 30 provides the resulting mooring-line loads for the above loading using the procedure outlined in Figure 34.

Table 30
Mooring-Line Loads for Low Tide, Fully Loaded Condition

Line Number	θ (degrees)	α (degrees)	L (feet)	$\frac{\cos^2\alpha \cos^2\theta}{L}$	F_i (pounds)
1,12	4.6	18	150.5	0.00597	27,372
2,11	4.9	28	140.5	0.00551	27,209
3,10	6.8	20	100.7	0.00865	40,266
4, 9	7.2	13	95.8	0.00975	43,849

$$\sum_{i=1}^{4} \frac{\cos^2\alpha \cos^2\theta}{L} = 0.02988$$

The fore lines (1, 2, 3, and 4) and the aft lines (9, 10, 11, and 12) are both analyzed for the largest lateral load; that is, F_y = - 129,843 pounds. This provides a conservative estimate of line loads and reduces the required number of calculations.

For example, for line 1 (and line 12):

Determine F_1:

$$F_1 = \frac{\cos\alpha \cos\theta}{L} \frac{F_y}{\sum_{i=1}^{4} \frac{\cos^2\alpha \cos^2\theta}{L}}$$

EXAMPLE PROBLEM 1 (Continued)

$$F_{1} = \frac{\cos(18)\cos(4.6)(129,843)}{(150.5)\ (0.02988)}$$

F_{1} = 27,372 pounds

Determine F_{T}:
$F_{T} = F_{1}$ + Pretension = 27,372 + 5,000 = 32,372 pounds.

The maximum mooring-line load is 48,849 pounds.

Check factor of safety:

$$\text{Factor of safety} = \frac{\text{breaking strength}}{\text{line load}} = \frac{300,000}{48,849}$$

$$= 6.1 > 6;\ \text{ok}$$

(b) High Tide: Following the procedure outlined in Figure 38, determine the increase in line loads due to an increase in water level (H = 12 + 6 = 18 feet).

Calculate new line angles, line lengths, and pretensions at high tide:

For example, for lines 1 and 12:

L_{H} = 150 feet

Determine vertical line angle:

$$[\theta] = \arctan\left(\frac{H}{L_{H}}\right) = \arctan(18/50) = 6.8\text{deg.}$$

Determine actual line length:

$$L = \frac{L_{H}}{\cos[\theta]} = \frac{150}{\cos(6.8)} = 151.1\ \text{feet}$$

Determine percent elongation: L_{un1} is given in Table 29.

$$\text{Percent elongation} = \left[\frac{L - L_{un1}}{L_{un1}}\right](100)$$

$$= \left[\frac{151.1 - 149.4}{149.4}\right](100)$$

Percent elongation = 1.14 percent

Determine percent of breaking strength from Figure 7 for used polypropylene rope:

EXAMPLE PROBLEM 1 (Continued)

Percent breaking strength = 3.75 percent

New pretension = (0 .0375) (300,000) = 11,250 pounds

Similar calculations performed for each line are summarized in Table 31.

Table 31
Line Lengths and Pretensions For High Tide, Fully Loaded Condition

Line Number	L_H (feet)	[theta] (degrees)	L (feet)	Percent Elongation	Percent of Breaking Strength	New Pretension (pounds)
1,12	150	6.8	151.1	1.14	3.75	11,250
2,11	140	7.3	141.1	1.15	3.75	11,250
3,10	100	10.2	101.6	1.6	7	21,000
4, 9	95	10.7	96.7	0.9	8	24,000

Mooring-line loads for a high tide and a fully loaded condition are computed in a manner similar to that used above for low tide. Results are given in Table 32.

Table 32
Mooring-Line Loads for High Tide, Fully Loaded Condition

Line Number	[theta] (degrees)	[alpha] (degrees)	L (feet)	$\frac{\cos^2[\text{alpha}] \cos^2[\text{theta}]}{L}$	F_i (pounds)	(
1,12	6.8	18	151.1	0.0059	28,177	
2,11	7.3	28	141.1	0.0054	27,984	
3,10	10.2	20	106.6	0.0080	39,115	
4, 9	10.7	13	96.7	0.0095	44,638	

$$\sum_{i=1}^{4} \frac{\cos^2\alpha \cos^2\theta}{L} = 0.0288$$

The maximum mooring-line load is 68,638 pounds.

Check factor of safety:

$$\text{Factor of safety} = \frac{\text{breaking strength}}{\text{line load}} = \frac{300{,}000}{68{,}638}$$

$$= 4.4 < 6$$

Therefore, unless the mooring lines are tended, the factor of safety will be less than required, and stronger mooring line will be required.

(2) Case 2 (F_{yB} and F_{yS} both positive): Determine breasting-structure loads using the procedure outlined in Figure 35. From Table 20, the maximum positive lateral load under the fully loaded condition is due to an E wind with a flood current:

F_{yT} = 272,175 pounds

$M_{xyt} = 1.59 \times 10^{6}$ foot-pounds

$$F_A = \frac{F_{yT}}{2} \quad \frac{M_{xyt}}{L_F} \quad \frac{272{,}175}{2} \quad \frac{1.59 \times 10^{6}}{320}$$

F_A = 131,120 pounds

$F_F = F_{yT} - F_A$ = 272,175 - 131,120

F_F = 141,055 pounds

f. Longitudinal Load: Fully Loaded Condition:

(1) Low Tide: Determine vertical line angles and line lengths; H = 12 feet. The calculations, identical to those above for lateral load and yaw moment, are summarized in Table 33.

Table 33
Unloaded Line Lengths for Low Tide, Fully Loaded Condition

Line Number	L_H (feet)	[theta] (degrees)	L (feet)	Preload (pounds)	Percent of Breaking Strength	Percent Elongation	L_{un1} (feet)
5,8	300	2.3	300.2	5,000	1.67	0.75	298
6,7	260	2.6	260.3	5,000	1.67	0.75	258.4

Determine Line Loads: According to Table 20, the maximum longitudinal load on the mooring under the fully loaded

EXAMPLE PROBLEM 1 (Continued)

condition is F_{xT} = - 34,454 pounds for a N wind and a flood current. Table 34 provides the mooring-line loads obtained using the procedure outlined in Figure 37.

Table 34
Mooring-Line Loads for Low Tide, Fully Loaded Condition

Line Number	θ (degrees)	β (degrees)	L (feet)	$\frac{\cos^2\beta \cos^2\theta}{L}$	F_i (pounds)	F_T (pou
5,8	2.3	3.5	300.2	0.0033	16,122	21,1
6,7	2.6	3.2	260.3	0.0038	18,595	23,5

$$\sum_{i=1}^{2} \frac{\cos^2\beta \cos^2\theta}{L} = 0.0071$$

The maximum mooring-line load is 23,595 pounds.

