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Mooring of Ships *to* Piers and Wharves

Mooring Analysis Task Committee

ASCE

Edited by
John W. Gaythwaite, P.E.

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COASTS, OCEANS,
PORTS AND RIVERS
INSTITUTE

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Mooring of Ships to Piers and Wharves

Prepared by
the Mooring Analysis Task Committee
of the Technical Committee on Ports and Harbors of
the Coasts, Oceans, Ports, and Rivers Institute of
the American Society of Civil Engineers

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MANUALS AND REPORTS ON ENGINEERING PRACTICE

(As developed by the ASCE Technical Procedures Committee, July 1930, and revised March 1935, February 1962, and April 1982)

A manual or report in this series consists of an orderly presentation of facts on a particular subject, supplemented by an analysis of limitations and applications of these facts. It contains information useful to the average engineer in his or her everyday work, rather than findings that may be useful only occasionally or rarely. It is not in any sense a "standard," however; nor is it so elementary or so conclusive as to provide a "rule of thumb" for nonengineers.

Furthermore, material in this series, in distinction from a paper (which expresses only one person's observations or opinions), is the work of a committee or group selected to assemble and express information on a specific topic. As often as practicable the committee is under the direction of one or more of the Technical Divisions and Councils, and the product evolved has been subjected to review by the Executive Committee of the Division or Council. As a step in the process of this review, proposed manuscripts are often brought before the members of the Technical Divisions and Councils for comment, which may serve as the basis for improvement. When published, each work shows the names of the committees by which it was compiled and indicates clearly the several processes through which it has passed in review, so that its merit may be definitely understood.

In February 1962 (and revised in April 1982), the Board of Direction voted to establish a series titled "Manuals and Reports on Engineering Practice," to include the Manuals published and authorized to date, future Manuals of Professional Practice, and Reports on Engineering Practice. All such Manual or Report material of the Society would have been refereed in a manner approved by the Board Committee on Publications and would be bound, with applicable discussion, in books similar to past Manuals. Numbering would be consecutive and would be a continuation of present Manual numbers. In some cases of joint committee reports, bypassing of Journal publications may be authorized.

A list of available Manuals of Practice can be found at http://www.asce.org/bookstore.

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CONTENTS

PREFACE

At the fall 2001 meeting of the ASCE Technical Committee on Ports and Harbors of the Coasts, Oceans, Ports, and Rivers Institute (COPRI), Robert N. Robertson recommended that a task committee be established to prepare a document on mooring analysis for fixed piers and wharves. A new committee proposal was submitted in December 2001, and the first meeting of the mooring analysis task committee was held in March 2002. Robert Robertson was selected as chairman and Martin Eskijian as secretary. The committee discussed many topics and issues and added much since the original series of meetings. In April 2007 the chairmanship passed to John W. Gaythwaite at the direction of the Ports and Harbor Committee of COPRI, and the focus of the group subsequently became the development of an ASCE Manual of Practice (MOP) for the mooring of ships at fixed harbor facilities.

The purpose of this MOP is to provide designers of piers and wharves and other fixed marine facility structures with the necessary background and resource information to ensure that their structure designs are sound and adequate and provide a safe berth for the types of vessels to be accommodated. This is necessary because currently no single building code or standard specifically addresses the design of berthing and mooring facilities in general, and the guideline documents that do exist have varying requirements for specific facility types. In addition, many costly mooring incidents have occurred, emphasizing the need for a better understanding of mooring design principles. The chairman wishes to thank all of those involved in this process and trusts that the guidance provided herein will provide useful and timely information to the port engineering community.

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NOTATION

Acronyms and Abbreviations

ACI	American Concrete Institute
ADCP	acoustic doppler current profiler
AISC	American Institute of Steel Construction
bbl	barrel
BCM	bow-to-center manifold
BSI	British Standards Institute
BWL	beam at waterline
CCW	counter clockwise
CEM	*Coastal Engineering Manual*
cg	center of gravity
COPRI	Coasts, Oceans, Ports, and Rivers Institute
CRREL	Cold Regions Research and Engineering Laboratory
CW	clockwise
DAS	docking aid system
DGPS	differential global positioning system
DoD	U.S. Department of Defense
DOF	degree of freedom
DT	displacement tonnage
DWL	design waterline
DWT	deadweight tonnage (kDWT = 1,000 DWT)
EAU	Committee for Waterfront Structures, Harbors, and Waterways (Germany)
FB	freeboard
FC	fiber core
FDD	floating dry dock
FDS	fully developed sea
FS	factor of safety
FWD	forward

GM	vessel metacentric height
GRT	gross registered tonnage
HCF	hydrodynamic coefficient file
HMPE	high modulus polyethylene
IACS	International Association of Classification Societies
IFG	infragravity
IMO	International Maritime Organization
ISO	International Standards Institute
IWRC	independent wire rope core
JONSWAP	Joint North Sea Wave Project
LAT	lowest astronomical tide
LBP	length between perpendiculars
LNG	liquefied natural gas carrier
LOA	length overall
LPG	liquefied petroleum gas
LPM	length of parallel mid-body
LWL	length on the waterline
LWT	light-weight tonnage
MARIN	Maritime Research Institute Netherlands
MBL	minimum breaking load
MEG-3	*Marine Equipment Guidelines*, 3rd Edition
MLI	moment to list one inch
MLLW	mean lower low water
MOT	marine oil terminals
MOTEMS	marine oil terminals engineering and maintenance standards
MTI	moment to trim one inch
NAVD	North American Vertical Datum
NAVFAC	Naval Facilities Engineering Command
NAVSEA	U.S. Naval Sea Systems Command
NCL	Norwegian Cruise Lines
NFESC	Naval Facilities Engineering Service Center
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Survey
NRT	net registered tonnage
OBO	ore-bulk oil
OCIMF	Oil Companies International Marine Forum
OTC	Offshore Technology Conference
PIANC	Permanent International Association of Navigation Congresses
QRH	quick-release mooring hooks
RANS	Reynolds Averaged Navier Stokes
RAO	response amplitude operator

RC	Royal Carribean
RMS	root mean square
ROM	Spanish Guidelines on Marine Structures
RO-RO	roll on-roll off
RTK	real-time kinematic global positioning system
SG	spheroidal graphite
SLR	sea level rise
SNAME	Society of Naval Architects and Marine Engineers
SPM	single point mooring
STS	ship to ship
SWL	safe working load or still water level
TEU	20-ft equivalent container unit
UFC	Unified Facilities Criteria
UHMW-PE	ultra-high molecular weight polyethylene
UKC	under-keel clearance
ULCC	ultra large crude carrier
USACE	U.S. Army Corps of Engineers
VLCC	very large crude carrier
WIS	Wave Information Study
WMO	World Meteorological Organization

Symbols

A^*	area (further defined by subscript in text)
B	beam (vessel width)
C^*	coefficient (further defined by subscript in text)
D	alternate symbol for vessel draft (see also T)
D_s	hull depth
d	water depth
E^*	modulus of elasticity
E_p	encounter probability
e	eccentricity
F^*	force (further defined by subscript in text)
g	acceleration of gravity
H^*	wave height (further defined by subscript in text)
h	height
h_{so}	standoff force pressure head
K^*	spring constant (further defined by subscript)
k	wave number $= 2\pi/L$
L	wave length
M^*	mass (further defined by subscript in text)
Mym	yaw moment
m	number of breast lines or mass matrix
N	total number of waves

n	number or exponent
q	number of spring lines
R	Reynolds number
T	vessel draft (see also D)
T^*	wave period or line tension (further defined by subscript)
T_r	return period
t	time
U_c	current velocity
V_w	wind velocity
W	channel width or width
X	surge of vessel
x	displacement, rotation, vector
Y	sway of vessel
z	elevation or depth
α	mooring line angle in plan view
β	mooring line vertical angle
γ	unit weight
Δ	vessel displacement
δ	deflection or elastic elongation of mooring line
θ	angle of yaw
ζ	wave amplitude
ρ	mass or fluid density
Φ	wave potential (defined by subscript)
φ	angle of pitch
ψ	angle of roll (or heel)
ω	radian wave frequency

CHAPTER 1
INTRODUCTION

1.1 PURPOSE AND SCOPE

The purpose of this manual is to provide general guidance to determine forces acting upon piers, wharves, and other fixed structures such as berthing and mooring dolphins due to berthed vessels and to provide background for safe and efficient fixed mooring design practice. The ultimate goal is to provide vessels with a "safe berth" with adequate and sound mooring structures and arrangements. This manual is not, however, intended to be a complete, standalone mooring analysis and pier design document, because the subject matter is too complex and the variety of vessel and facility types with specific requirements is too wide. The reader is directed to the various important documents that cover these areas as introduced in the last section of this chapter and referred to throughout this manual.

Ships were once much smaller than they are today. Ports provided mooring accessories on wharves and piers based on a local standard, which proved adequate through many years of experience. Ship captains and pilots could direct the line handlers to tie up a ship in accordance with years of experience as mariners and based on tradition. However, ships built today are increasingly larger and more complex such as tankers, container ships, roll on-roll off (RO-RO), ships, bulk carriers, cruise ships, military vessels, etc. These ships typically have a larger area exposed to wind and deeper draft hulls exposed to current and passing ship effects. Old standards and methods are often inadequate, and analytical methods have been developed to determine mooring forces and optimize the arrangement of mooring lines. Safe mooring also includes limiting the movement of the ship in berth. Preventing parted lines and ship breakaways is another goal of performing a mooring analysis.

This Manual of Practice provides guidelines to determine safe mooring practices for vessels in ports and harbors. These guidelines include design criteria, analysis methodologies, and other relevant information. Although more comprehensive and detailed publications are available, this manual provides an overview of the subject and guides the reader to the use of important design standards and other sources. This manual is primarily concerned with large ocean-going vessels at somewhat protected locations, although many of the basic principles presented are applicable to small craft and at more exposed locations as well. Dynamic analysis is introduced to familiarize the reader with the procedures and provide an understanding of when it is a necessity. The manual does not attempt to provide a rigorous, comprehensive coverage of this topic however. Offshore, single-point, and spread moorings are not addressed herein. In addition, this manual does not deal with the design and/or selection of fender systems for the berthing of vessels. This topic is well covered elsewhere, such as in basic texts dealing with port and harbor engineering and the fender manufacturer's product literature. However, as fenders do constitute an important part of the vessel-mooring system, discussion of fender systems in relation to the moored vessel is included.

1.2 GENERAL CONSIDERATIONS

Berthed vessels are subject to various forces associated with environmental conditions such as air and sea motions and other disturbing forces. The vessel's response is controlled by the arrangement and characteristics of its mooring system, which typically consists of wire and/or fiber lines connected to fixed hardware and a resilient fender system that is ultimately resisted by the pier structure. The geometry of the mooring arrangement is subject to change with fluctuations in water levels and the vessel's draft as cargo is loaded or discharged. The nature of environmental loads is highly probabilistic, and therefore selection of appropriate design criteria is a central focus of the pier structure design problem. In addition, environmental loads are stochastic and random in nature. Although treating wind and current forces on relatively protected port and harbor structures as static or quasi-static loads is common practice, dynamic analysis must be applied under certain conditions. Wind gusts and current eddies and turbulence may render the steady flow assumption invalid under certain circumstances, thus requiring dynamic analysis at otherwise protected locations. Sections of this manual assume that the reader has some familiarity with basic fluid mechanics.

This manual is organized as follows. Relevant vessel characteristics and dimensions, port facilities, typical mooring arrangements and berth configurations, and prominent industry standards are overviewed in the remainder of this introductory chapter. Chapter 2 introduces the selection of appropriate design criteria for specific environmental conditions and as may be required by various standards. The chapter also reviews representative loads and design factors of safety. Chapter 3 reviews mooring system components, including lines, fittings, and hardware; fenders as they relate to berthed vessels; various equipment for line handling, line monitoring, and automated mooring systems; and shipboard equipment. Chapter 4 describes sources of mooring loads and presents principles of calculating loads on moored vessels, including review of accepted standards and methodologies. Chapter 5 follows with methods of static analysis and an introduction to dynamic analysis to determine resultant line and hardware loads and sections on available software and physical modeling. Chapter 6 introduces operational considerations and includes discussion of limiting vessel movements at berth, breakaway incidents, and mooring system maintenance. An extensive list of references is provided at the end of this manual.

Most data and equations in this manual are presented in U.S. customary and nautical units as are normally encountered in U.S. practice. Data or equations reproduced from other sources, however, are generally presented in the units of the original source. Port engineers and designers of marine facilities need to be familiar with various units. Important unit conversions are presented in the Appendix at the end of this manual.

1.3 VESSEL CHARACTERISTICS

A berthed vessel's principle dimensions, overall size and configuration, and mode of cargo transfer are of primary importance in mooring analysis and in the ultimate design of the berth structure. The effect of vessel types, such as tankers and bulk carriers versus containerships and ferries for example, on mooring arrangements is discussed in this section. Important definitions common to all vessel types relative to their principle dimensions and size are defined in the following paragraphs. Figure 1-1 illustrates a vessel's general dimensions. The forward (FWD) end of the vessel is referred to as the bow and the after end as the stern. The horizontal distance from the most forward part of the bow to the farthest aft end of the stern is the length overall (LOA), which is of obvious importance to the overall berth dimensions, wind exposure, and extreme forward and aft locations of mooring lines. The length on the waterline (LWL) is the distance between where the forward and after portions intersect the water surface. It is usually given as the vessel's design

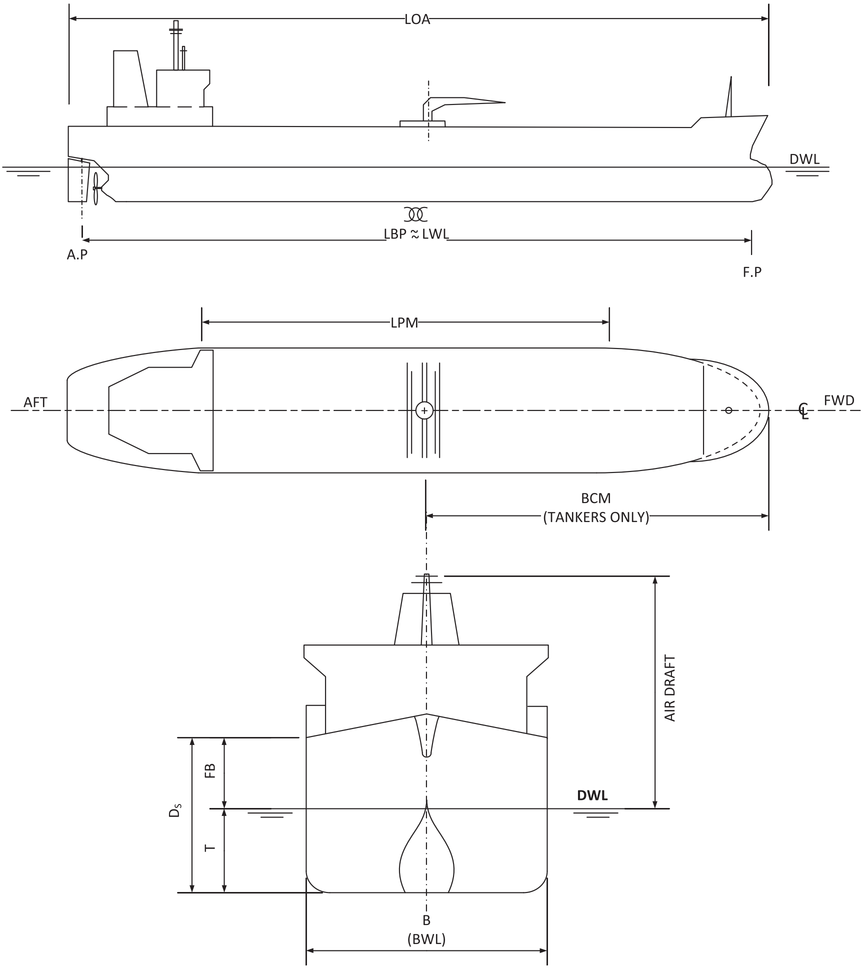


Fig. 1-1. Vessel dimensions definition sketch

waterline (DWL), which is the LWL at which the vessel was designed to operate. This length may vary with the vessel's load condition, however, and is critical in the calculation of hydrodynamic loads due to currents and waves. The length between perpendiculars (LBP) is the horizontal distance between where the vertical portion of the vessel's bow intersects the waterline, the forward perpendicular F.P., and the centerline of the rudder post at the aft end of the vessel, the aft perpendicular A.P., typically given for the vessel on its DWL. The LBP is the dimension most often given on the vessel's plans and registry and for most cases of ocean-going vessels can be considered very nearly equal to the LWL at the DWL. For most large commercial vessel types including tankers, bulk carriers, containerships, and ships with similar hull shapes, the LBP is on the order of 95% of LOA. Additional important length dimensions are the ship's length of parallel mid-body (LPM), which varies with draft and is important in determining fender contact length. For tanker and liquid bulk-type vessels, the bow-to-center manifold (BCM) distance is important to the ship's location along the berth.

The vessel's overall width, referred to as the beam, *B*, and the width at the waterline, BWL, are typically equal at half way through the LBP; a point that is denoted in Fig. 1-1. The beam and BWL are of obvious importance to wind and current load calculations respectively. The overall depth of the hull, often cited as the "moulded depth," referring to the line plan's lay-up dimensions, is usually denoted D_s. The draft is depth below the water surface and varies with load condition and often along the length of the vessel as well. The draft is normally given for the loaded condition at DWL and is designated by the letter *T*, as typically used by naval architects and adopted herein, although the letter *D* is also commonly used. Freeboard (FB) is the difference between D_s and *T*. The draft varies from forward to aft with the vessel's "trim" or difference between the forward and aft *T*. For a loaded vessel at DWL the mean draft is nearly equal along its LWL, whereas for a vessel in "ballast," referring to the condition of having taken water into its ballast tanks to remain stable after discharging its cargo, considerable trim may exist. Certain vessels, typically smaller types such as fishing boats, have a built-in "drag" to their keel such that they have a deeper draft aft when floating level. This is not to be confused with trim that is a change from the vessel's DWL. The term "list" refers to a side-to-side difference in FB due to uneven load distribution or the downward component of mooring lines along one side of the vessel. The "air draft" is the height of the highest fixed structure or mast above the waterline and is of obvious importance where vessels must clear bridges or other overhead obstructions to reach their berth.

Commercial vessels can be classified by size based on their cargo-carrying capacity. Tankers, bulk carriers, and general cargo vessels are typically referred to in terms of their deadweight tonnage, DWT, which includes the weight of fuel, stores, crews' quarters, cargo, etc. The lightweight tonnage (LWT) is essentially the weight of the hull structure and outfit, and the sum of the LWT and DWT is the displacement tonnage (DT), which is of primary interest to dock designers. These weights are typically given in metric tons (mt) of 2,205 lbs, although the traditional long ton (2,240 lbs, lt) is sometimes used. Gross registered tons (GRT) and net registered tons (NRT) are often used as an index of passenger and ferry vessel size and are not a measure of weight (or displacement). Registered tons measure a vessel's interior space in units of 100 cubic feet (ft^3), representing the total enclosed space and space available for passengers and crew respectively. Container ships are typically referred to in terms of the number of 20-ft equivalent container units (TEUs), they can carry. LNG (liquid natural gas) and LPG (liquid petroleum gas) carriers are sized in terms of cubic meters (m^3) of liquefied gas they hold. Tank barges may be classified in terms of barrels (bbl) of oil they hold. Tables 1-1 through 1-5 summarize approximate ranges of vessel dimensions and characteristics for various vessel types. Further description including additional vessel types and characteristics can be found in Gaythwaite (2004) and

Table 1-1. Vessel Class General Dimensions and Measures—Product and Crude Oil Tankers

Classification	DWT (1,000s)	LOA (m)	*B* (m)	*T* (m)
Handy	10–60	114–228	17–32.3	6–13.5
Panamax	60–80	183–250	32–32.3	11.5–15.0
Aframax	80–120	210–273	32.3–49	12.0–16.0
Suezmax	120–200	250–290	42–53	15–18.5
Very large crude carrier (VLCC)	200–320	320–340	56–60	19.0–23.0
Ultra large crude carrier (ULCC)	320–550	330–380	60–70	21.0–24.5

Table 1-2. Vessel Class General Dimensions and Measures—Dry Bulk Carriers

Classification	DWT (1,000s)	LOA (m)	*B* (m)	*T* (m)
Handy	10–60	114–228	17–32.3	6.0–13.5
Panamax	60–100	183–250	32–32.3	11.3–15.0
Capesize	100–400	235–360	40–65	13.5–23.0

Table 1-3. Vessel Class General Dimensions and Measures—Containerships

Classification	TEU	LOA (m)	*B* (m)	*T* (m)
Feeder	100–500	75–150	10–21.5	4.0–8.0
Feedermax	500–1,000	100–180	16.0–27.0	6.0–10.0
Sub Panamax	2,000–3,000	175–272	27.0–32.3	9.5–12.5
Panamax	3,000–5,000	215–294	32.2–32.3	10.0–13.7
Post-Panamax	5,000–15,500 (+)	228–398	35.0–56.0	11–16
New Panamax	13,000–18,000	366–400	49–59	14.5–16.0

Table 1-4. Vessel Class General Dimensions and Measures—Vehicle Ferries (RoPax)

Classification	Displacement (mt)	LOA (m)	*B* (m)	*T* (m)
Small, inland routes	500	55	15.0	2.5
Small, coastal	1,650	85	18.6	3.8
Intermediate, coastal	2,950	110	24.0	4.5
Large, coastal	11,500	168	27.2	5.5
Large, ocean going	18,840	203	25.0	6.6

Table 1-5. Vessel Class General Dimensions and Measures—Cruise Ships

Vessel Name	GRT (mt)	Passenger Capacity	LOA (m)	*B* (m)	*T* (m)
Seabourn Legend	9,961	208	135	19.0	5.2
Radisson Diamond	20,295	354	131	32.0	8.0
Pacific Princess	30,277	826	181	25.5	5.8
The World	43,188	300	196	29.2	6.8
Costa Romantica	53,049	1,356	221	30.8	7.6
Fantasy	70,367	2,056	261	31.5	7.8
Carnival Spirit	88,500	2,680	293	32.2	7.8
Radiance of the Seas	90,090	2,500	293	32.2	8.1
Carnival Conquest	110,000	2,975	290	35.0	8.3
Voyager of the Seas	138,000	3,114	311	48.0	8.8
Freedom of the Seas	154,400	4,370	339	38.6	8.5
Oasis of the Seas	225,282	6,296	361.6	47.0	9.3

This table was compiled by committee from various open sources.

Lamb (2003), and PIANC (2002) includes useful tables of vessel principle dimensions for various types and size ranges within specified confidence limits. Detailed information on U.S. Navy vessels can be found in the Naval Facilities Engineering Command's "Ships Characteristics Data Base," which can be accessed online through the Whole Building Design Guide website; wbdg.org. Registration with NAVFAC is required.

No universally recognized size classifications exist for RoPax vessels (i.e., vessels that carry vehicles in roll on-roll off mode and have passenger accommodations). The classifications provided here are for illustrative purposes only based on actual in-service operating routes.

Note that although cruise ships are sometimes classified by size, the classifications tend to be associated with a particular cruise line's vessels. No universally recognized classification for the industry as a whole exists.

Table 1-5 presents a selection of particular cruise vessels representing a wide range in vessel types and sizes.

Regardless of the vessel measurement given, ultimately the actual weight or displacement of the vessel at a given draft is of primary interest. As, according to Archimedes' Principle, a floating body displaces a volume of water equal to its own weight and hence a vessel's DT can be estimated by multiplying the LWL × BWL × T × unit weight of water × a coefficient that accounts for the volume of the underwater shape known as the block coefficient, C_b. Table 1-6 gives approximate ranges of C_b for various vessel types at their DWL. Vessels with large C_b values tend to have longer lengths of parallel mid body important for fender contact length. It is important to note that for vessels at any given draft other than near its DWL the value of C_b may vary considerably. Curves of displacement versus draft prepared by the naval architect are most useful for this purpose when available through the vessel owner/operator. A vessel's general arrangement plan, when available, is most useful and typically gives all principle dimensions and locations of mooring hardware and equipment. Figure 1-2 shows an example of a LNG vessel's mooring equipment arrangement and side profile showing fender contact locations within the vessel's parallel mid-body area. A lines plan defines the vessel's three-dimensional hull form and is most useful in determining length of parallel mid-body and variation of hull shape with draft, etc.

In addition to the block coefficient other coefficients of form that may come into play in mooring analysis include the midship section

Table 1-6. Block Coefficients for Selected Vessel Types (Typical Ranges)

Vessel Type	Block Coefficient
Tankers	
Chemical and product	0.73–0.82
VLCC	0.82–0.84
ULCC	0.85–0.86
Bulk carriers and OBO (ore/bulk/oil)	0.78–0.87
Containerships	0.63–0.71
General cargo	0.71–0.77
Vehicle carriers	0.56–0.66
RO/RO (cargo)	0.71–0.80
Ferries	0.57–0.63
Cruise ships	
Cunard	0.58–0.61
Royal Carribean, Norwegian Cruise Lines, Carnival Cruise Lines	0.70–0.75

Source: Adapted from data in PIANC (1997)

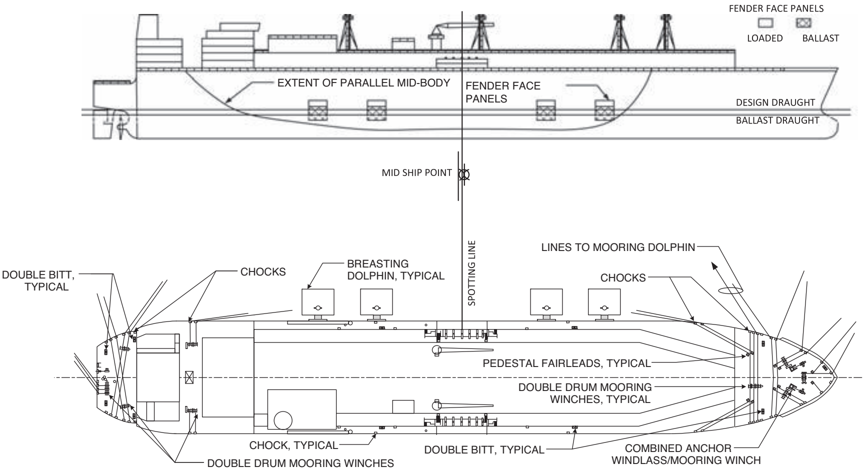


Fig. 1-2. Vessel mooring equipment arrangement plan and profile showing fender contact area

coefficient, relating the underwater cross-sectional area to the block area as given by $B \times T$; the waterplane area coefficient, C_{wpa}, relating the waterplane area to the block area given by LBP × B; and the prismatic coefficient, C_p, which defines the "fineness" of the underwater shape. The relative proportions of a vessel such as length-to-beam ratio and beam-to-draft ratios are important to keep in mind when evaluating generic coefficient data and data from model tests for specific vessel types. Most ocean-going ships have LBP/B ratios on the order of 5.5 to 7.0, with extreme values from around 3.5 to 10.0 and typical B/T ratios on the order of 2.7 to 4.0 with extremes of 1.8 to 5.0.

Specific vessel types may have particular features that affect its safe mooring with regard to fender contact length, lead of mooring lines, limitations on its position at berth, etc. For example, most ocean-going commercial vessels have bulbous bows that protrude well forward of the LWL. Cruise ships and container ships have flaring bows and overhanging bridge structures that may require fending the vessel farther off the pier face. RO-RO and ferries often have belted or straked sides that may hang up on and damage fendering. Barges typically have low freeboard in the loaded condition that may allow them to get caught below fenders and cause mooring lines to lead over the pier deck edge. Cruise ships, ferries, car carriers, and container ships typically have high freeboard with high wind areas making them active at berth under windy conditions. Some vessels such as LNG carriers and lightly constructed high-speed ferries have low allowable hull pressures that may be as critical as line loads in a mooring analysis.

1.4 PORT FACILITIES

A *port* in general is a site that provides some kind of facility for berthing and mooring of vessels for the transfer of cargo and/or passengers and/or for servicing and repair. Ports are typically located within natural or artificial harbors that provide some degree of protection from ocean waves. Artificial harbors are typically formed by breakwaters that provide varying degrees of protection. Ports are often located within estuaries at the mouths of rivers or along rivers themselves well inland. Ports for liquid and bulk cargos in particular may be located at more exposed locations within open bays or even at sites fully exposed to the open ocean from certain directions. The site exposure to prevailing wind, wave, and current directions is extremely important in determining design criteria for mooring analysis. Facilities within estuaries and along rivers may be exposed to strong reversing type currents on a regular basis and to extreme currents and sudden rises in water level associated with dam release, storm water runoff, or moving ice floes during spring break up. Sites along steep mountainous coastlines may periodically be subject to strong directed wind flows such as "katabatic" downslope winds. Artificial and natural harbors may be subject to periodic water level oscillations known as "seiche" that induce large and sometimes unacceptable vessel movements and high mooring loads. Offshore facilities exposed to ocean waves must be designed to accommodate vessels up to some limiting sea state condition beyond which the berth must remain unoccupied. Older, existing port facilities are more often located in natural harbors or estuaries and rivers but are often inadequate for the contemporary vessels that visit them. Therefore, a mooring analysis may be required to determine the limiting environmental conditions under which a vessel may remain, whereas for a new facility the design criteria should consider the worst conditions that are likely to occur when the berth is occupied. Vessels are generally moored to fixed structures of varying configurations, although floating ports and floating piers or transfer bridges known as "link spans" are provided at some locations. Vessels moored to floating piers or structures that are not themselves fixed to the shore or seabed can be regarded as a ship-to-ship (STS) type mooring situation that is not specifically addressed herein.

Piers are fixed structures typically built normal or nearly normal to the shoreline and in water of sufficient depth to secure vessels alongside. In the United Kingdom and much of the world they are commonly referred to as *jetties*. *Wharves* are built essentially parallel to the shoreline and may protrude outward somewhat to gain sufficient water depth. A *quay* wall or simply a quay is parallel to and mostly contiguous with the shoreline and is typical of dock construction in river ports. Piers and wharves may also be constructed in various configurations such as T-head and L- and U-shape plan dimensions. A *dock* in general can refer to any type of structure or facility used to secure vessels. A *berth* is the space occupied by the vessel in the water. *Dolphins* are isolated structures that are used to fend vessels (berthing- or breasting-type dolphins) and/or to secure mooring lines (mooring-type dolphins). Mooring dolphins are typically set back some distance from the berth face to gain more favorable mooring line angles. All these structures can be either "open-" or "closed-"type construction or some combination thereof. Open structures that are pile supported allow water to flow past, whereas solid fill-type structures such as cells, caissons, and walls obstruct the flow of water. This has important implications during berthing and for vessels moored in currents and/or subject to wave action as discussed in Chapter 4.