Check factor of safety:

$$\text{Factor of safety} = \frac{\text{breaking strength}}{\text{line load}} = \frac{300{,}000}{23{,}595}$$

$$= 12.7 > 6; \text{ ok}$$

(2) High Tide: Following the procedure outlined in Figure 38, determine the increase in line loads due to an increase in water level (H = 12 + 6 = 18 feet).

New line angles, line lengths, and pretensions at high tide are calculated in a manner similar to that for the lateral load above. The results are given in Table 35.

Table 35
Line Lengths and Pretensions for High Tide, Fully Loaded Condition

Line Number	L_H (feet)	[theta] (degrees)	L (feet)	Percent Elongation	Percent of Breaking Strength	New Pretension (pounds)
5,8	300	3.4	300.5	0.84	3.7	11,100
6,7	260	4	260.6	0.85	3.7	11,100

EXAMPLE PROBLEM 1 (Continued)

Mooring-line loads for a high tide and a light-loaded condition are computed in a manner similar to that used above for low tide. Results are given in Table 36.

Table 36
Mooring-Line Loads for High Tide, Fully Loaded Condition

Line Number	θ (degrees)	β (degrees)	L (feet)	$\frac{\cos^2\beta \cos^2\theta}{L}$	F_i (pounds)	F┌ (pou
5,8	3.4	3.5	300.5	0.0033	16,090	27,1
6,7	4	3.2	260.4	0.0038	18,561	29,6

$$\sum_{i=1}^{2} \frac{\cos^2\beta \cos^2\theta}{L} = 0.0071$$

The maximum mooring-line load is 29,661 pounds.

Check factor of safety:

$$\text{Factor of safety} = \frac{\text{breaking strength}}{\text{line load}} = \frac{300{,}000}{29{,}661}$$

$$= 10.1 > 6;\ \text{ok}$$

g. Berthing Loads: Check for the fully loaded condition only as this will provide the maximum KE_B. Determine KE_B using the procedure outlined in Figure 40:

(1) Determine Vessel Weight:

D = 53,600 long tons

Convert long tons to pounds to obtain W:

$W = 2{,}240\ D = (2{,}240)(53{,}600) = 1.2006 \times 10^{8}$ pounds

(2) Determine Normal Component of Approach Velocity:

V_N is given in Figure 42 for sheltered conditions and vessel displacement in long tons (D = 53,600 long tons):

V_N = 0.19 foot per second

(3) Determine Berthing Coefficient:

C_B = 0.5

EXAMPLE PROBLEM 1 (Continued)

(4) Determine Hydrodynamic Mass Coefficient:

C_H is given in Figure 43 as a function of B/wd and T/wd.

B/wd = 107/65 = 1.65

T/wd = 41/65 = 0.63

From Figure 43:

$C_H = 3.65$

(5) Determine KE_B:

EQ. (4-67) $$KE_B = 1/2 \frac{W}{g} V_N{}^2 C_B C_H$$

$$KE_B = 1/2 \left(\frac{1.2006 \times 10^8}{32.2}\right)(0.19)^2(0.5)(3.65)$$

KE_B = 122,824 foot-pounds = 122.8 foot-kips

6. Design of Fixed-Mooring Structures:

a. Breasting structures: Design the breasting structures following the procedure outlined in Figure 44, assuming the breasting structures are rigid:

(1) Determine Maximum Mooring Load: The maximum mooring load on the breasting structures determined above is F_M = 141,055 pounds or F_M = 141 kips.

(2) Rigid or Flexible Design: For the purposes of this example problem, assume the breasting structures to be rigid.

(3) Design Structure and Select Preliminary Fendering System: A giant cylindrical fender will be used for the purposes of this example problem. As a first try, check a 3-foot section of 60-inch O.D. fender.

(4) Develop Load-Deflection Curve for Fender: The load-deflection curve for the giant cylindrical fender is shown in Figure 48 (top). An energy absorption-deflection curve is also shown in Figure 48 (bottom); the use of this curve simplifies the design process as it eliminates the need to determine the area under the load-deflection curve.

$$\text{Energy to be absorbed per foot} = \frac{122.8 \text{ foot-kips}}{3 \text{ feet}}$$