Piers and wharves are typically outfitted with a fender system along the berthing face to absorb the energy of impact of berthing vessels and provide a resilient buffer between pier and ship while moored. Some facilities may also provide "camels," floating separators ranging in size and type from timber logs to large steel pontoons that increase the standoff distance and/or help distribute the breasting forces to fender pile systems. Piers and wharves are also outfitted with mooring hardware as described in detail in Chapter 3, and many facilities are also equipped with utility systems, crane rails and/or railroad rails, curbs and railings, and access bridges and/or gangways—any of which may interfere with an otherwise optimal mooring arrangement. Ship building and repair facilities and military bases in particular typically have many shore connections to supply power and other services to the berthed vessel that may interfere with mooring lines and restrict vessel movements.

1.5 MOORING ARRANGEMENTS

A mooring arrangement in general refers to the layout and geometry of mooring lines, including their size and type and the locations, type, and capacities of the hardware to which they are attached. Vessel type and means of cargo transfer determine the type of berth and associated berthing structures and mooring arrangements. Mooring arrangements can be broadly classed into three major generic types. The most common arrangement is the "alongside" type, typically associated with general cargo, containerships, and other general purpose piers and wharves and along quay walls (Fig. 1-3). Fender units are often spaced at 8 to 15% of the ship length, or the fender system may be of the continuous timber fender pile type. Liquid bulk, tankers, and many dry bulk operations often use open "island"-type berths with discrete berthing and mooring dolphins for breasting the vessel and securing mooring lines respectively as illustrated in Fig. 1-4, which shows four breasting dolphins that

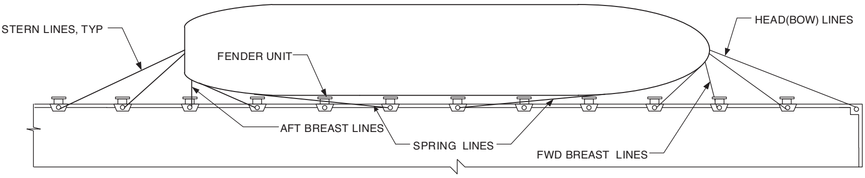


Fig. 1-3. *Typical alongside type berth mooring arrangement*

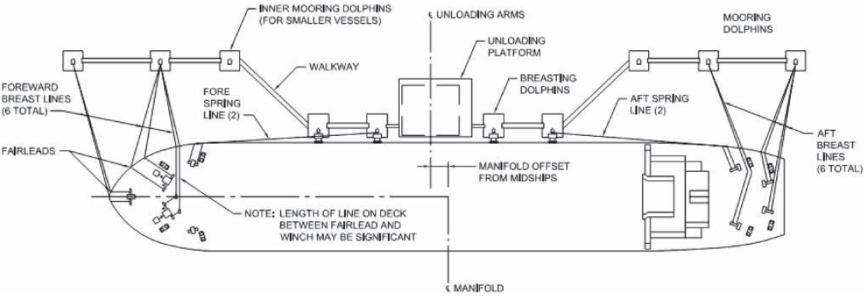


Fig. 1-4. *Island type berth mooring arrangement with multiple breasting dolphins to accommodate a range of vessel sizes*

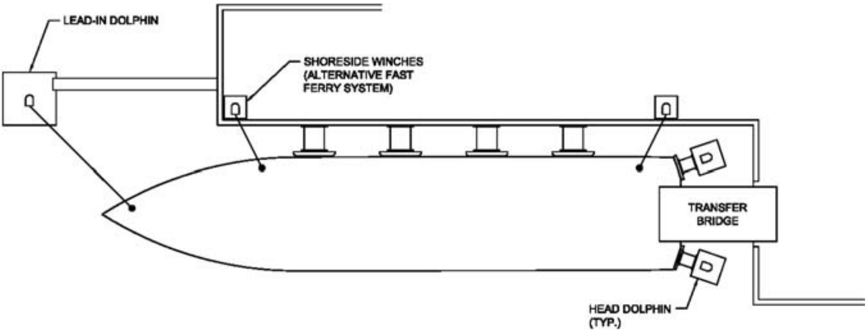


Fig. 1-5. *Slip type berth mooring arrangement*

allow for the berthing of vessels of varying lengths. Many, if not most, island-type berths have only two dolphins spaced at 25 to 40% of the vessel length and are thus restricted to only small variations in vessel lengths. Ferries and RO-RO operations often use "slip" type berths with end-on berthing for vehicle transfer via transfer bridges as illustrated in Fig. 1-5. Alongside fenders are ideally spaced at approximately 25% of the vessel length. Some high-speed ferries and RO-ROs on dedicated routes may be secured to shore-based winches with fixed locations for

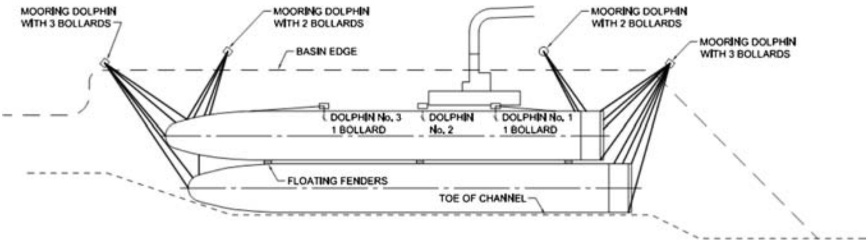
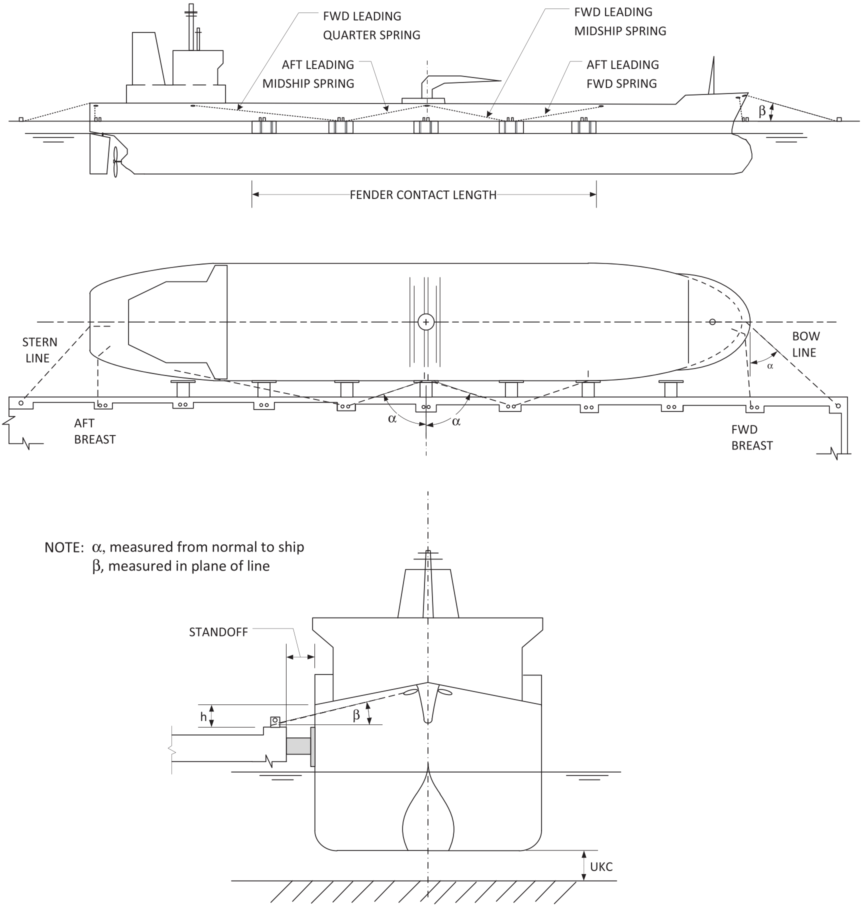


Fig. 1-6. Multiple vessel lay-up berth arrangement

securing lines ashore and on the vessel to facilitate fast turnaround. Vessels may also be “rafted” or “nested” in multiple berth type arrangements as in lay-up berths, shipyard operations, or under conditions of limited docking space as illustrated by the example lay-up berth in Fig. 1-6. Some permanently moored vessels such as floating dry docks; museum ships; and floating restaurants, hotels, and marine terminals may be “rigidly moored” via fixed mooring spuds or articulated mooring arms that hold the vessel at two or more points while allowing it to move vertically with changes in water level and draft. The distribution of mooring forces for such systems can generally be carried out using straightforward application of statics. Rigid systems should only be used at relatively sheltered locations as they are susceptible to wear and fatigue damage from repeated motions. A further and important caveat in the design of rigid systems is that they are also vulnerable to very large seismic forces due to the inertia of the relatively large mass plus entrained water that resists any movement at the top of the mooring resulting from ground movement (Keith et al. 1986). Mechanical and proprietary automated rigid systems are described further in Section 3.6.

Mooring lines may be broadly classed as to their function, such as breast, spring and bow, and stern lines, and as to their material and construction type such as steel wire and synthetic fiber of various constructions as described in Section 3.1. Fig. 1-7 illustrates definitions and the functional layout of mooring lines. Breast lines lead normal or nearly normal to the vessel’s longitudinal axis to provide primarily lateral restraint. Ideally, the line lead should be within 15 deg. of normal in plan view to serve as a pure breast line. Spring lines provide primarily longitudinal restraint and are nearly parallel, within 15 deg. of the longitudinal axis, with the vessel’s side. Spring lines are referred to as forward or after springs depending on the direction they lead from the vessel as shown in Fig. 1-7. Bow and stern lines lead at a variable angle from the ship’s ends and provide some degree of both lateral and longitudinal restraint. Bow and stern lines are typically employed at alongside type berths to give mostly lateral restraint when true breast



NOTE: α, measured from normal to ship
β, measured in plane of line

Fig. 1-7. Typical mooring arrangement definition sketch

lines are not practical because of short length and steep vertical angles. Some pier or wharf facilities may be equipped with “storm bollards” located at the opposite side of the pier or ashore to provide a proper line lead and greater security when a vessel may need to remain alongside under storm conditions. At island-type berths where fore and aft mooring dolphins can be set back an adequate distance from the berth face normally only breast and spring lines are provided, allowing a distinct division of function. Vertical angles should be kept as small as possible, preferably less than about 25 deg., with adequate allowance for draft and water level changes as discussed in Section 4.7. In general, the minimum number of lines required for strength is the most efficient, but in practice additional and sometimes redundant lines are employed for added security.

The geometry of the mooring layout determines the distribution of tensions among the individual lines. The efficiency of a mooring arrangement is therefore related to the total restraint of all the lines to the breaking load of the most critically loaded line, because the maximum restraint of the mooring layout is reached when the most heavily loaded line is at its limiting tension. It follows then that the efficiency of any given line in resisting the mooring load is related to the geometry of the most critical line, as well as its own. The load in any given line is also a function of the line's stiffness as determined by its elastic properties, area, and length, which in turn are determined by its diameter, material, and construction. Ideally then, all lines should be sized and oriented to reach their capacity simultaneously under a given imposed load. This is difficult to achieve in practice, however, especially considering that loads may come from any direction as is typically the case for wind. For special cases of directional loadings such as with strong currents from a predominant direction, the mooring layout may be designed to achieve a higher efficiency. Most pier and wharf facilities must also accommodate a range of vessel sizes, which further complicates the optimal location of mooring hardware and fenders. In general, mooring layouts should be as symmetrical as possible and mooring lines as near horizontal as possible. The subject of mooring line loads and geometry is treated in greater detail in Section 5.1.

Other factors affecting the mooring arrangement and analysis of mooring forces include the distance between the pier face and the vessel's side known as the *standoff* distance and the clearance below the vessel's keel to the sea bed, or under-keel clearance (UKC). The standoff distance is set by the depth of the fender system and/or the width of camels and separators and is often a trade-off among the need to keep the vessel close for loading equipment operations, the required depth of fenders for adequate energy absorption, and/or the need to fend the vessel off for adequate clearance of overhanging deck structures or other vessel features. The UKC has an important effect on current and wave loads as discussed in Chapter 4.

1.6 INDUSTRY STANDARDS

Several government, institutional, and industry consensus standards and references are particularly relevant to mooring analysis. In the United States, the U.S. Department of Defense (DoD) publishes joint military service design criteria documents known as United Facilities Criteria (UFC) of which *UFC 4-159-03,* "Design: Moorings" (DoD 2005a) and *UFC 4-152-01,* "Design: Piers and Wharves" (DoD 2005b) provide important design guidance in general and are mandatory in the design of facilities supporting any U.S. government service vessels. These documents originated with U.S. Navy NAVFAC Design Manuals to Military Handbooks and have evolved into the current UFCs. *UFC 4-159* provides design guidance for determining design criteria and for the calculation of wind and current forces on U.S. Navy vessels. *UFC 4-152* provides general design guidance and criteria for functional and structural design of piers and wharves that berth U.S. Navy vessels including fender system design calculations and load factors for berthing and mooring load combinations. The State of California's State Lands Commission has developed design standards for marine oil terminals that have been incorporated into the state building code. The "Marine Oil Terminal Engineering and Maintenance Standards" (MOTEMS 2011) provide both design criteria and general design guidance for new and evaluation, upgrading, and rating for existing marine oil terminals that are relevant to other types of marine facilities as well.

The British Standards Institute (BSI) standards, "Maritime Structures, Part 1: Code of Practice for General Criteria" (BSI 2000) and "Maritime Structures, Part 4: Code of Practice for Design of Fendering and Mooring Systems" (BSI 1994) provide valuable design guidance for mooring analysis of various facility types. The Oil Companies International Marine Forum (OCIMF) has developed an industry consensus document titled *Marine Equipment Guidelines*, 3d edition (MEG-3; OCIMF 2008) that, although specifically written for the design of shipboard equipment for tankers larger than 16 kDWT and LNG carriers, provides means and experimental wind and current coefficients for calculating wind and current loads on these vessels. It also provides helpful design guidance for berth and mooring line layout and arrangements. The Permanent International Association of Navigation Congresses (PIANC) is an international organization devoted to providing safe navigation for ships in waterways and harbors worldwide, and among its numerous publications three guideline documents are of particular interest in mooring analysis. "Criteria for Movements of Ships in Harbours: A Practical Guide" (PIANC 1995) provides guidelines for limiting motion criteria for moored vessels and mooring design analysis guidance. This document has been recently supplemented by PIANC Report No. 115, "Criteria for the (Un)Loading of Container Vessels" (PIANC 2012a). "Guidelines for the Design of Fenders Systems: 2002" (PIANC 2002) provides important discussion on fenders as part of a mooring system and modeling guidelines and generic vessel data. Other notable international standards containing information and design guidance useful in mooring analysis includes the Japanese *Technical Standards and Commentaries for Port and Harbour Facilities in Japan* (OCADI 2009), the German

Recommendations of the Committee for Waterfront Structures, Harbors, and Waterways (EAU 2004), and the Spanish "Maritime Works Recommendations: Actions in the Design of Maritime and Harbor Works" (ROM 1990).

Although not considered to be industry standards or definitive guides, a few additional publications are worthy of mention as they provide guidance for evaluating environmental loads and/or for mooring analysis and design. The U.S. Naval Sea Systems Command's "Calculations for Mooring Systems," DDS 582-1-C, provides nondimensional graphs for calculating wind and current forces on moored vessels and a methodology for manual calculation of mooring line loads (NAVSEA 1987). Although this document is specifically for the ship's mooring hardware and equipment, it is also useful for mooring analysis in general and especially instructive when designing facilities to accommodate U.S. Navy vessels. PIANC Report No. 116, "Safety Aspects Affecting the Berthing Operations of Tankers to Oil and Gas Terminals," provides a comparative review of mooring load calculations as presented by various international standards and other valuable information for designers of tanker and gas carrier facilities (PIANC 2012b). PIANC Report No. 117, "Use of Hydro/Meteo Information for Port Access and Operations," provides valuable guidance for collecting, analyzing, and applying environmental design criteria to vessel berthing and mooring applications (PIANC 2012c).

CHAPTER 2

MOORING PRACTICE AND DESIGN REQUIREMENTS

2.1 GENERAL CONSIDERATIONS

The first step in any mooring analysis is to establish the facility design criteria, including any additional constraints. In general the following information must be considered:

- Design vessel and/or range of vessels and their characteristics as discussed in Section 2.3;
- Operational criteria, including vessel location(s) within the berth to accommodate cargo-handling equipment, boarding platforms, etc., and allowable range of vessel movements due to environmental conditions as discussed in Section 6.2;
- Facility configuration, including water depth, berth dimensions, approach conditions and exposure to vessel traffic, mooring hardware and fender locations, etc.;
- Mooring arrangement, including line sizes and characteristics, fender characteristics, and allowable hull pressures as discussed in Chapter 3; and
- Environmental conditions, including extreme, operational, and/or any other controlling conditions; environmental design criteria include the following and the minimum variables to be specified:
    - ◦ Wind, for which a basic design wind speed must be specified by direction and reference height and duration;
    - ◦ Current, for which current velocities must be specified by direction at a given water depth;
    - ◦ Wave climate, including heights and periods by direction and/or energy spectrum for dynamic analysis and evaluation of any long wave and harbor resonance effects if present;

- Tide and water levels, including normal and extreme water level variations; and
- Ice, for which thickness, strength, and movement characteristics must be defined.

Forces associated with environmental conditions are discussed in Chapter 4, whereas Section 2.1.1 will define the nature of these environmental elements.

2.1.1 Risk Assessment

Design environmental conditions are determined with regard to risk versus cost and safety typically by considering the probability of occurrence of a given event in terms of a long-term statistical return period. A commonly accepted way to define risk for marine design purposes is to determine the probability of encounter (E_p) of some specified extreme event with a given statistical return period (T_r) relative to the structure's lifetime (n) in years as given by the following relation:

$$E_p = 1 - \left(1 - \frac{1}{T_r}\right)^n \tag{2-1}$$

The nominal design life for mooring analysis purposes typically ranges from 25 to 100 years depending on the application and considering such factors as berth occupancy times and other uncertainties. The design environmental conditions may be limited by operational criteria such as for threshold wind speeds and/or wave heights beyond which operations cease and the vessel may need to vacate the berth. Limiting wind speeds for most crane and container-handling systems are typically within the range of 25 to 35 knots, near gale force conditions. Large ferries may operate in sheltered berths up to around 40 knots. Wind direction may be as important a factor as the speed itself. Limiting vessel motion criteria and thus limiting sea state conditions are discussed in Section 6.2.

2.1.2 Principles of Mooring Practice

Certain fundamental principles of accepted practice relating to mooring layout and design features exist. The following points, adapted in part from MEG-3 (OCIMF 2008) should always be kept in mind:

- Mooring points should be placed as symmetrically as possible about the berth centerline and in sufficient number and capacity to accommodate the range of expected vessels.
- Bow and stern lines typically employed at alongside berths are not absolutely necessary to safely moor a large vessel and may in fact reinforce oscillations under certain circumstances. Fore and aft breast lines should be located at the vessel's extremities and lead

normally to the vessel's side to resist lateral forces. Spring lines should lead as nearly parallel to the vessel's side as possible and be sized to resist the sum of longitudinal forces. By separating the functions of lateral and longitudinal restraint the vessel can be safely moored within its own length.

- Lines should have a minimum length on the order of 35 to 50 m, and lines in the same service should be of similar size and type, e.g., wire rope and synthetic lines should not be used together as breast lines.
- Lines should lead as nearly horizontal as possible, and the maximum allowed vertical lead angle should not exceed 25 degrees.
- Fender contact should be within the extent of the vessel's parallel mid body, ideally over the middle one third of the vessel's LOA but within the range of 25 to 40% LOA.
- An adequate factor of safety (FS) must be provided on the mooring points for the expected loads. Assuming that the mooring lines have been properly sized with regard to their FS, then the minimum safe working load (SWL) of the mooring hardware should not be less than the minimum breaking load (MBL) of the line. Factors of safety are discussed in more detail in Section 2.5.

An additional consideration is the pretensioning of mooring lines. Pretensioning mooring lines sufficiently to remove sag and often to precompress the fenders, especially at exposed locations, and minimize vessel movements is common practice. Initial pretensions are often on the order of 10 tons or more for large vessels. Slack lines are not acceptable and in fact have contributed to many mooring incidents. At some locations and under certain circumstances "shore augmentation" may be required to supplement the vessel's mooring equipment, such as storm bollards and additional heavy mooring lines. Shore pulleys at some facilities, typically liquid bulk type, effectively double the capacity of a single wire rope line. The importance of not mixing line types for the same purpose cannot be overemphasized. Figure 2-1 illustrates this point with an example of the load distribution between steel wire rope and polypropylene line of the same length and MBL in a mixed mooring scenario. The steel wire lines take 95% of the total lateral load. The addition of an elastic nylon "tail" improves the situation only very slightly. The steel wire and nylon tail behave as springs in series and for the short length of tail illustrated are still much stiffer than an all-polypropylene line.

2.2 ENVIRONMENTAL CONDITIONS

Accurate determination of environmental criteria for mooring analysis and design is vitally important. The following paragraphs provide an overview of the key parameters involved. A thorough treatment of the

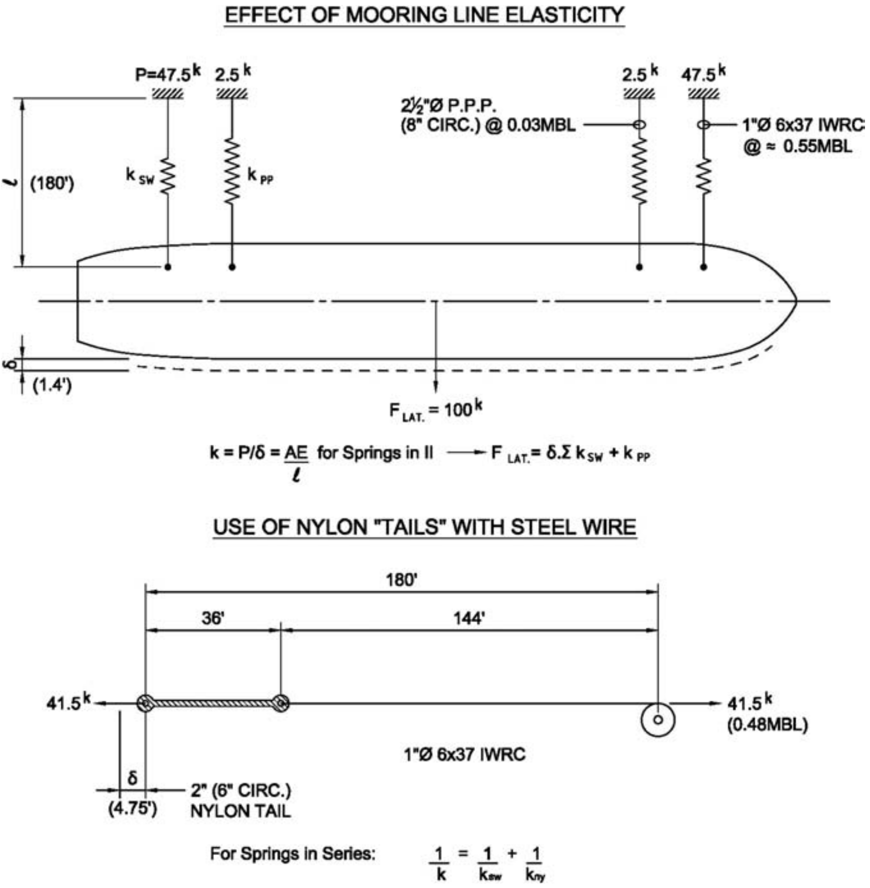


Fig. 2-1. The effect of mooring line elasticity in a mixed mooring
P = line load in kips, δ = deflection in feet, K = spring constant, A = cross sectional area of line, E = modulus of elasticity of line, PPP = polypropelene, and IWRC = independent wire rope core
Source: Gaythwaite and Eskijian (2010).

acquisition, forecasting, and application of meteorological and oceanographic data required is provided in PIANC (2012c). Additional information sources include the World Meteorological Association (WMO), the National Oceanic and Atmospheric Administration (NOAA), the National Ocean Survey (NOS), and the United States Army Corps of Engineers (USACE), including the *Coastal Engineering Manual* (CEM) and Wave Information Study (WIS) data.

2.2.1 Wind

Wind is universally present and of central importance in almost all mooring analyses. Wind is the movement of air that exhibits temporal and spatial variability that must be accounted for in the design criteria. Although many, if not most, applications of interest herein take the wind speed to be steady, in reality it is constantly varying over time. Peaks in the wind record are known as gusts and can greatly exceed the time-averaged wind speed. Wind turbulence may manifest itself over relatively short time scales of .05 to 20 s. Wind record and design data may be reported in terms of peak gusts, 1 min, mean hourly, or some other averaging time that must be converted to a minimum duration equivalent wind speed capable of overcoming the moored vessel's inertia and fully mobilizing the wind pressure forces. A 30-s gust duration is often applied in mooring analysis, although other durations may be more appropriate such as shorter durations for small craft and longer for very large vessels as discussed in greater detail in Section 4.2. In some cases, such as hurricanes with very high wind speeds, thunderstorm gust fronts, and/or other sensitive situations where dynamic analysis is required, a more complete description of the wind, such as wind spectra, may be required.

The wind speed also increases exponentially with height aboveground, or sea level, within the atmospheric boundary layer in accordance with a power law determined in large part by surface roughness, temperature differences and thermal stratification, and the magnitude of the wind speed itself. Accordingly, wind speeds must be reported at some anemometer height and need to be corrected to some reference height, and/or the variation with height must be integrated over the vessel's profile. The most commonly accepted standard reference height is 10 m, or 33 ft, although airports and ocean data buoys often have lower anemometer heights resulting in higher speeds when corrected to the 33-ft reference height. Records from offshore oil rigs are often reported at much higher heights, often 30 m, and the seaman's "Beaufort Scale" for describing sea state conditions is based on a 6-m reference height. The generally accepted correction procedure for mooring analysis is described in Section 4.2.

Wind record data are often necessarily taken from sites fairly remote from the port facility, or in the case of long-term data, may be smoothed from records over a broad area. For records taken inland from the site an overland/overwater correction is normally applied. An increase of 10% higher than the inland value is commonly applied in the absence of better data. The air-to-sea temperature difference may also be a factor when it is known, as colder air accelerates when passing over warmer water and vice versa. This increase can be on the order of 20% for a 20° F difference. Local topography may also result in localized effects such as jets and funneling and "katabatic" down-slope winds and buffeting due to nearby obstructions. *ASCE 7-10* (ASCE 2010) reports long-term design wind speeds for the United States and its territories and correction factors for local topography and other effects, and Seelig (1999) includes long-term wind speeds for design for U.S. Navy sites, including selected locations worldwide. Considering that large vessels typically put to sea when extreme winds are forecast obtaining wind data that do not include extreme events such as hurricanes in the long-term averages is often desirable.

2.2.2 Current

Currents in general are a consequence of changing water levels and are normally associated with tidal variations at most port locations, although river runoff or hydraulic flows in canals may dominate at certain sites. Well offshore tidal currents are rotary in nature, varying through all points of the compass over a tide cycle. In bays and harbors the current direction is more restricted and becomes reversing in nature within estuaries and river mouths, flooding and ebbing in opposite or very nearly opposite directions. The general direction of the current is known as the "set" and its average speed as the "drift." Strong winds can induce near-surface currents that are generally 1 to 3% of the wind speed. Strong winds can also affect the tidal currents and water levels. The strength or speed of the current typically varies in direct proportion to the tide range. Current velocities are generally maximum near mid tide and exhibit a period of "stand" at high and low water as the direction reverses. Current velocity typically varies in direct proportion to the tide range or water level differences. This fact can be useful in estimating maximum and minimum values from tide records or measurements taken over a limited period.

Tidal currents typically exhibit a boundary layer type vertical profile, similar to wind, increasing exponentially with height above the sea bed to a maximum at the surface. Therefore, verifying the depth at which the current measurement was taken is very important. This and other important aspects of currents as related to forces on moored ships are discussed in greater detail in Section 4.3. River and estuary currents also exhibit horizontal variation in velocity; they are typically stronger near mid channel and in deeper water near the thalweg of the river flow.

Current speeds and directions are reported by NOAA and the NOS for many port and coastal stations; however, gathering site-specific data may be necessary for facilities remote from reporting stations and essential for cases where currents are known to be strong (>1.5 knots). Acoustic doppler current profilers (ADCPs) are readily available at modest cost and can be relatively easily installed on nearby piles or structures or on the seabed.

2.2.3 Waves

Although most port locations are somewhat well protected from potentially damaging wave action, all sites should be evaluated for exposure to such waves. The ocean is in constant motion with its surface energy distributed over a wide range of frequencies. The overall "wave climate" at a given site needs to be evaluated for both short-term and long-term conditions and events with regard to design mooring conditions and/or to determine conditions under which vessels need to vacate the berth. The wave climate in general consists of any or all of the following components:

- Locally generated wind waves, limited by fetch length and water depths;
- Ocean swell and longer period waves that have penetrated the harbor entrance, limited by offshore wave climate and harbor and coastal bathymetry;
- Harbor resonance phenomena, or "seiche," limited by harbor geometry, bathymetry, and meteorological and oceanographic disturbing forces;
- Vessel wakes, limited by vessel traffic and speed restrictions (Note: wake waves should not be confused with passing vessel effects as described in Section 4.4.); and
- Wave conditions modified by refraction, shoaling, diffraction, reflection, wave systems interactions, currents and water levels, and tide range.

Waves are periodic undulations of the sea surface that exhibit a very wide range of periods (T), or time between successive crests or troughs, that may be problematic for moored vessels even for waves of low height (H), or the vertical distance between trough and crest. Most waves of interest are generated by wind, and waves still under the influence of the generating wind, known as "wind waves," are typically generated locally over some controlling "fetch" length, the distance over water that the sustained wind blows. Wave heights may be limited by wind speed, fetch length, and/or the duration of time over which the wind blows at a given speed. If the wind blows for a sufficient length of time over a given fetch, then a near steady-state condition termed a fully developed sea (FDS) may be reached under which no further wave development occurs. Wind waves typically have periods in the range of a few to 20 s, because as waves get longer they may outrun the wind speed, thus slowing further development. Waves that continue after the wind has slowed, or that have left the generating area, are known as "swell" and have periods in the range of 10 to 25 s and sometimes longer. Even longer period waves known as "infragravity" waves have periods on the order of 25 to 300 s or more. Such waves may excite harbor resonance motions known as "seiche," as discussed in more detail in Section 4.6.

Waves with fairly uniform lengths between crests are termed regular, such as some swell; however, most waves or "sea states" are irregular with wave heights typically distributed over a range of periods. The most common way of defining a sea state is in terms of the significant wave height (H_s), which is the average of the highest one-third of all waves present. Waves then are assumed to follow a Rayleigh distribution of heights with the following relationship to H_s:

Average = $0.64H_s$;
Root mean square (RMS) = $0.707H_s$;
Highest 10% = $1.27H_s$; and
Highest 1% = $1.67H_s$.

The maximum or most probable maximum wave height to occur over a given time interval is a function of the average period and the duration as described in Section 4.5.3. A common way of presenting wave data for design purposes is in the form of wave energy spectra that gives the spectral density, proportional to the sea surface energy at a given frequency. Various spectral formats are in common use such as the JONSWAP, TMA, Pierson-Moskowitz, Bretschnieder, and others that may be variously preferred under different circumstances. Michel (1968, 1999) provides a comprehensive overview of the various spectral formats and their marine engineering applications. Wave spectra have a peak corresponding to some spectral peak period (T_p) at which the greatest energy is concentrated. As the wind speed increases, and if it blows for sufficient duration, the peak shifts toward lower frequencies as illustrated in Fig. 2-2, which shows a hypothetical family of spectra for an offshore site under FDS conditions associated with wind events of various return periods. Note the shift to lower frequencies with increasing wind speed. A similar shift occurs under developing sea conditions. Further description of wave spectra and wave mechanics in general is beyond the scope of this manual, and the reader is referred to the literature on this topic for further enlightenment.