= 40.9 foot-kips per
foot

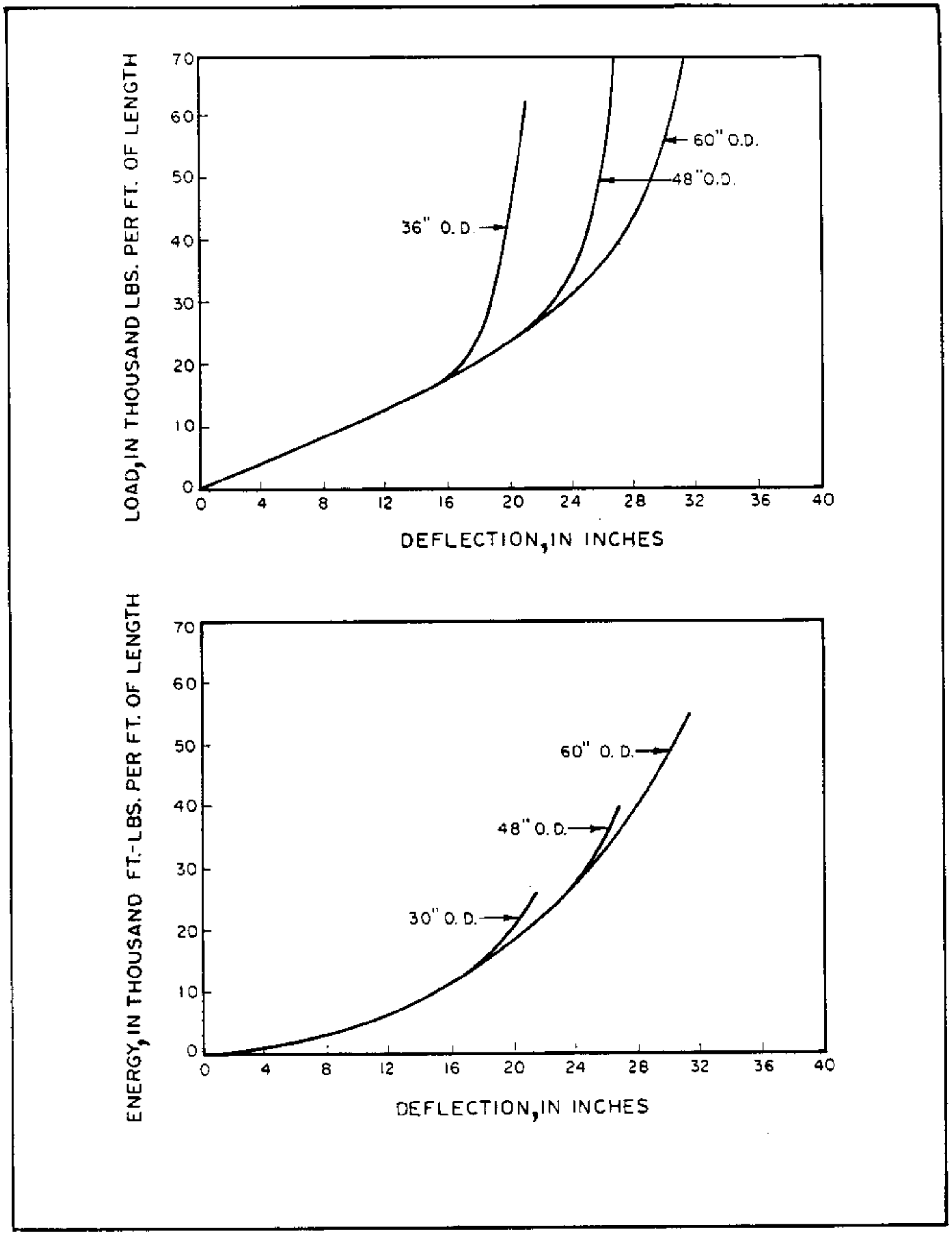


FIGURE 48
Giant Cylindrical Fender Characteristics

EXAMPLE PROBLEM 1 (Continued)

From Figure 48 (bottom), the fender deflects about 28.5 inches to absorb 40.9 foot-kips per foot of length. From the load-deflection curve in Figure 48 (top), the load at 28.5 inches deflection is 45 kips per foot.

Total load, F_B, in 3-foot fender due to berthing:

F_B = (3) (45) = 135 kips

F_B = 135 kips [similar, equals]F_M = 141 kips

No further iterations are required.

The following pages illustrate the use of the computer program described in Appendix B of DM-26.5 to solve Example Problem 1. The first page of computer output summarizes the geometry of the mooring, and the mooring-line and fender characteristics. Page 2 summarizes the loads in the mooring elements for the vessel in a light-loaded condition under a SW wind and ebb current. Page 3 summarizes the loads in the mooring elements for the vessel in a light-loaded condition under an E wind and a flood current.

FIXED MOORING ANALYSIS

EXAMPLE1

FENDER INPUT DATA:

Fender No.	Location X	Location Y	Minimum Load	Minimum Defl	Maximum Load	Maximum Defl
1	160.0	65.0	0	0.0	180000	1.8
2	-160.0	65.0	0	0.0	180000	1.8

MOORING LINE INPUT DATA:

Line No.	Chock Coordinates X	Chock Coordinates Y	Chock Coordinates Z	Anchor Coordinates X	Anchor Coordinates Y	Anchor Coordinates Z
1	410.0	0.0	36.0	450.0	140.0	0.0
2	385.0	20.0	36.0	450.0	140.0	0.0
3	290.0	40.0	36.0	250.0	140.0	0.0
4	280.0	40.0	36.0	250.0	140.0	0.0
5	140.0	50.0	36.0	-160.0	65.0	0.0
6	110.0	50.0	36.0	-160.0	65.0	0.0
7	-110.0	50.0	36.0	160.0	65.0	0.0
8	-140.0	50.0	36.0	160.0	65.0	0.0
9	-280.0	50.0	36.0	-250.0	140.0	0.0
10	-290.0	50.0	36.0	-250.0	140.0	0.0
11	-395.0	30.0	36.0	-450.0	140.0	0.0
12	-395.0	0.0	36.0	-450.0	140.0	0.0

Line No.	Type Code	Length On-deck	Length Tail	Breaking Strength	Preload	Steel Hawser Modulus	Steel Hawser Area
1	3	0.0	0.0	300000	5000		
2	3	0.0	0.0	300000	5000		
3	3	0.0	0.0	300000	5000		
4	3	0.0	0.0	300000	5000		
5	3	0.0	0.0	300000	5000		
6	3	0.0	0.0	300000	5000		
7	3	0.0	0.0	300000	5000		
8	3	0.0	0.0	300000	5000		
9	3	0.0	0.0	300000	5000		
10	3	0.0	0.0	300000	5000		
11	3	0.0	0.0	300000	5000		
12	3	0.0	0.0	300000	5000		

RESULTS FOR LOAD CASE 0 INITIAL POSITION Tide = 0

	Applied Load	Load Error	Displacement
Surge	0.000E+00	-0	-0.0
Sway	0.000E+00	0	0.4
Yaw	0.000E+00	-172	0.0

Mooring Legs

No.	Horiz Load	Total Load	Chock-Anchor	Horiz Angle
Fenders				
1	14429		0.4	90.0
2	14075		0.3	90.0
Lines				
1	3890	4007	145.5	74.0
2	3912	4047	136.2	61.5
3	3570	3766	107.4	111.9
4	3495	3690	104.1	106.8
5	4932	4960	300.4	177.2
6	4918	4961	270.4	176.9
7	4938	4982	270.4	3.1
8	4951	4907	300.4	2.8
9	3448	3689	94.5	71.5
10	3546	3777	98.2	66.0
11	3826	3987	122.7	116.6
12	4002	4115	150.1	111.5

RESULTS FOR LOAD CASE 1 L.L. SW WIND EBB CURRENT Tide = 0

	Applied Load	Load Error	Displacement
Surge	2.145E+04	0	1.9
Sway	-1.567E+05	1	-4.1
Vow	2.080E+07	86	0.3

Mooring Legs

No.	Horiz Load	Total Load	Chock-Anchor	Horiz Angle
Fenders				
1	0		-3.3	90.3
2	0		-5.0	90.3
Lines				
1	8977	9242	147.1	75.0
2	8018	8288	137.5	62.7
3	16835	17701	110.8	112.1
4	17138	18073	107.5	107.2
5	7696	7750	302.3	176.5
6	8026	8095	272.3	176.1
7	2733	2758	269.0	4.2
8	2922	2943	299.0	3.8
9	29296	31148	99.7	73.5
10	26615	28193	103.0	68.2
11	32477	33712	129.5	116.1
12	27441	28154	156.9	111.3

RESULTS FOR LOAD CASE 2 L.L. E WIND FLOOD CURRENT Tide = 0

	Applied Load	Load Error	Displacement
Surge	-2.586E+03	-0	-0.3
Sway	2.992E+05	0	1.7
Vow	2.800E+05	36	0.0

Mooring Legs

No.	Horiz Load	Total Load	Chock-Anchor	Horiz Angle
Fenders				
1	152268		1.7	90.0
2	149304		1.7	90.0
Lines				
1	519	535	144.1	73.7
2	893	924	135.1	61.1
3	0	0	106.0	112.0
4	0	0	102.7	106.8
5	4354	4386	300.0	177.5
6	4268	4306	270. 0	177.2
7	5364	5412	270.7	2.8
8	5346	5385	300.6	2.5
9	0	0	93.4	71.0
10	0	0	97.1	65.4
11	0	0	121.3	116.8
12	226	232	140.7	111.6

EXAMPLE PROBLEM 2: SPUD MOORING FOR FLOATING DRYDOCK

Given: a. Spud mooring for an AFDM-8 with an AS-36 on the blocks. (Mooring configuration is Shown in Figure 49.)
b. The water depth at the site is 60 feet mean lower low water (MLLW).
c. The tide range from MLLW to mean higher high water (MHHW) is 8 feet.
d. Wind data for the site are given in Table 37.
e. Currents are negligible.