2.2.4 Tide and Water Level Variations

Tide refers to the periodic rise and fall of water levels in response to the gravitational attraction of the moon and sun and their positions

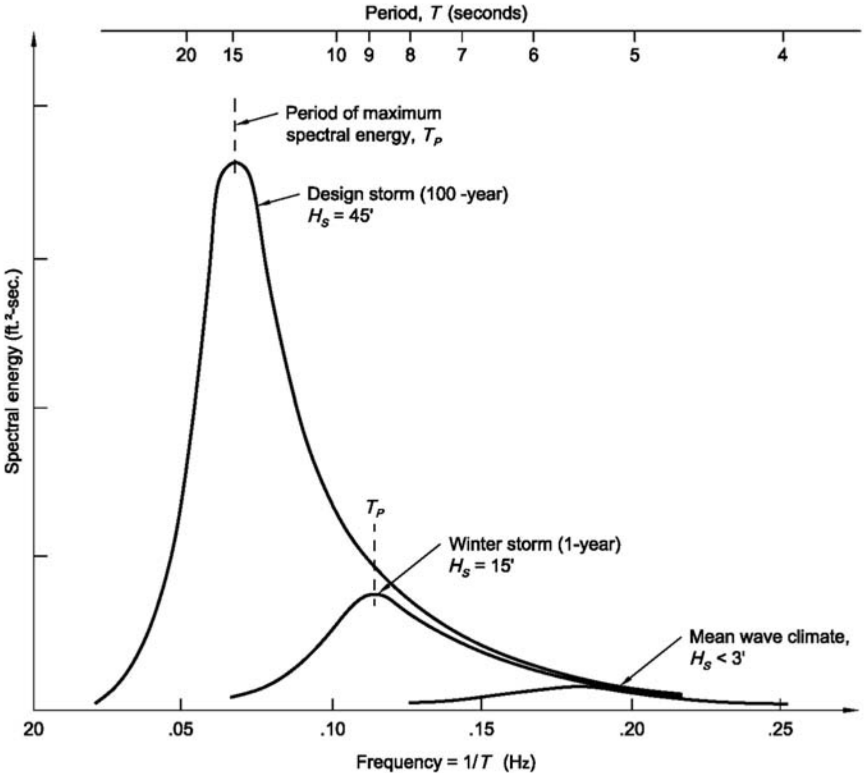


Fig. 2-2. Hypothetical design wave spectra at offshore site
Source: Adapted from Gaythwaite (1981)

relative to the earth and may be greatly modified by local bathymetry and coastal topography. Tides are generally classified as diurnal, having one high and one low per day; semi-diurnal, having two highs and two lows per day; and mixed, falling anywhere in between with one of the highs and lows typically of greater or lesser range. Tides go through significant variations in range over periods of weeks and months and complete a cycle of variations over a period of 18.6 years known as the "metonic cycle," which determines a tidal epoch. Over a synodic month (29.5 days), a series of two successively higher alternating with lower ranges occur, which are known as springs and neaps respectively due to the alignment of the sun and moon. Spring tides can be up to 40% or more of the normal mean tide range.

Tides are predicted by NOAA and NOS from many coastal recording stations and for many nearby sub-stations as well. In the United States the reference datum used is mean lower low water (MLLW), which is the long-term average of the lower low waters. In many European countries tide elevations are commonly referenced to the lowest astronomical tide (LAT). In the United States, MLLW is in turn measured relative to the current national survey datum, the North American Vertical Datum (NAVD), although at some locations the outdated National Geodetic Vertical Datum (NGVD) may still be in use. Verifying the tidal datum in use and its relation to the pier deck and mooring fixtures and water depths within and adjacent to the berth is important.

Extreme water levels may occur on a long-term basis related to storm surges and/or extreme river runoff flood events. Although investigating the effects of long-term extreme water levels is not typical when a vessel is unlikely to be in the berth under extreme storm conditions, for certain facilities such as floating dry docks, floating habitats or aquariums, etc., that must remain in place over lengthy design lives long-term water levels, highest and lowest, must be considered. Sea level rise (SLR) must also be considered for permanently moored floating structures and facilities with long design lives in general.

2.2.5 Ice

Ice action has been responsible for vessel breakaway incidents (see Section 6.3) and damage at berth, as described in Section 4.8. Sites located in cold regions should be assessed for potential ice problems such as thickness of solid ice cover and ice types and movements. Moving ice in particular presents a potential hazard to moored vessels, including the impact and pile up of moving ice floes during spring break up and the thrust of solid ice sheets driven by wind and current and passing vessels as discussed in Section 4.8. Reliable data on ice formation is often difficult to find. The World Meteorological Organization (WMO) and the USACE Cold Regions Research and Engineering Laboratory (CRREL) may provide useful information for certain locations.

2.3 DESIGN VESSELS AND BERTH OCCUPANCY

A mooring analysis necessarily requires that a certain design vessel and/or vessels be specified, which includes the vessel's principal dimensions, draft and trim conditions, and position within the berth as may be limited by loading arms or crane reach, etc. The locations of the ship's chocks and mooring hardware must be known, as well as the size and type of mooring lines, etc. At facilities where a specific vessel is not known, a representative vessel or vessels may be used.

Berth occupancy time is affected by vessel calling schedules, loading/unloading times, navigation approach conditions as affected by water levels, and weather and vessel movements and safety considerations while in berth due to environmental conditions. At offshore oil and gas terminals, for example, a 10% down time where the berth cannot be occupied due to wave action is considered the norm.

2.4 DESIGN CRITERIA

No general or universal set of design criteria exists, even for facilities of a given type. In general, design criteria should be determined judiciously for site-specific conditions and with regard to operational constraints, facility lifetime, use, etc. The facility owner/operator typically provides the design vessel(s), operational requirements, expected lifetime, etc., but the designer usually determines adequate environmental design criteria to ensure a safe berth is provided over the facility's lifetime. Following are certain specific design criteria and design analysis guidance for specific facility types. *UFC 4-159* is specific to and typically required for the design of U.S. Navy and other U.S. services facilities and defines four basic types of moorings relevant when considering environmental loads:

- Type I: mild weather, current less than 1 knot, wind less than 35 knots;
- Type II: used during storms, but vessels would leave before a hurricane;
- Type III: used for vessels that cannot get underway to avoid severe weather conditions; and
- Type IV: permanently moored (floating dry docks, museums, inactive vessels, etc.).

Requirements vary depending on the type. This provides a useful guide for determining design criteria of the berth (Table 2-1).

These various types of moorings determine the appropriate design wind, current, and wave loads. Type IIB is intended to be the standard for naval vessels' gear and is perhaps the most relevant for typical applications.

Special considerations are recommended if any of the following conditions apply:

- Wave heights greater than 4 ft;
- Winds greater than 75 knots;
- Current greater than 3 knots;
- Wave period greater than 4 s;
- Exposure to long waves, seiche, or passing vessel effects; and
- Exposure to hurricanes, ice, or other site-specific hazards.

Under any of these conditions a dynamic analysis or a more rigorous static analysis is generally required.

Table 2-1. Suggested Criteria for Mooring Service Types

Mooring Service Type	WIND	CURRENT	WATER LEVEL	WAVES
Type I	$\leq$35 knots	$\leq$1 knot	MLL to MHH	NA
Type IIA	$\leq$50	$<$1.5	EL to MHH	$R = 1$ yr
Type IIB	$\leq$64	$<$2.0	EL to MHH	$R = 1$ yr
Type III	$R = 50$ yr	$R = 50$ yr	EL to MHH	$R = 1$ yr
Type IV	$R = 100$ yr	$R = 100$ yr	EWL	$R = 100$ yr

Notes: MLL = mean low water; EL = extreme low water; MHH = mean higher high water; EWL = extreme water levels; R = return period, years

Source: UFC 4-159-03

Recommendations for VLCCs provided by OCIMF (2008) are intended for tankers of 16 kDWT and larger but provide some useful guidance in mooring analysis for oil and gas carrier facilities:

- 60 knots wind (30-s gust, any direction, 10 m above water line);
- 3 knots current at 0 and 180° (in line with the longitudinal axis of the vessel);
- 2 knots current at 10 and 170°;
- 0.75 knot beam current;
- Currents on average greater than vessel's draft for $d/T = 1.1$ to nearly 1.0; and
- For combined loads, $d/T = 1.1$ to 3.0 for vessel in full load to light condition, whereas for LNG $>$ 150 m LOA use $d/T = 1.1$ for all conditions.

Site-specific current speeds and directions should be used instead of the aforementioned in conducting a facility mooring analysis.

The California State Lands Commission has developed a maintenance and design standard for marine oil terminals (MOTEMS 2011) that is incorporated into the state building code, specifies design criteria for new and existing marine oil terminals (MOTS), and provides useful design guidance for any such facility in other states or locations as well. The following summarizes some of the key points with regard to environmental criteria, but the reader is referred to the original document for further description and additional requirements.

- Maximum wind, current, waves, and combinations thereof shall be defined as limiting conditions for vessels at each berth with and without product transfer.
- MOTEMS (2011) provides "risk classifications"; wind velocity, $V_w > 50$ knots and/or current velocity, $U_c > 1.5$ knots are considered "high risk."

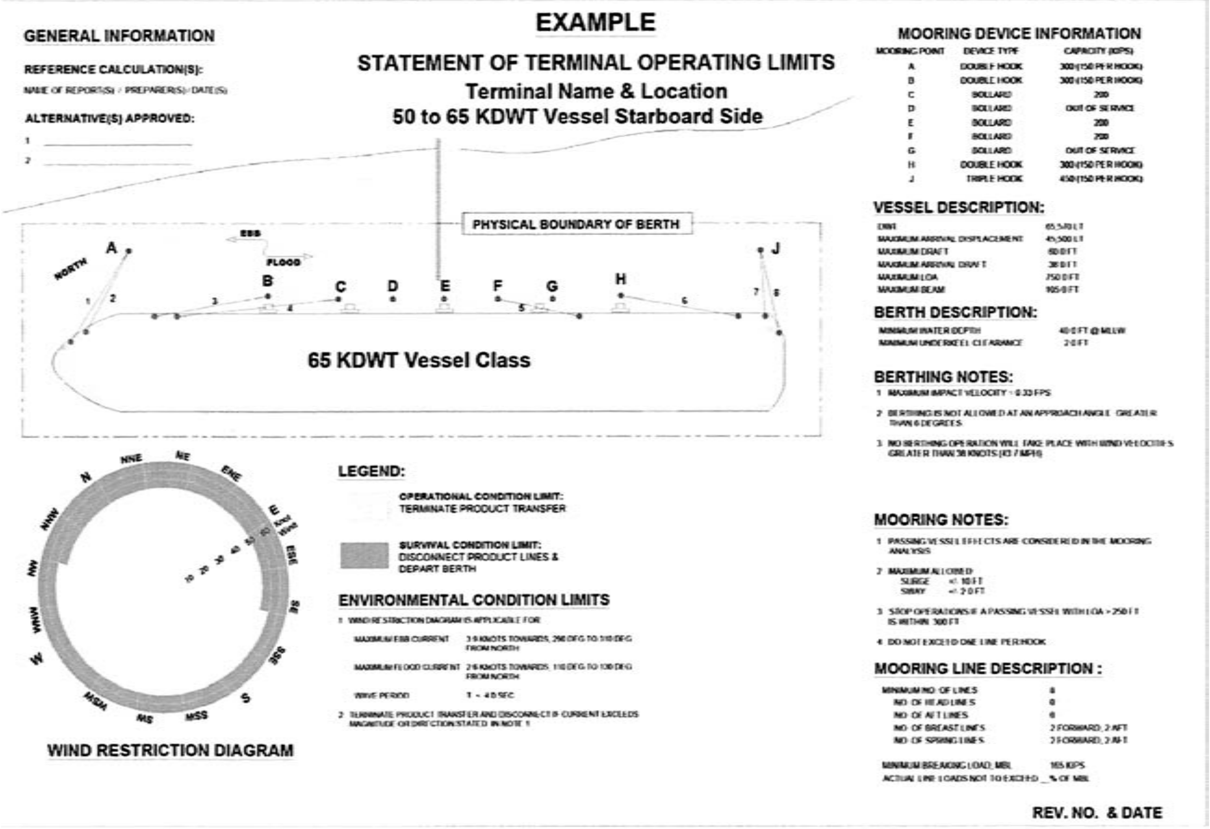
- For wind, design for a minimum 25-year R_t for new MOTS and determine the threshold V_w for a vessel to vacate berth for existing MOTS. V_w must represent the 30-s gust duration and must check a minimum of eight directions in 45° increments.
- For current, site-specific data are required when $U_c > 1.5$ knots based on at least 1 year's record and must check two directions, flood and ebb, and two tide levels, min/max and min/max draft for worst combination with V_w direction.
- For waves, if $T_s > 4$ s for the annual maximum H_s, then dynamic analysis is required. Possible effects of seiche and tsunami must be evaluated.

MOTEMS further requires that a statement of terminal operating limits then be prepared (see Fig. 2-3). The reader is referred to MOTEMS (2011) for additional design and operational requirements.

The foregoing discussion should make it clear that wide variation exists in specific design criteria for a given application. Some important points to consider in conducting a mooring analysis for a new facility with regard to environmental design criteria follow. In general for wind and current the worst conditions and combination thereof that is likely to occur with a ship in berth should be considered. For a transient berth a 25-year event compatible with other risk factors would seem a likely minimum, whereas for a permanent berth, such as a floating dry dock or other moored vessel that cannot get underway when severe conditions threaten, a 100-year or other extreme event should be considered. Although the traditional assumption is that vessels would put to sea at some minimum threshold wind speed, often around 50 knots, a design wind speed on the order of 60 knots from the worst direction should be considered in lieu of other data to account for the possibility of thunderstorm gust fronts or microbursts that may arise suddenly and without warning in areas susceptible to such weather events. Currents in general should correspond to at least the annual maximum. If local wind wave or swell periods exceed around 4 s then a dynamic analysis should be conducted. The site should be evaluated for possible long wave, or seiche, effects (see Section 4.6) and exposure to tsunami effects.

Waves can influence the loading or unloading of vessels. Long-period swells can cause vessels to surge fore and aft, which could have several detrimental impacts including

- Damage to petrochemical unloading/loading arms (and associated possibility of a spill);
- Damage to petrochemical hoses (and associated spill potential);
- Damage to containers or container-handling equipment; and
- Overload of mooring lines or mooring points (e.g., quick release hooks).



GENERAL INFORMATION

REFERENCE CALCULATION(S):

NAME OF REPORT(S) / PREPARER(S) / DATE(S)

ALTERNATIVE(S) APPROVED:

1 ____________

2 ____________

EXAMPLE

STATEMENT OF TERMINAL OPERATING LIMITS

Terminal Name & Location

50 to 65 KDWT Vessel Starboard Side

WIND RESTRICTION DIAGRAM

LEGEND:

OPERATIONAL CONDITION LIMIT:
TERMINATE PRODUCT TRANSFER

▨ **SURVIVAL CONDITION LIMIT:**
DISCONNECT PRODUCT LINES &
DEPART BERTH

ENVIRONMENTAL CONDITION LIMITS

1 WIND RESTRICTION DIAGRAM IS APPLICABLE FOR:

MAXIMUM EBB CURRENT	3.9 KNOTS TOWARDS, 290 DEG TO 310 DEG FROM NORTH
MAXIMUM FLOOD CURRENT	2.6 KNOTS TOWARDS, 110 DEG TO 130 DEG FROM NORTH
WAVE PERIOD	T < 4.0 SEC

2 TERMINATE PRODUCT TRANSFER AND DISCONNECT IF CURRENT EXCEEDS MAGNITUDE OR DIRECTION STATED IN NOTE 1

MOORING DEVICE INFORMATION

MOORING POINT	DEVICE TYPE	CAPACITY (KIPS)
A	DOUBLE HOOK	300 (150 PER HOOK)
B	DOUBLE HOOK	300 (150 PER HOOK)
C	BOLLARD	200
D	BOLLARD	OUT OF SERVICE
E	BOLLARD	200
F	BOLLARD	200
G	BOLLARD	OUT OF SERVICE
H	DOUBLE HOOK	300 (150 PER HOOK)
J	TRIPLE HOOK	450 (150 PER HOOK)

VESSEL DESCRIPTION:

DWT	65,500 LT
MAXIMUM ARRIVAL DISPLACEMENT	45,500 LT
MAXIMUM DRAFT	60.0 FT
MAXIMUM ARRIVAL DRAFT	38.0 FT
MAXIMUM LOA	750.0 FT
MAXIMUM BEAM	105.0 FT

BERTH DESCRIPTION:

MINIMUM WATER DEPTH	40.0 FT @ MLLW
MINIMUM UNDERKEEL CLEARANCE	2.0 FT

BERTHING NOTES:

1 MAXIMUM IMPACT VELOCITY = 0.33 FPS

2 BERTHING IS NOT ALLOWED AT AN APPROACH ANGLE GREATER THAN 6 DEGREES

3 NO BERTHING OPERATION WILL TAKE PLACE WITH WIND VELOCITIES GREATER THAN 38 KNOTS (43.7 MPH)

MOORING NOTES:

1 PASSING VESSEL EFFECTS ARE CONSIDERED IN THE MOORING ANALYSIS

2 MAXIMUM ALLOWED:
SURGE <= 1.0 FT
SWAY <= 2.0 FT

3 STOP OPERATIONS IF A PASSING VESSEL WITH LOA > 250 FT IS WITHIN 300 FT

4 DO NOT EXCEED ONE LINE PER HOOK

MOORING LINE DESCRIPTION :

MINIMUM NO. OF LINES	8
NO. OF HEAD LINES	0
NO. OF AFT LINES	0
NO. OF BREAST LINES	2 FORWARD, 2 AFT
NO. OF SPRING LINES	2 FORWARD, 2 AFT

MINIMUM BREAKING LOAD, MBL 165 KIPS
ACTUAL LINE LOADS NOT TO EXCEED _ % OF MBL

REV. NO. & DATE

Fig. 2-3. Certificate of facility operating limits
Source: MOTEMS (2011)

Shorter-period waves or surges can cause the vessel to roll when the waves approach from the vessel beam. These waves can also be detrimental to port operations by causing

- Damage to petrochemical unloading/loading arms (spill potential);
- Damage to petrochemical hoses (spill potential);
- Damage to containers or container-handling equipment;
- Overload of mooring lines or mooring points (e.g., quick release hooks); and
- Damage to fender systems.

A clear set of design criteria needs to be established at the outset of the design process. The criteria should state the allowable vessel movement that will be tolerated during port operations at the port facilities. Once the allowable vessel movements are determined, design of the port structures can proceed with adjustments being made such that maximum values are not exceeded. For oil terminals, the loading arms must be designed for allowable limits of surge/sway/heave combined with maximum tidal variations and range of operational drafts.

2.5 ALLOWABLE LOADS AND FACTORS OF SAFETY

Adequate factors of safety (FS) are required both for the mooring lines and for the bitts/bollards or mooring hooks used for the safe mooring of vessels. Mooring hardware is usually specified with an allowable load, most often referred to as safe working load (SWL), based on standard structural design procedures and/or the manufacturer's proprietary design and testing. In general the SWL should exceed or at least equal the mean breaking load (MBL) of the line times the number of such lines that will be secured to it, although in many instances additional lines may be provided for added security beyond the required capacity. There also are many instances in which the exact line size and MBL of the vessels that may call are uncertain. In such cases the maximum line load from a mooring analysis should be used to determine the MBL of the line that would be required to determine the required SWL of the mooring hardware. Mooring hardware must also be rated with regard to the direction of line pull, including vertical angle, as is discussed further in Section 3.2. Once the required SWL of the mooring fitting has been determined, the installation design should be in accordance with the relevant material building code(s) such as ACI or AISC. *UFC 4-152-01* provides design load factors and load combinations specific to piers and wharves.

A possible exception to designing for the full SWL is the case of quick release hooks with multiple hooks where it is unlikely that all of the hooks would be loaded to their individual SWL simultaneously. In such cases a reduction factor to account for the expected maximum total of line loads as determined by mooring analysis may be justified. Some owners/operators may have their own proprietary rules for determining appropriate load factors so that new structures are not overdesigned and existing structures can be retrofitted without additional overall strengthening. Clearly, experienced engineering judgment supported by rigorous mooring analysis is crucial in this case.

According to *UFC 4-159-03* a FS = 3.0 should be applied to the maximum line load determined by analysis to select the MBL required for wire rope and most synthetic line types. The strength of polyamide (nylon) lines should be reduced by 15%, FS = 3.5, to account for reduced strength when wet. The UFC then requires that mooring hardware be designed for three parts of the line to be used, 3 × MBL, times a factor of 1.3 implying an overall FS = 3.9 × MBL. The SWL must be equal to or greater than this load, which may be overly conservative in many applications where the actual fitting load may be only the equivalent of a single part of line, even though three parts may be employed. The UFC further requires that the mooring arrangement continue to provide at least 75% of its original full design capacity should any single element of a multicomponent mooring system fail.

OCIMF (2008), in contrast, requires the SWL of a vessel's fittings be at least equal to or greater than the MBL of the largest line likely to be used. The OCIMF requires the following FS be applied to the minimum required line size based on analysis using OCIMF (2008) vessel equipment design criteria (see Section 2.4):

- Steel wire rope: FS = 1.82 (55% of MBL);
- Synthetics, except nylon: FS = 2.0 (50% of MBL);
- Polyamide, nylon (wet): FS = 2.22 (45% of MBL);
- Rope tails: For wire rope: FS = 2.28 synthetic tails and FS = 2.5 nylon tails; for synthetics: FS = 2.50 synthetic tails and FS = 2.27 nylon tails; and
- Joining shackles: FS = 2.0 or > SWL of line.

In all cases the FS for rope tails should be greater than that for the mooring lines. The UFC requirements may often result in overly conservative designs and, depending on the size of lines actually carried by a given vessel, may be impractical to design for, especially for existing facilities. The OCIMF criteria appear to provide an adequate FS for most applications, assuming the line has been properly sized by analysis. Ultimately, the final design FS requires experienced engineering judgment with consideration of the environmental design criteria, severity of conditions expected, consequences of line or hardware failure, and level of confidence in the mooring analysis results.

CHAPTER 3

MOORING SYSTEM COMPONENTS

Mooring arrangements consist of two primary components: mooring lines and fenders. The vessel typically provides mooring lines that extend from mooring points on the vessel to mooring points on the berth. The lines provide restraint in tension. The fenders are attached to the berth at the berth's contact locations with the vessel and provide restraint through compression of the fenders.

Mooring lines consist of steel wire, artificial (or natural) fibers, or combinations of the two. Historically these two types could be distinguished by the trade-off in benefits between the two. Steel wire lines provide greater minimum breaking loads (MBLs) and abrasion resistance but are difficult to handle, allow for little elongation, do not dissipate shock loads, and hence do not distribute loads as evenly. Artificial fibers are easier to handle and, compared with steel wires, are somewhat elastic. Unfortunately, they are weaker and wear and abrade more easily. Some of the newer artificial proprietary fibers combine some of the benefits of both.

3.1 MOORING LINES

Three types of mooring lines may be encountered when designing a mooring system and conducting a mooring analysis: wire rope, fiber rope, and chain. The following discussion covers the ropes and chains that are commonly used in pier-side mooring systems and not those that might be used in offshore moorings.

3.1.1 Wire Rope

Many forms and types of wire rope and cable exist. The most common form and type used on ships is 6 × 36 class steel, either independent wire rope core (IWRC) or fiber core (FC). Further strength and weight characteristics can be found in Tables 23 and 24 of the Wire Rope User's Manual, WRTB (2005).

The stretch characteristics of fiber core and IWRC wire rope are shown in Fig. 3-1. The stretch characteristic of a wire rope is essentially linear. For long line lengths, the catenary effect can be significant and needs to be considered.

OCIMF (2008) recommends that the highest load imposed on a wire mooring line should not exceed 55% of new minimum breaking strength.

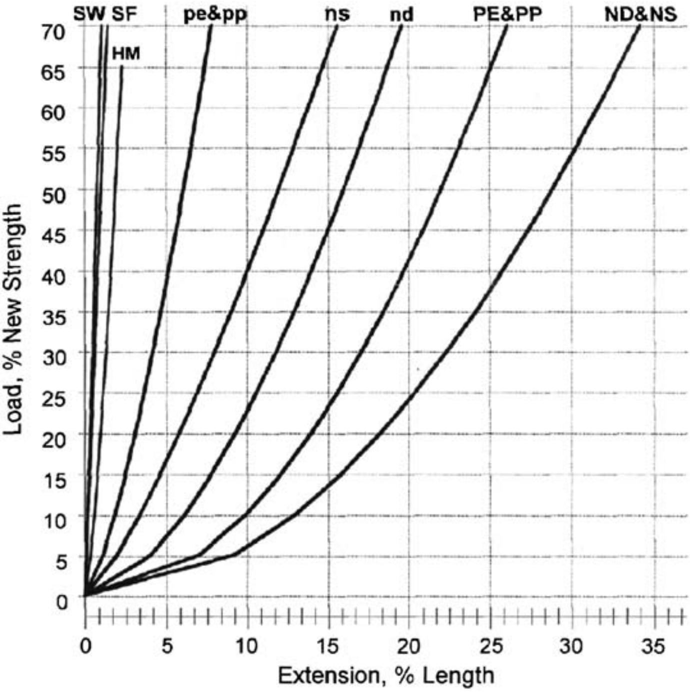


Fig. 3-1. Typical wire and synthetic fiber rope stretch characteristics
Notes: SW = Steel with wire core; SF = Steel with fiber core; HM = HMPE = high modulus polyethylene; pe & pp = broken-in polyester and polyester; PE & PP = new polyester and polypropylene; ns = broken-in nylon 3- and 8-strand; NS = new nylon 3- and 8-strand; nd = broken-in nylon double braid; ND = new nylon double braid
Source: Optimoor User's Guide (2011), reproduced with permission

3.1.2 Fiber Rope

The common fiber rope materials used on ships are nylon (polyamide), polyester, polypropylene, and mixtures of polyester and polypropylene. High-modulus polyethylene, known by tradenames Dyneema and Spectra, is now becoming common.

The common fiber rope constructions used on ships are 3-strand, 8-strand plaited, 12-strand braided, and double braid. These are illustrated in Fig. 3-2.

The stretch properties of the various fiber rope materials differ greatly. Fiber rope construction generally has little effect on stretch characteristics. Typical tension versus stretch curves for the various fiber ropes are shown in Fig. 3-1. Note that most fiber ropes become significantly stiffer and "broken in" in only a few tension cycles, which remove construction stretch. After that, the stretch does not change significantly.

When loaded to 50% of breaking strength, the stretch of broken-in nylon rope typically ranges from 12 to 15% of the broken-in length, depending on the grade of nylon and other factors. At 50% of breaking load, the stretch of both polyester and polypropylene rope is typically about 6%. HMPE (high modulus polyethelene) rope has the least stretch, about 2% at 50% tension. Note that the stretch characteristics of polyester, polypropylene, and nylon are nonlinear.

The strength properties of these various fiber ropes also differ greatly. Nylon and polyester ropes of the same size are about equal in strength. Note that wet nylon rope typically loses about 10% strength.

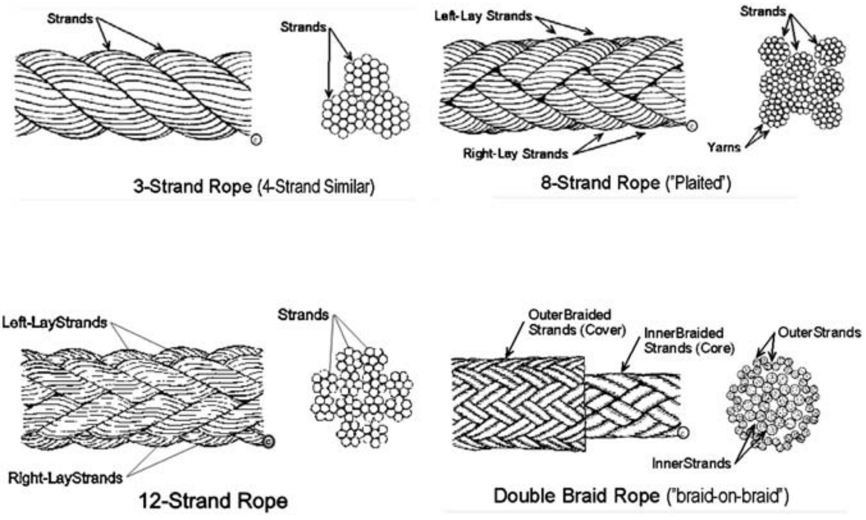


Fig. 3-2. Common fiber rope constructions
Source: Optimoor User's Guide (2011), reproduced with permission

Polypropylene rope is generally weakest, sometimes as low as about 60% of the strength of a polyester rope of the same size. HMPE ropes can be significantly stronger than these, and for that reason, smaller HMPE ropes are typically used. Table 6.4 of OCIMF (2008) summarizes fiber rope strengths. Tables of rope size versus strength for the various fiber ropes can be found in manufacturers' catalogs (accessible on the Internet) and in Cordage Institute or ISO rope standards.

OCIMF recommends that the highest load imposed on polyester, polypropylene, and HMPE mooring lines not exceed 50% of new minimum breaking strength. OCIMF recommends that nylon mooring lines not be loaded above 45% of new minimum breaking strength to account for both wet strength reduction and greater internal wear due to cyclic loading of wet nylon rope.

Selecting the proper rope properties to use in a mooring analysis is generally difficult, except in the rare case in which only a limited fleet of well-documented ships will be berthed. Thus, conducting the analysis using the lowest strength material, polypropylene, may be wise. However, if rope stretch is a concern, then the characteristics of nylon should be used. And if HMPE is known to be used, then its characteristics should be used because of its low stretch.

Short lengths of fiber rope, known as "tails," are sometimes placed in series with wire ropes to provide more stretch in critical applications. The tails are typically of nylon for greater stretch and should be stronger than the mooring line itself. Mooring lines should be fitted with chafe protection at eye ends and where they pass around sharp bends.

3.1.3 Chain

Chain alone is seldom used to moor a ship at a pier. The ship's anchor with chain is sometimes deployed at a pier.

Various grades of chain exist, differing in strength. The most common grade is U3 (or similar designation). Grade U2 is not as strong and is not commonly used.

The stretch characteristic of a chain mooring line is principally due to the catenary effect. The tension versus geometry and stretch characteristics of a catenary is difficult to calculate. Computer programs are available for such calculations; refer to Gaythwaite (2004) for an introduction to the catenary equations. Chain also has an axial stretch characteristic, similar to that of wire rope, which can be significant as the catenary becomes highly loaded.