Find: Determine loads on the spud mooring due to wind load.

Solution: 1. Determine Vessel Characteristics for AFDM-8 from DM-26.6, Table 3:

Length on pontoons, L = 552 feet
Extreme beam, B = 124 feet
Maximum draft, T = 52.8 feet
Draft over blocks, T = 29.6 feet
Draft with vessel on blocks, T = 16 feet
Maximum displacement, D = 43,300 long tons
Displacement with maximum vessel on blocks, D = 27,200 long tons
Light displacement, D = 7,800 long tons
Broadside wind area with maximum vessel on blocks, A_y = 62,000 square feet
Frontal wind area with maximum vessel on blocks, A_x = 10,800 square feet

2. Mooring Configuration: mooring configuration is shown in Figure 49.

3. Evaluate Environmental Conditions:

a. Seafloor Soil Conditions: This example problem illustrates the procedures for determining loads on fixed-mooring structures, but does not include structural-design calculations. Consequently, although they are important in structural design, soil conditions are not needed for this example problem.

b. Design Water Depth:

(1) Water depth at low tide, $wd_{low\ tide}$ = 60 feet

(2) Water depth at high tide, $wd_{high\ tide}$ = 60 + 8 = 68 feet

c. Design Wind:

(1) Obtain Wind Data: Wind data obtained for the site are presented in Table 37. These data provide yearly maximum windspeeds for all directions combined (that is, directional data are not available). Therefore, the

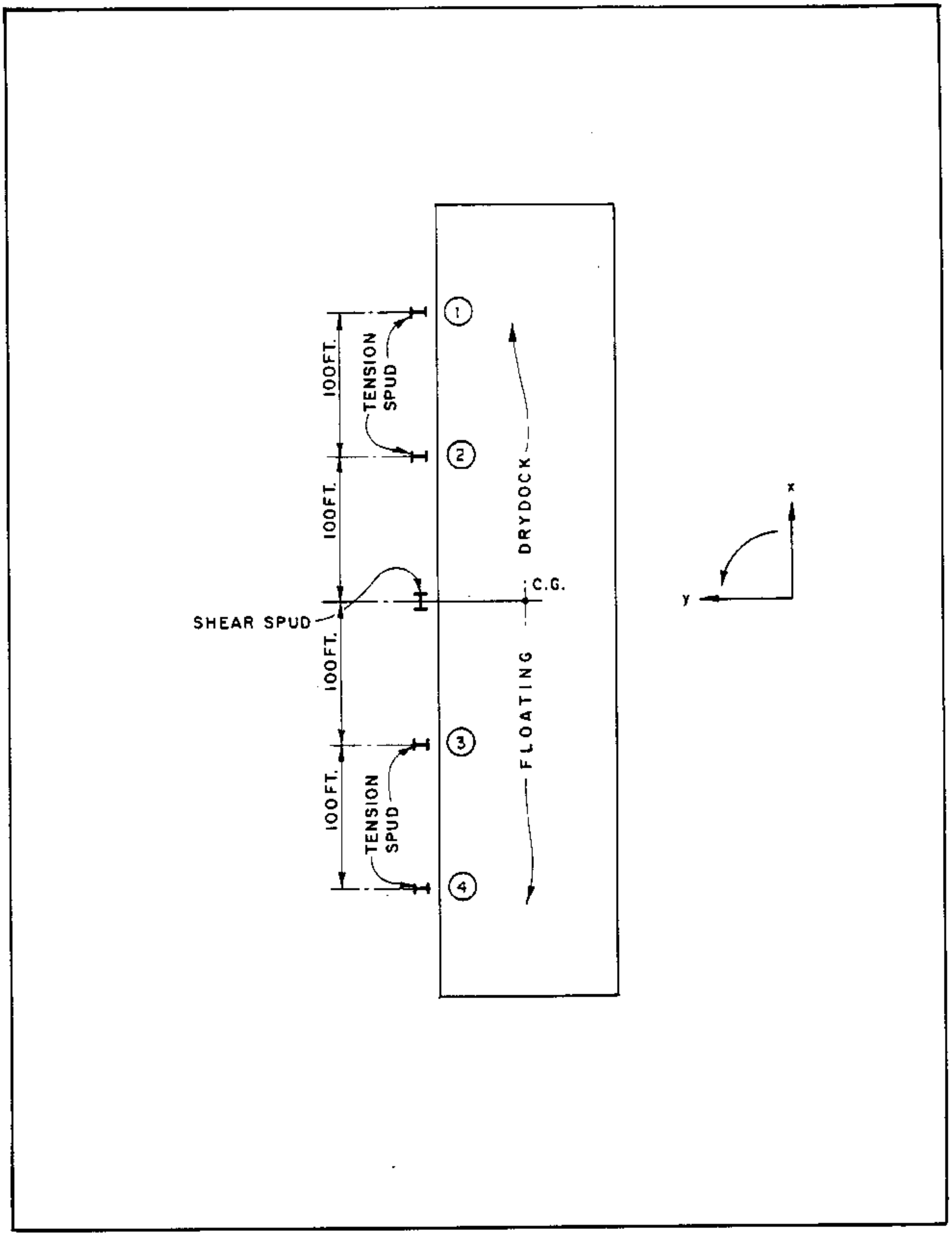


FIGURE 49
Mooring Configuration (Example Problem 2)

EXAMPLE PROBLEM 2 (Continued)

TABLE 37
Wind Data for Site

Year	Peak-Gust Windspeed (miles per hour)	Direction
1950	62	E
1951	38	NE
1952	53	N
1953	46	SW
1954	41	S
1955	41	NE
1956	43	N
1957	41	S
1958	38	W
1959	34	S
1960	41	NE
1961	42	SW
1962	47	E
1963	54	N
1964	70	N
1965	50	E
1966	42	E
1967	65	NE
1968	46	N
1969	50	N
1970	39	SE
1971	46	NW
1972	44	NW
1973	47	W
1974	44	SE
1975	60	N
1976	42	W
1977	34	W
1978	39	SW
1979	35	NE

[1]Data were collected over water at an elevation of 43 feet.

EXAMPLE PROBLEM 2 (Continued)

approximate method for determining directional probability must be used.