3.2 FITTINGS AND HARDWARE

Mooring hardware provides the critical interface between the pier structure and ships mooring lines. This section provides an overview of typical mooring hardware, including types and sizes, anchorage requirements and typical locations, materials, rated capacities and safe working loads.

3.2.1 Bollards, Bitts, and Cleats

Dockside bollards, bitts, and cleats of various sizes and configurations are the primary mooring appurtenances. Their purpose is to hold the ship safely and securely in place at the dock. Bollards are typically the largest of these fittings and are sometimes used to aid in berthing by helping to check the vessel's motion. Larger bollards are commonly placed at the extreme ends of a pier or wharf and are sometimes referred to as corner posts. Mooring lines from the ship are secured to the fittings either by placing an eye on the end of the line over the fitting or by wrapping the line around the fitting in a prescribed manner.

Bollards are typically large castings although they may alternatively be fabricated from pipe. They are usually fitted with horns or cross arms to prevent lines from slipping upward and lifting off. There may be horns on each side, oriented parallel to the face of the wharf, or there may be one horn on the back side of the bollard facing away from the pier. Traditional bollards, especially large corner bollards, have bulbous shaped tops, whereas T-head bollards have a large cross arm at the top of the bollard and are preferred where steep vertical line angles are unavoidable. Other proprietary bollard configurations include lobed or "stag horn" bollards that are suitable for steep angles and may accept lines from two ships and kidney-shaped bollards that are suited to warping of vessels (see Fig. 3-3). Typical cast steel bollard capacities vary from about 20 to 225 tons or more. In the United States bollard capacities were traditionally given in short tons, however, today metric tons are commonly used, so the designer should be careful to verify the load rating and the range of line directions allowed.

Bitts are similar to but typically shorter than bollards and consist of one or two cylindrical posts, sometimes with a lip at the top and a base plate at the bottom. Single bitts with a horizontal cross bar are called cruciform bitts. The posts of double bitts are referred to as barrels. The barrels may be vertical or angled. Double bitts typically have capacities from 10 to 100 tons. The designer should be careful to determine whether the capacity refers to the entire bitt or just one barrel, although in general the rated capacity should be the maximum total line pull allowed, either barrel alone should be designed to take the full SWL. This is so because if the line is simply led around one barrel, then to the other and back, and then secured, the load on both barrels will be twice the MBL of the single line.

Cleats are narrow double horn fittings with generally lower capacities than bitts and bollards. They are most often used for smaller vessels such as fishing boats or recreational vessels. In the past they were used on

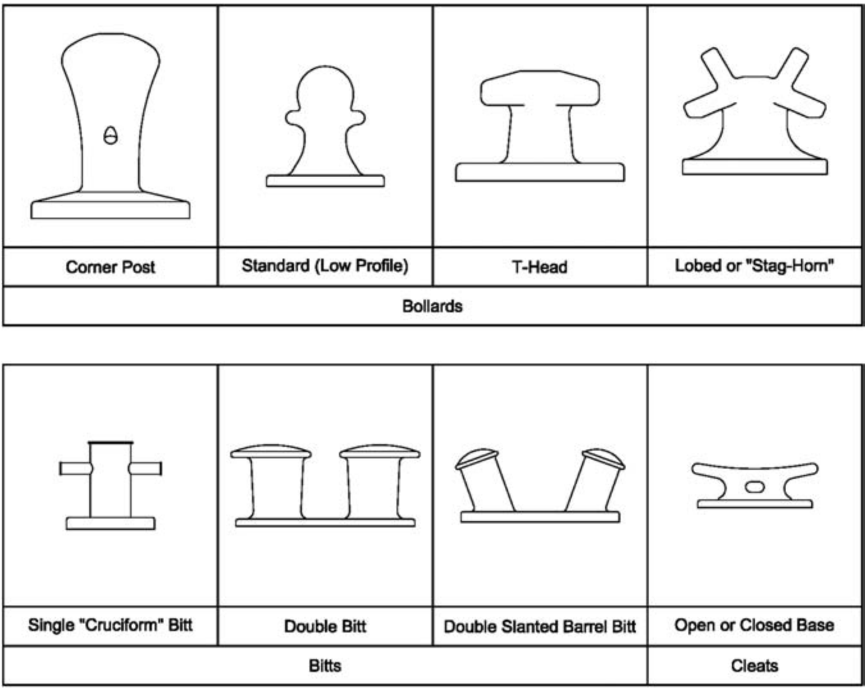


Fig. 3-3. Typical mooring hardware

docks for smaller seagoing vessels than exist today. Cleats are inadequate for large ships. The largest cleat capacities are in the range of 10 to 20 tons. Some are not load rated.

Mooring fittings are usually anchored to the pier by vertical bolts that act in combined shear and tension. The bolts may be cast in place in concrete or sleeved for through bolting, or may be postinstalled by drilling and grouting. Sleeved bolts offer the advantage of future removal for inspection and replacement. The fitting base should preferably be set into the concrete deck for additional shear resistance and be bedded in grout to ensure uniform bearing below its base. Bolt heads should be recessed and protected. Line loads should be assumed to act at the level of the horns or top of the cross arms and be checked for a range of vertical and horizontal lead angles. The load on double bitts without bars or cross arms should be assumed to act at least 1 to 1.2 barrel diameters above the base (OCIMF 2008).

3.2.2 Chocks and Fairleads

Chocks and fairleads are typically used on ships (see Section 3.7) but may be used on shoreside mooring structures as well. Their purpose is to change the direction of a line or to guide a line between points of attachment.

They can be open at the top or closed. Some have roller guides, either horizontally or vertically mounted, which reduce friction and chafing.

3.2.3 Miscellaneous Hardware

Miscellaneous hardware includes pad eyes, rings, pulleys, and other fabrications, such as rubbing strips cast into the deck edge to reduce line chafe. Rounded nose rubbing strips are especially important where mooring lines may lead downward from the pier deck, such as for laden barges at low water at tanker berths. Mooring rings may be set into the face of concrete quaywalls for use by small craft. Shore pulleys may sometimes be employed with wire rope to effectively double the capacity of the wire. Shackles are used to connect wire rope, chain, and pulleys to pad eyes.

3.2.4 Mooring Hardware Location for Piers of Wharves

The spacing of mooring fixtures along the pier face is an important factor in properly securing a vessel. Closer spacing in general allows for a greater range of vessel sizes to be accommodated. A ship should generally be able to use at least four mooring points, and therefore the spacing should be based on the smallest vessel. Mooring hardware is typically located approximately 40 to 80 ft apart along the face of a continuous pier or wharf for ocean-going vessels. Cleats are often located between bitts and bollards to accommodate occasional use by tugs and smaller vessels. Larger bollards are located at the ends of the structure to accommodate heavily loaded bow and stern lines and for snubbing the line to stop the motion of the ship or adjust its position. If a particular class or type of ship is to be berthed at a facility, bollards would be located to fit the optimum mooring arrangement. For extreme storm conditions, storm bollards can be installed about 100 ft or more behind the face of the wharf.

3.2.5 Materials

Fittings and hardware are typically cast from steel, ductile iron, or gray cast iron. Gray cast iron is brittle and may break without warning. It has a lower cost per unit weight but requires a heavier section because of its lower strength. Gray cast iron has good corrosion resistance and may be found in older structures. Most modern bollards are cast from ductile iron, sometimes referred to as spheroidal graphite (SG) iron, which is less brittle than gray iron and has higher strength and greater impact resistance. It also has good corrosion resistance and smooth surface texture that holds coatings well. Material should conform to ASTM A536, Grade 80-55-6 or 65-45-12.

Hardware may alternatively be made of cast steel. Advantages are high strength and high resistance to damage, particularly from impact, because its greater elongation provides a high degree of toughness. Cast steel has a somewhat low cost-to-weight ratio and is amenable to welding for repairs or attachment. The main disadvantage is low corrosion resistance and poor ability to retain coatings so that cast steel needs to be periodically recoated to protect it from corrosion. Cast steel should conform to ASTM A27 Grade 65-35 through Grade 70-40 or Grade A148 through Grade 80-50.

Mooring hardware should have a protective coating with good abrasion resistance. Typical coatings for fittings include a zinc primer with epoxy or polyurethane top coat. A final protective top coating can be applied after installation. Cleats are often supplied hot-dipped galvanized but may also be painted with a protective coating.

Fittings can be surface mounted or set in a recess. The recess helps transfer horizontal forces into the structure and is generally preferred in new structures. Nonshrink grout should be placed below the base for leveling and to ensure uniform bearing. Countersunk bolt holes should be filled with lead or mastic for corrosion protection.

Anchorage hardware can be embedded bolts, with washers or bearing plates within the concrete; through bolts in a sleeve; or drilled and epoxy-grouted anchor bolts. Anchorage through sleeves completely through the structure provides easier future inspection and replacement. Anchor bolts may be specified under ASTM F-1554 with grade depending on tension and shear capacity required. Bolts, nuts, and washers are normally supplied hot-dipped galvanized. Anchorages are typically designed in accordance with the applicable sections of ACI 318-11 and AISC 360-10 building codes and specifications. Adequate embedment depth, edge distances, and local concrete stresses must be ensured.

3.2.6 Load Rating and Safe Working Load

Required capacity of the dock fittings should be determined by a mooring analysis. If an analysis has not been done, then capacities may be based on the size of the ship or on the breaking strength of the lines to be placed on the fitting with some factor of safety, as discussed in Section 2.5. The rated capacity or safe working load (SWL) must then equal or exceed the required capacity. The SWL is determined by standard methods of structural analysis and design with the factors of safety inherent in the design code or standard for the given material. Manufacturers may have their own proprietary standards, which often include test results. The SWL should also be determined over a range of horizontal and vertical angles. Load-rated hardware is often restricted to a vertical angle on the order of 30 to 45° at the SWL, and sometimes reduced capacities are given by the manufacturer for steeper angles. Regardless of the load-rating angle, the anchorage design should consider steeper vertical angles of 45 to 60° due to the possibility of poorly placed mooring lines.

The anchor bolts are thus subject to combined shear and direct tension plus an additional tension resulting from the moment of the load times the height of the load above the base.

Table 3-1 gives dimensions, number of bolts, and working capacities for typical pier fittings used by the U.S. Navy.

3.3 DOCKSIDE EQUIPMENT

Prominent dockside equipment found on piers, wharves, and dolphins include capstans and winches for hauling vessels' lines into position and quick-release mooring hooks typically employed at tanker and gas carrier berths to allow for the immediate release of mooring lines in emergency situations.

3.3.1 Winches and Capstans

Winches and capstans are electrically powered mechanical equipment used for line handling and for drawing the ship up to the dock or moving it along the face of the dock. Dry dock capstans are used to position the ship properly on the blocks prior to dewatering. Capstans typically have a vertical rotating drum, and winches have horizontal drums. Wire lines are stored on the drums of winches. Capstans and winches should have reversing capability and have an appropriate hazard rating suitable for the facility type and exposure.

Winches and capstans are standard equipment aboard ship but are sometimes provided at certain facilities. Refer to the discussion of shipboard equipment in Section 3.7 for further discussion of winches. Capstans are generally used to receive messenger lines from the ship and haul the ship's mooring lines into position. They may be free standing or mounted on quick-release hooks as described in Section 3.3.2. They typically have capacities in the range of 5 to 20 tons and variable haul-in speeds up to around 100 ft/min. Shoreside winches are less common but may be provided for shore augmentation purposes at exposed sites where the facility provides additional storm lines to the ship.

3.3.2 Quick-Release Hooks

Quick-release mooring hooks (QRH) are provided at facilities serving larger ships, such as gas carriers and tankers in particular, to facilitate safety and security in releasing heavily loaded mooring lines quickly. Fig. 3-4 shows a multihook QRH fitted with its own capstan to facilitate line handling. Frequently QRHs are located on isolated dolphins accessible from catwalk trestles and can be activated remotely or at the hook. Hooks can be released by tag lines from the ship to allow a quick

Table 3-1. Size and Capacities of Typical U.S. Navy Pier Fittings

Description	Size	Bolts	Working Capacity (kips)
Special Mooring Bollard "A"	Height = 48 in.; Base 48 × 48 in.	12 × 2.75-in. dia.	Horz. = 660; @45 deg = 430; Nom. = 450
Special Mooring Bollard "B"	Height = 44.5 in.; Base 39 × 39 in.	8 × 2.25-in. dia.	Horz. = 270; @45 deg = 216; Nom. = 200
Large Bollard with Horn	Height = 44.5 in.; Base 39 × 39 in.	4 × 1.75-in. dia.	Horz. = 104; @45 deg = 66; Nom. = 70
Large Double Bitt with Lip	Height = 26 in.; Base 73.5 × 28 in.	10 × 1.75-in. dia.	Nom. = 75*
Low Double Bitt with Lip	Height = 18 in.; Base 57.5 × 21.5 in.	10 × 1.625-in. dia.	Nom. = 60*
42-in. Cleat	Height = 13 in.; Base 26 × 14.25 in.	6 × 1.125-in. dia.	Nom. = 40
30-in. Cleat	Height = 13 in.; Base 16 × 16 in.	4 × 1.125-in. dia.	Nom. = 20

*Working capacity per barrel; after NAVFAC Drawing No. 1404464.

Source: UFC 4-159-03

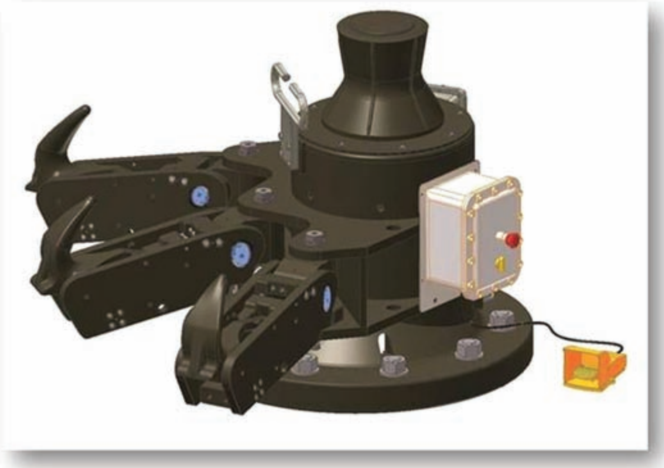


Fig. 3-4. Triple quick-release hook with capstan. Note the line guide for leading messenger line to capstan and remote foot switch
Source: Courtesy of Trelleborg Marine Systems

departure without assistance from the dock crew. Multiple hooks can be provided with typical capacities ranging from 40 to 200 tons per hook and up to around 600 tons or more total. Up to four hooks per unit are standard, but a greater number of hooks can be used. The hooks are swivel mounted to allow the hook to line up with the direction of the load (horizontal and vertical). Hooks can be fitted with load cells for load monitoring as described in Section 3.5.2. QRHs should in general be loaded with only one line per hook (single part). In certain situations, such as may occur at older terminals receiving larger vessels than originally designed for where multiple lines are led to a single hook (not recommended), the total MBL of all the lines should not exceed the SWL of the single hook. Load cells normally measure the hook load and do not measure individual line loads. MOTEMS (2011) requires a minimum of three hooks at breast line locations for vessels $>50{,}000$ DWT and two hooks at breast line locations for vessels $<50{,}000$ DWT at new marine oil terminals. Further description of the sizing and applications of QRHs can be found in BSI (1994) and PIANC (2012b).

3.4 FENDER SYSTEMS

Fenders act as compression members in a mooring system, and their stiffness is important in mooring analysis. Ideally, fenders should have similar stiffness to the mooring lines; inevitable differences result in nonlinear behavior that complicates dynamic mooring analysis. Basically, two general classes of elastomeric fender units are in common use for large vessels:

- Radially loaded hollow-bore cylinders that are initially “soft” at low loads and have reaction forces that go asymptotic once the bore has closed; and
- Axially loaded buckling-column-type units consisting variously of cylinders, cones, arches, and straight leg elements that are initially stiff and absorb large amounts of energy when buckling occurs and the fender deflection increases to a maximum rated capacity without an increase in reaction force.