(2) Correct for Elevation:

EQ. (4-1)

$$V_{33.33} = V_h \left(\frac{33.33}{h}\right)^{1/7} = V_{43}\left(\frac{33.33}{43}\right)^{1/7} = 0.964\, V_{43};\ \text{use}$$

$0.96\ V_{43}$

Therefore, elevation correction factor = 0.96

(3) Correct for Duration: The recorded windspeeds are peak-gust values; reduce the windspeeds by 10 percent to obtain the 30-second windspeeds. Therefore, duration correction factor = 0.90.

(4) Correct for Overland-Overwater Effects: Data were collected over water; therefore, no correction is necessary.

THEREFORE: Total correction factor a (0.9)(0.96) = 0.864.

Multiply each value in Table 37 by 0.864 to obtain the 30-second windspeed at 33.33 feet above the water surface. The results are shown in Table 38.

(5) Determine Windspeed Probability:

(a) Determine mean value, $\bar{x}$, and standard deviation, σ, for windspeed data:

EQ. (4-4)

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i = 39.57$$

EQ. (4-5)

$$\sigma = \frac{1}{N-1}\sum_{i=1}^{N} (x_i - \bar{x})^2 = 7.76$$

Note that $\bar{x}$ and σ can be computed with most hand-held calculators.

(b) Use Gumbel distribution to determine design windspeeds for all directions combined:

(i) Compute Gumbel parameters [alpha] and u:

EQ. (4-7)

$$\alpha = \frac{1.282}{\sigma} = \frac{1.282}{7.76} = 0.1652$$

EQ. (4-8)

$$u = \bar{x} - \frac{0.577}{\alpha} = 39.57 - \frac{0.577}{0.1652} = 36.08$$

EXAMPLE PROBLEM 2 (Continued)

TABLE 38
Adjusted Wind Data for Site

Year	Peak-Gust Windspeed (miles per hour)	Direction
1950	53.6	E
1951	32.8	NE
1952	45.8	N
1953	39.7	SW
1954	35.4	S
1955	35.4	NE
1956	37.2	N
1957	35.4	S
1958	32.8	W
1959	29.4	S
1960	35.4	NE
1961	36.3	SW
1962	40.6	E
1963	46.7	N
1964	60.5	N
1965	43.2	E
1966	36.3	E
1967	56.2	NE
1968	39.7	N
1969	43.2	N
1970	33.7	SE
1971	39.7	NW
1972	38.0	NW
1973	40.6	W
1974	38.0	SE
1975	51.8	N
1976	36.3	W
1977	29.4	W
1978	33.7	SW
1979	30.2	NE

EXAMPLE PROBLEM 2 (Continued)

(ii) Compute VR for 25- and 50-year return periods:

EQ. (4-6)

$$V_R = u - \frac{\ln \{- \ln [1 - P(X \geq x)]\}}{\alpha}$$

From Table 4, for a return period of 25 years, $P(X \geq x) = 0.04$, and for a return period of 50 years, $P(X \geq x) = 0.02$.

THEN:

$$V_{25} = 36.08 - \frac{\ln [- \ln (1 - 0.04)]}{0.1652}$$

$$= 55.4 \text{ miles per hour}$$

$$V_{50} = 36.08 - \frac{\ln [- \ln (1 - 0.02)]}{0.1652}$$

$$= 59.7 \text{ miles per hour}$$

These two points are plotted on Gumbel paper in Figure 50 and designated "all directions" on the figure.

(c) Determine directional probabilities: Find $P(X \geq x) = 0$, the probability of exceedence for a windspeed from direction e, where 0 is one of the eight compass points (N, NE, E, SE, S, SW, W, and NW):

EQ. (4-9)

$$P(X \geq x)|_{\theta} = P(X \geq x) \frac{N_{\theta}}{N}$$

$P(X \geq x) = 0.02$ for a return period of 50 years

N_{θ} is determined by counting the number of times that the extreme wind came from a particular direction (in Table 38).

N is the total number of extreme windspeeds in the data (in Table 38): N = 30

Values for N_{θ} and N_{θ}/N are given in Table 39.

For example, for north:

SUBSTITUTING:

$$P(X \geq x)|_{\theta} = (0.02)\left(\frac{7}{30}\right) = 0.0047$$

Values of $P(X \geq x)|_{\theta}$ for the eight compass points are given in Table 40.

The probability of exceedence $[P(X \geq x)]|_{\theta}$ for each compass point is plotted on Gumbel paper versus

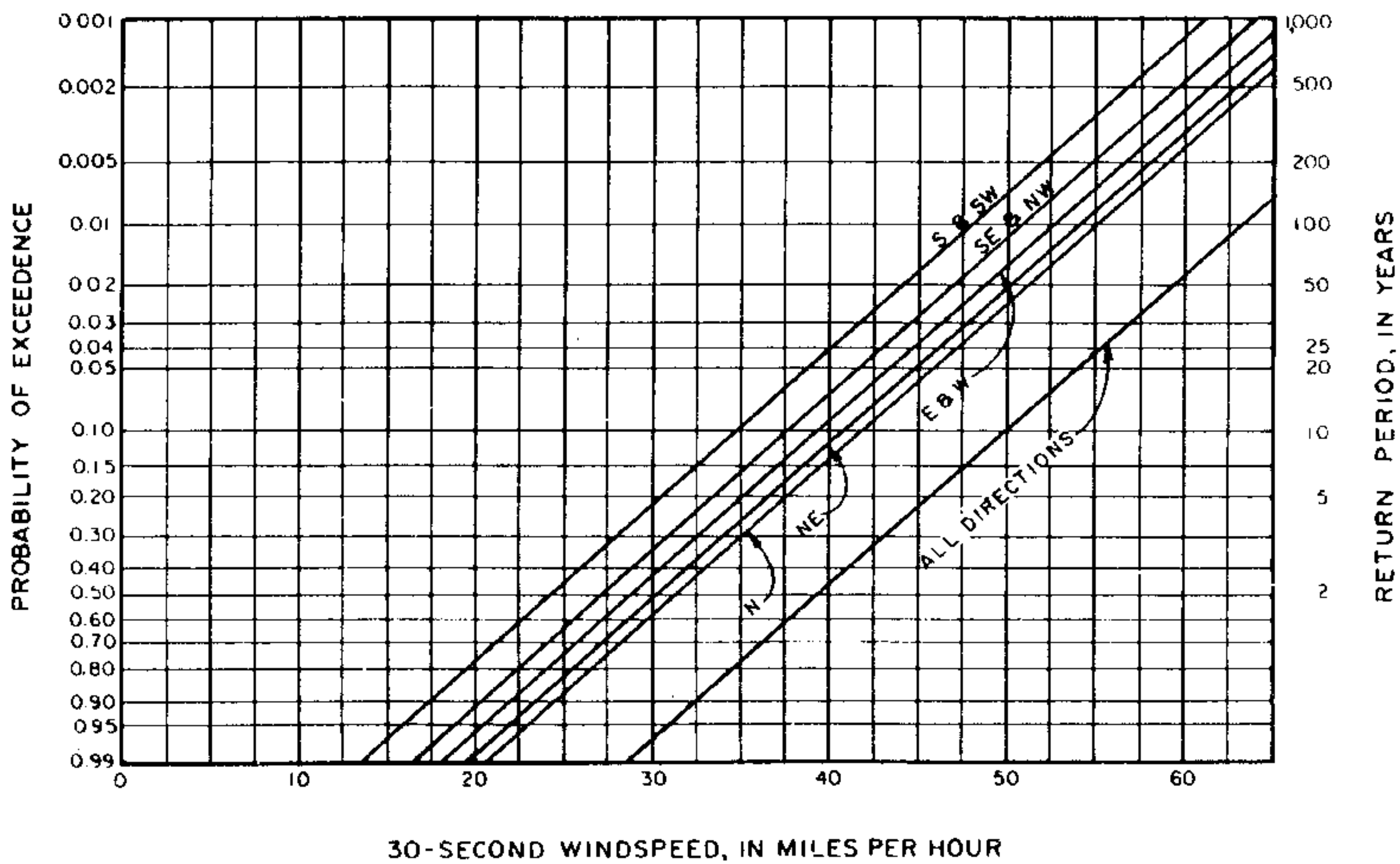


FIGURE 50
Design Windspeeds (Example Problem 2)

the 50-year design windspeed (V_{50}) determined in Step (b), above (59.7 miles per hour). Using this plotted point, a straight line is drawn parallel to the line plotted in Step (b) for "all directions." Results are shown in Figure 50.

TABLE 39
N_{θ} and N_{θ}/N

Direction (θ)	N_{θ}	N_{θ}/N
N	7	7/30
NE	5	5/30
E	4	4/30
SE	2	2/30
S	3	3/30
SW	3	3/30
W	4	4/30
NW	2	2/30

TABLE 40
$P(X \geq x)|_{\theta}$

Direction (θ)	Probability of Exceedence $[P(X \geq x)|_{\theta}]$
N	0.0047
NE	0.0033
E	0.0027
SE	0.0013
S	0.0020
SW	0.0020
W	0.0027
NW	0.0013

The probability of exceedence $[P(X \geq x)|_{\theta}]$ for each compass point is plotted on Gumbel paper versus the 50-year design windspeed (V_{50}) determined in Step (b), above (59.7 miles per hour). Using this plotted point, a straight line is drawn parallel to the line plotted in Step (b) for "all directions." Results are shown in Figure 50.

EXAMPLE PROBLEM 2 (Continued)

From the lines for each direction plotted in Figure 50, V_{50} is found for each direction by determining the value of the 30-second windspeed (abscissa) at a return period of 50 years (right ordinate). Results are given in Table 41.

TABLE 41
Design Windspeed, V_{50}, for Each Direction

Direction	V_{50} (miles per hour)	V_{50} (feet per second)
N	51.2	75.1
NE	50.2	73.6
E	48.8	71.6
SE	46.7	68.5
S	44	64.5
SW	44	64.5
W	48.8	71.6
NW	46.7	68.5

Note: 1.467 feet per second = 1 mile per hour

d. Design Current: Currents at the site are negligible.

e. A summary of design wind conditions is shown in Figure 51.

4. Evaluate Environmental Loads:

a. Wind Load: The maximum loads on the drydock will occur when the maximum vessel is on the blocks of the drydock. As a result, only this case will be checked, which assumes the dock as ship-shaped.

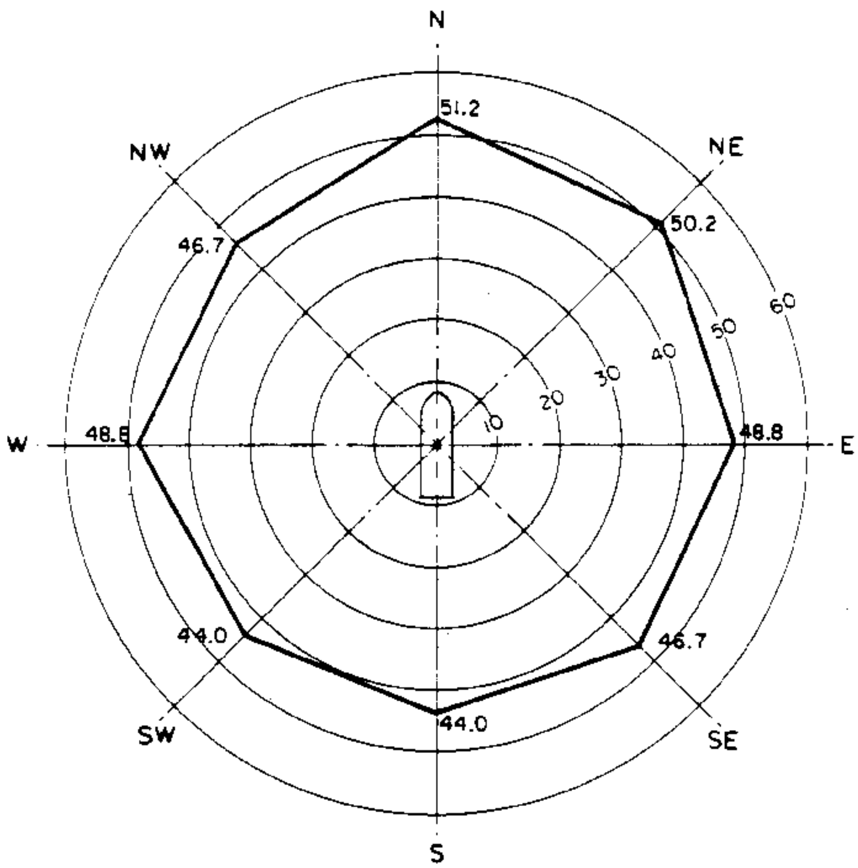
(1) Lateral Wind Load: Find F_{yw}:

EQ. (4-11)
$$F_{yw} = 1/2\ \rho_a\ V_w^2\ A_y\ C_{yw}\ f_{yw}(\theta_w)$$

ρ_a = 0.00237 slugs per cubic foot

A_y = 62,000 square feet

EQ. (4-12)
$$C_{yw} = 0.92 \left[\left(\frac{V_S}{V_R}\right)^2 A_S + \left(\frac{V_H}{V_R}\right)^2 A_H \right] / A_y$$



NOTE: WIND VELOCITIES ARE IN MILES PER HOUR

FIGURE 51
Summary of Design Wind Conditions (Example Problem 2)

EXAMPLE PROBLEM 2 (Continued)

EQ. (4-13)
$$\frac{V_S}{V_R} = \left[\frac{h_S}{h_R}\right]^{1/7}$$

EQ. (4-14)
$$\frac{V_H}{V_R} = \left[\frac{h_H}{h_R}\right]^{1/7}$$

h_R = 33.33 feet

Assume h_s = 50 feet and h_H = 20 feet:

THEN:
$$\frac{V_S}{V_R} = \left[\frac{50}{33.33}\right]^{1/7} = 1.06$$

AND:
$$\frac{V_H}{V_R} = \left[\frac{20}{33.33}\right]^{1/7} = 0.93$$

Assume:

$A_S = 0.30\ A_y = (0.3)(62{,}000) = 18{,}600$ square feet

$A_H = 0.70\ A_y = (0.7)(62{,}000) = 43{,}400$ square feet

THEN: $C_{yw} = 0.92\ [(1.06)^2\ (18{,}600) + (0.93)^2\ (43{,}400)]/62{,}000$

$C_{yw} = 0.87$

AND: $F_{yw} = 1/2\ (0.00237)\ V_w^2\ (62{,}000)(0.87)\ f_{yw}(\theta_w)$

EQ. (4-15)
$$f_{yw}(\theta_w) = \frac{+\left[\sin\theta_w - \dfrac{\sin 5\theta_w}{20}\right]}{1 - 1/20}$$

$F_{yw} = 63.92\ V_w^2\ f_{yw}(\theta_w)$

This equation is used to determine F_{yw} for V_w θ_w. Results are given in Table 42.

(2) Longitudinal Wind Load: Find F_{xw}:

EQ. (4-16) $$F_{xw} = 1/2\ \rho_a\ V_w^2\ A_x\ C_{xw}\ f_{xw}(\theta_w)$$

ρ_a = 0.00237 slugs per cubic foot

EXAMPLE PROBLEM 2 (Continued)

TABLE 42
Lateral Wind Load

Direction	θ_w (degrees)	V_w (feet per second)	$f_{yw}(\theta_w)$	F_{yw} (pounds)
N	0	75.1	0	0
NE	45	73.6	0.782	270,769
E	90	71.6	1	327,690
SE	135	68.5	0.782	234,544
S	180	64.5	0	0
SW	225	64.5	-0.782	-207,952
W	270	71.6	-1	-327,690
NW	315	68.5	-0.782	-234,544

A_x = 10,800 square feet

EQ. (4-19) For AS-36, $C_{xwB} = 0.70$

EQ. (4-22) $C_{xwS} = 0.80$

Assume the AS-36 is above dock and has distributed superstructures:

EQ. (4-26)
$$f_{xw}(\theta_w) = \frac{-\left[\sin\gamma - \dfrac{\sin 5\gamma}{10}\right]}{1 - 1/10}$$

EQ. (4-27)
$$\gamma_{(-)} = \left[\frac{90\text{deg.}}{\theta_{wz}}\right]\theta_w + 90\text{deg. for}$$
$$\theta_w < \theta_{wz}$$

EQ. (4-28)
$$\gamma_{(+)} = \left[\frac{90\text{deg.}}{180\text{deg.} - \theta_{wz}}\right]\theta_w + \left[180\text{deg.} - \frac{90\text{deg. } \theta_{wz}}{180\text{deg.} - \theta_{wz}}\right]$$
$$\text{for } \theta_w > \theta_{wz}$$

From Table 5 (superstructure just forward of midship), θ_{wz} = 80deg..

THEN:

$$[\text{gamma}](-) = \left[\frac{90\text{deg.}}{80\text{deg.}}\right] [\text{theta}]_{w} + 90\text{deg.} = 1.125\ [\text{theta}]_{w} + 90\text{deg.}$$

AND:

$$[\text{gamma}](+) = \left[\frac{90\text{deg.}}{180\text{deg.} - 80\text{deg.}}\right] [\text{theta}]_{w} + \left[180\text{deg.} - \frac{(90\text{deg.})(80\text{deg.})}{180\text{deg.} - 80\text{deg.}}\right]$$

$$= 0.9\ [\text{theta}]_{w} + 108$$

EXAMPLE PROBLEM 2 (Continued)

THEN: $F_{xw} = 1/2\ (0.00237)\ V_w^{2}\ (10{,}800)\ C_{xw}\ f_{xw}(\theta_w)$

$F_{xw} = 12.8\ V_w^{2}\ C_{xw}\ f_{xw}(\theta_w)$

This equation is used to find F_{xw} for V_w, C_{xw} (C_{xwB} or C_{xwS}), and θ_w. Results are given in Table 43.

TABLE 43
Longitudinal Wind Load

Direction	θ_w (degrees)	V_w (feet per second)	C_x	$f_{xw}(\theta_w)$	F_{xw} (pounds)
N	0	75.1	0.7	-1	-50,534
NE	45	73.6	0.7	-0.737	-35,771
E	90	71.6	0.8	0.095	4,987
SE	135	68.5	0.8	0.948	45,550
S	180	64.5	0.8	1	42,601
SW	225	64.5	0.8	0.948	40,386
W	270	71.6	0.8	0.095	-4,987
NW	315	68.5	0.7	-0.737	-30,985

[*]$f_{xw}(\theta_w)$ is symmetrical about the longitudinal axis of the vessel

(3) Wind Yaw Moment: Find M_{xyw}:

EQ. (4-29) $M_{xyw} = 1/2\ \rho_a\ V_w^{2}\ A_y\ L\ C_{xyw}(\theta_w)$

ρ_a = 0.00237 slugs per cubic foot

A_y = 62,000 square feet

L = 552 feet

$C_{xyw}(\theta_w)$ is found in Figure 21 for a vessel with superstructure just forward of midship.

THEN: $M_{xyw} = 1/2\ (0.00237)\ V_w^{2}\ (62{,}000)(552)\ C_{xyw}(\theta_w)$

$M_{xyw} = 40{,}555\ V_w^{2}\ C_{xyw}(\theta_w)$

This equation is used to determine M_{xyw} for V_w and θ_w. Results are given in Table 44.

b. Current Load: Currents are negligible.

TABLE 44
Wind Yaw Moment

Direction	θ_w (degrees)	V_w (feet per second)	$C_{xyw}(\theta_w)$	M_{xyw} (foot-pounds)
N	0	75.1	0	0
NE	45	73.6	0.05	1.098×10^7
E	90	71.6	0.0225	4.68×10^6
SE	135	68.5	-0.03	-5.71×10^6
S	180	64.5	0	0
SW	225	64.5	-0.03	5.06×10^6
W	270	71.6	-0.0225	-4.68×10^6
NW	315	68.5	-0.05	-9.5×10^6

5. Evaluate Loads on Mooring Elements:

a. Total Loads: Total loads on the mooring elements are determined using the following equations:

EQ. (4-62) $$F_{yT} = F_{yw} + F_{yc}$$

EQ. (4-63) $$F_{xT} = F_{xw} + F_{xc}$$

EQ. (4-64) $$M_{xyT} = M_{xyw} + M_{xyc}$$

Since currents are negligible, the total loads on the mooring are due to winds only:

$$F_{yT} = F_{yw}$$

$$F_{xT} = F_{xw}$$

$$M_{xyt} = M_{xyw}$$

These total loads are those loads given in Tables 42, 43, and 44.

b. Spud-Mooring Analysis: The procedure for distributing mooring loads to the spuds in a spud mooring is outlined in Figure 39.

(1) Determine e: The eccentricity, e, is determined for each loading case. For example, for a NE wind:

EXAMPLE PROBLEM 2 (Continued)

$$e = \frac{M_{xyT}}{F_{yt}} = \frac{1.098 \times 10^{7}}{270,769} = 40.6 \text{ feet}$$

The values for each wind direction are given in Table 45.

Table 45
Wind Moment Eccentricities

Wind Direction	$F_{yw} = F_{yT}$ (pounds)	$M_{xyw} = M_{xyT}$ (foot-pounds)	e (feet)
N	0	0	0
NE	270,769	1.098×10^{7}	40.6
E	327,690	4.68×10^{6}	14.3
SE	234,544	-5.71×10^{6}	-24.4
S	0	0	0
SW	-207,952	5.06×10^{6}	-24.3
W	-327,690	-4.68×10^{6}	14.3
NW	-234,544	-9.5×10^{6}	40.5

(2) Determine X_{ARM}: In this case, the C.G. of the dock coincides with the C.G. of the spuds. (See Figure 49.) Therefore, X_{ARM} = e for each load case.

(3) Determine M_{xys}:

$$M_{xys} = F_{yT} X_{ARM}$$

For this example, $X_{ARM} = e$

THEREFORE: $M_{xys} = F_{yT}\ e$

SUBSTITUTING: $$M_{xys} = F_{yT} \left[\frac{M_{xyT}}{F_{yT}}\right]$$

THEN: $M_{xys} = M_{xyT}$

(4) Determine n_T, C_i: The number of tension spuds, n_T, is four; therefore, $n_T = 4$. The value of C_i for each spud is shown in Figure 49:

$C_1 = 200$ feet

EXAMPLE PROBLEM 2 (Continued)

C_2 = 100 feet

C_3 = -100 feet

C_4 = -200 feet

(5) Determine I:

$$I = \sum_{i=1}^{n_T} C_i^{\,2}$$

THEN:

$$I = \sum_{i=1}^{4} C_i^{\,2} = 200^2 + 100^2 + (-100)^2 + (-200)^2$$

$$I = 100{,}000 \text{ square feet}$$

(6) Determine Load in Each Tension Spud:

$$F_{Ti} = \frac{F_{yT}}{n_T} + \frac{M_{xys}\ C_i}{I}$$

The load in each tension spud is determined for each wind direction:

For example, for tension spud 1 for a NE wind:

$$F_{T1} = \frac{F_{yT}}{n_T} + \frac{M_{xys}\ C_1}{I} = \frac{270{,}769}{4} + \frac{(1.098 \times 10^7)(200)}{100{,}000}$$

F_{T1} = 89,652 pounds

Results of this analysis are given in Table 46.

Table 46
Loads in Tension Spuds

Wind Direction	F_{yT} (pounds)	M_{xys} (foot-pounds)	F_{T1} (pounds)	F_{T2} (pounds)	F_{T3} (pounds)	F_{T4} (pounds)

N	0	0	0	0	0	0
NE	270,769	1.098×10^{7}	89,652	78,672	56,712	45,732
E	327,690	4.68×10^{6}	91,283	86,603	77,243	72,563
SE	234,544	-5.71×10^{6}	47,216	52,926	64,346	70,056
S	0	0	0	0	0	0
SW	-207,952	5.06×10^{6}	-41,868	-46,928	-57,048	-62,108
W	-327,690	-4.68×10^{6}	-91,283	-86,603	-77,243	-72,563
NW	-234,544	-9.5×10^{6}	-77,636	-68,136	-49,136	-39,636

EXAMPLE PROBLEM 2 (Continued)

(7) Determine Load in Shear Spud:

$$F_S = \frac{F_{xT}}{n_S}$$

The maximum longitudinal load on the vessel is F_{xw} = - 50,534 pounds (due to a N wind). (See Table 43.)

$F_{xw} = F_{xT}$ = - 50,534 pounds

THEN: $$F_S = \frac{F_{xt}}{n_S} = \frac{-50{,}534}{1} = 50{,}534 \text{ pounds}$$

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GLOSSARY

Caisson. (1) A watertight box used to surround the works involved in laying the foundation of a bridge or other structure below water. (2) A watertight box used as a closure for graving dock entrances.

Chock. A metal casting with two horn-shaped arms used for passage, guiding, or steadying of mooring or towing lines.

Cofferdam. A temporary wall serving to exclude water from any site normally under water so as to facilitate the laying of foundations or other similar work.

Degaussing. The process by which the magnetic field of a ship is neutralized.

Factor of Safety. The ratio of the breaking or ultimate strength of a mooring component to the working load of that component.

Fastest-Mile Windspeed. The highest measured windspeed with a duration sufficient to travel 1 mile.

Hawser. The mooring rope or line between a fleet-mooring buoy and the moored vessel. For a fixed mooring, the hawser is the mooring rope or line between the deck of a fixed-mooring structure and the moored vessel.

Hockle. A defect in a rope in which strands are kinked or twisted contrary to the direction of their normal lay. Usually caused by improper handling of the rope. Resembles a knot in the rope.

Hydrodynamic Mass. The mass of a berthing vessel, which includes the actual mass of the vessel itself and the mass of the water surrounding the vessel which moves with the vessel.

Mean High Water (MHW). The average height of the high waters over a 19-year period. For shorter periods of observation, corrections are applied to eliminate known variations and to reduce the results to the equivalent of a 19-year value.

Mean Higher High Water (MHHW): The average height of the higher high waters over a 19-year period. For shorter periods of observation, corrections are applied to eliminate known variations and reduce the result to the equivalent of a mean 19-year value.

Mean Lower Low Water (MLLW). The average height of the lower low waters over a 19-year period. For shorter periods of observations, corrections are applied to eliminate known variations and reduce the results to the equivalent of a mean 19-year value. Frequently abbreviated to lower low water.

Midships (Amidships). Midway between the bow and stern of a ship or vessel.

Peak-Gust Windspeed. A measure of the maximum windspeed for a given period of record; normally a high-velocity, short-duration wind.

Return Period. The average length of time between occurrences of a specified event. For example, a 50-year windspeed will occur, on the average, once every 50 years.

Sheaves. Wheels or disks with a grooved rim used as a pulley.

Tag Line. A line used to retrieve lines or activate quick-release hooks.

Tending. The laying, retrieving, or similar handling of mooring lines.

Working Load. The maximum allowable load on the mooring component. Usually, the working load is some fraction of the breaking strength of the component.

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