Other types of fender systems exist, such as traditional timber pile systems, solid rubber extrusions, pneumatic and foam-filled floating fenders, etc. These are well described elsewhere, such as in Brunn (1989), Gaythwaite (2004), and Thoresen (2004) and in fender manufacturers’ product literature and will not be described further herein.

In mooring analysis checking that individual fender loads do not exceed the manufacturer’s rated capacity such that the units are buckled or are fully compressed, which could result in overloading of the pier or mooring structure and/or damage to the vessel’s hull, is extremely important. The fender spacing along the pier face, known as the “pitch,” is important in this regard. Note that the rated fender reaction force is typically used as the basis for design of breasting dolphin-type structures. Buckling-column-type fender units are normally equipped with face panels designed to distribute the fender reaction force in accordance with an allowable hull pressure. Such a unit is illustrated schematically in Fig. 3-5. Note that when buckled, the rubber units may be compressed to 50 to 30% of their original depth, depending on unit type, with slackening of mooring lines a likely consequence. Panel-faced units are often fitted with restraining chains to prevent damage to rubber units under extreme movements. The chains may also limit the panel-face rotation, resulting in nonuniform bearing against the ship’s hull in some instances, which could be problematic in active wave environments.

Allowable hull pressures vary with vessel sizes and types. For larger vessels, including gas and bulk carriers, VLCCs, and post-panamax container ships, these pressures are generally less than around 4,200 psf, whereas for somewhat smaller vessels, including general cargo and oil tankers less than around 60 kDWT, these pressures are generally less than around 6,000 psf but can vary considerably for individual vessels. Cruise ships, ferries, and RO-RO vessels are often fitted with reinforced plating or belting that greatly increases contact pressures, while military and war ships may have extremely low allowable pressures. Information on allowable hull pressures should be obtained from the vessel

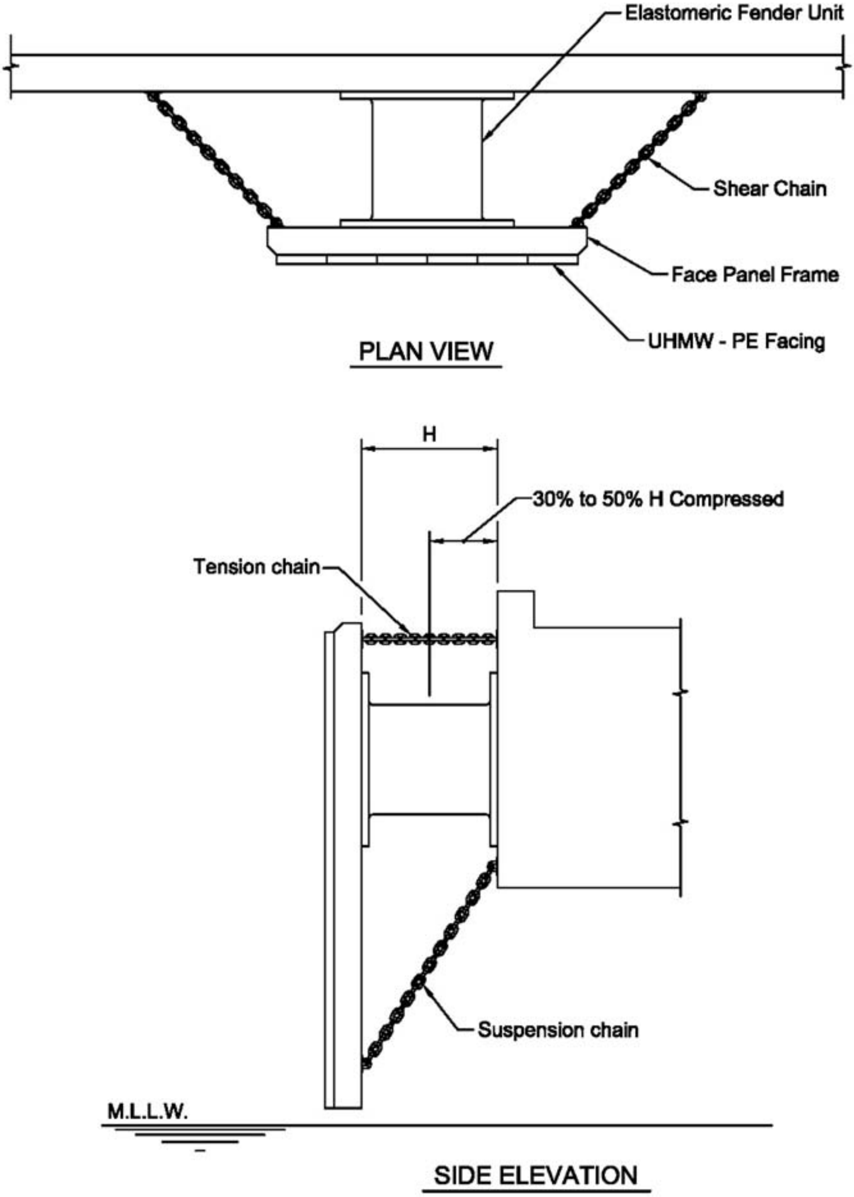


Fig. 3-5. Schematic of typical elastomeric fender unit equipped with face panel and restraining chains
Note: UHMW-PE = ultra high molecular weight polyethylene

owner/operator or naval architect as part of the facility design criteria. Additional discussion of allowable hull pressures on commercial vessels can be found in PIANC (2002) and for military vessels in *UFC 4-152-01*.

Fender face friction is another important aspect of fenders as part of the mooring system. Higher friction helps keep the vessel in position and limit vessel movements and is often favored by pilots and tug crews, whereas lower friction reduces vertical and longitudinal rubbing forces and is usually favored by facility designers and operators. Fender face panels are typically faced with low-friction, replaceable UHMW-PE (ultra-high molecular weight polyethylene) strips or pads. Coefficients of friction for fender face materials in contact with steel range approximately as follows: wood, 0.3 to 1.0; rubber, 0.5 to 1.0; steel, 0.15 to 0.75 with 0.25 more typical for wet steel on steel; and 0.08 to 0.20 for UHMW-PE. The application of fender stiffness and friction in mooring analysis is discussed further in Section 5.1.

3.5 DOCKING AID AND MONITORING SYSTEMS

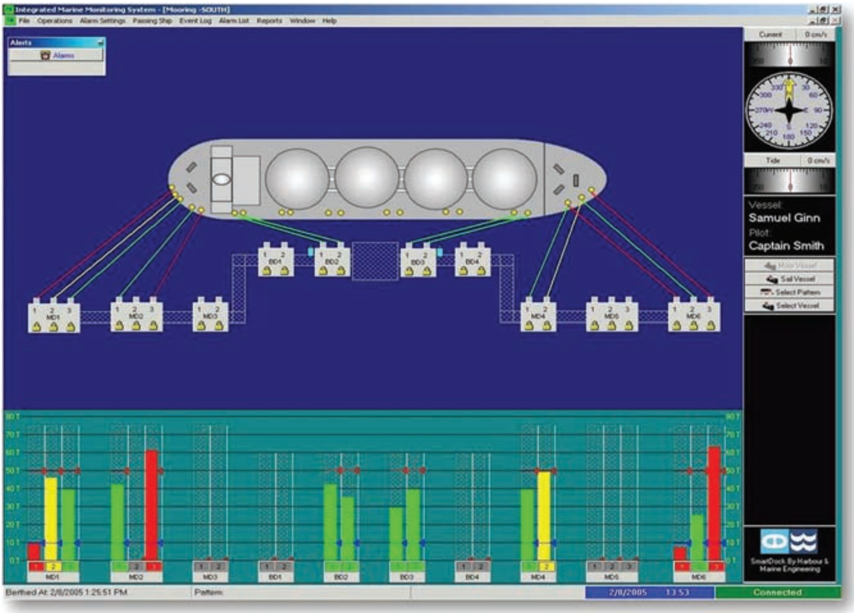
Docking aid and monitoring systems enhance the safety and security of moored vessels and are most commonly employed at facilities for larger vessels and especially those handling hazardous cargo.

3.5.1 Docking Aid Systems

Docking aid systems (DAS) help the pilot approach the dock safely. According to PIANC (2012b), "The DAS may be used to complement a properly designed and engineered berth and can assist with mitigating the risks associated with berthing operations and the potential for damage to fenders or the berth structure" (page 29). Some systems report the speed of the ship as it approaches the berth with a digital display of approach velocity, distance off, and angle with red, yellow, and green lights like a traffic signal. Measurements are typically made by laser devices, although some systems employ differential GPS (DGPS) or real-time kinematic GPS (RTK). A monitor is typically set up at each end of the dock or near the bow and stern of a ship and thus allows measurement of the ship's approach angle as well. These systems can also monitor ship movements while docked.

3.5.2 Line Monitoring Systems

Mooring line load monitoring systems record and continually monitor the line tensions while the vessel is at berth. They are often fitted to quick-release hooks and can be remotely monitored from both ashore and aboard the ship with color-coded graphical display screens. They should also be equipped with high- and low-tension alarms. Monitoring fender



Vessel: Samuel Ginn
Pilot: Captain Smith
Berthed At 2/8/2005 1:25:51 PM
Pattern:
2/8/2005 13:53

Fig. 3-6. Screen shot of mooring line monitoring display showing color-coded line loads at each mooring dolphin
Source: Courtesy of Trelleborg Marine Systems

compression by integrating the DAS system is also possible. Figure 3-6 shows an example screen shot of such a system display.

3.5.3 Environmental Monitoring and Instrumentation

Instruments measuring environmental actions, such as wind, waves, tides, currents, and other weather conditions, can also be integrated into a computer-based monitoring system. This information can also be available to the ship.

Selecting the appropriate instrumentation for a marine terminal is an essential component subsequent to a mooring assessment. The recommendations grow in number and complexity as the mooring and berthing requirements increase. The following is a list of such recommendations:

- For all terminals that require a mooring assessment (i.e., all terminals except small barges), an anemometer is recommended. If a terminal has any sort of wind restriction, the real-time monitoring of wind magnitude and direction is essential.
- If a fender system is suspect and possibly inadequate for the vessel's berthing, either due to larger arrival mass or insufficient energy absorption, a velocity-monitoring system is recommended.

- If the terminal has a history of passing vessel incidents, real-time sway and tension monitoring during transfers is recommended. This can also provide a date stamp as to exactly when an event occurred, and tensions/sway can be recorded.
- If the terminal is not in a port and current velocities are greater than 1.5 knots and vary in direction, a recording current meter is recommended.
- For terminals located in open waters or semiexposed locations, a wave measurement sensor is recommended.
- Where a terminal is located in a region subject to high tidal variations, a water level and tide sensor is recommended.
- For new VLCC or ULCC terminals, a full suite of instrumentation including all of the above and two large scoreboards to indicate approach velocities fore and aft are recommended. If the terminal is within a port with current velocities less than 1 knot, a current meter would not be necessary.
- For LNG terminals, following industry best practice, a full suite of instrumentation is recommended.

3.6 MECHANICAL AND AUTOMATED MOORING SYSTEMS

Not all mooring systems use mooring lines. Permanent moorings in particular, such as floating dry docks (FDD) and others mentioned in Section 1.5, may be “rigidly” moored by spuds or gripper arms, and small craft and pontoons may be moored by traditional pile and hoop arrangements such as those found in marinas. Spuds may consist of driven W- or H-pile sections that are supported by the pier structure near their tops and are engaged by grippers that slide up and down freely. Longitudinal loads are sometimes taken by shear spuds if the W or H sections are not strong enough. Spuds may alternatively be secured to the FDD or pontoon with the grippers fixed to the shore mooring structure. Another alternative is to employ articulated mooring arms fixed to the pier face or mooring dolphins at two or more locations that engage T sections mounted on the FDD or pontoon. Such systems clearly must be designed to accommodate the operational trim and list of the FDD or pontoon and are subject to long-term wear and fatigue. The design of such systems is outside of the scope of this manual.

Other, proprietary “semirigid” type mooring systems use vacuum pads to hold the ship in place at the wharf or pier and are applicable to semisheltered port environments. Vertical movement and horizontal movement perpendicular to the structure are allowed by an articulated frame that supports the vacuum pads. The overall capacity of the mooring system can be increased by adding mooring points and vacuum pads at various mooring stations. Such a system has been developed by Cavotec of Christchurch, New Zealand. As such systems are proprietary, the manufacturer must be contacted for specific details and information. A dynamic analysis of a container ship moored in waves by such Moormaster units is reported by de Bont et al. (2010).

3.7 SHIPBOARD EQUIPMENT

The mooring line arrangement for a given vessel is ultimately restricted by the number and locations of the vessel's fittings and equipment. Mooring lines are secured on board the vessel in one of three basic ways:

- Made fast directly to mooring hardware;
- Wrapped around the drum of a winch and held by a winch brake; and
- Wrapped around the drum of a self-tensioning winch at some preset tension.

Lines may be secured directly to bitts and/or cleats after being led through chocks or fairleads along the vessels sides. Chocks may be either open or closed, and fairleads are typically fitted with rollers to redirect the line where abrupt changes in direction are required. Lines are typically hauled into position by capstans and "stoppered" so that they can be "turned up," most usually on double bitts on larger vessels.

Lines may alternatively be hauled into place using winches equipped with brakes to hold them in place. The brake's maximum holding capacity with only a single layer of line around the winch barrel is known as its rated brake holding capacity and is required to be 80% MBL per ISO 3730:2012. Additional turns of line on the barrel effectively reduce the holding capacity of single drum winches to 50 to 60% MBL (Clark 2009). Split drum winches overcome this difficulty by providing a separate haul-in tension drum and spooling/storage drum so that they can be loaded to the full 80% MBL.

Larger vessels may be equipped with self-tensioning type winches that can be set to maintain a constant line tension. Such winches should have a suitable "dead band" range of tension over which it will neither pay out nor haul in to preclude excessive responses to slight changes in loadings. ISO standards require that the maximum set pay-out load not exceed 50% MBL and the minimum pick-up haul-in load to be 50% of the rated capacity. Self-tensioning winches work well when pretensioned against compressed fenders under somewhat steady load conditions; however, under certain circumstances, such as increasing winds and/or longitudinal forces, they may be problematic. For these reasons the use of self-tensioning winches is prohibited at most oil, chemical, and LNG terminals. They are in common use, however, at containership and car carrier facilities. Clark (2009) and OCIMF (2008) provide detailed description of shipboard equipment and its use.

Although ISO has standards for mooring hardware and equipment that is referenced by OCIMF (2008), most vessel classification societies do not include such requirements. They do provide recommendations for mooring lines based on the International Association of Classification Societies' guidelines (IACS 2007). The number, length, and MBL of the lines to be carried by a given vessel are based on an "equipment number" calculated from a formula based on the vessel's principal dimensions. For example, a typical 20 kDWT vessel would be required to carry a minimum of five 200-m long lines with an MBL = 420 kN (94.4 kips) and a 150 kDWT vessel would require eight 200-m long lines with a minimum MBL = 685 kN (154 kips). IACS (2007) has additional criteria for the lines themselves.

CHAPTER 4

FORCES ON MOORED VESSELS

4.1 GENERAL CONSIDERATIONS

Loads on moored vessels arise from the following sources:

- Wind
- Current
- Passing vessel effects
- Wave action
- Water level and draft changes
- Operations and movements at berth
- Ice

4.1.1 Mooring Loads and Vessel Motions

Wind and current forces are by far the most common and universal to be designed for. They are typically treated as static forces associated with steady flow and hence controlled by fluid velocities. However, unsteady or turbulent flow is prominent in some instances, and thus fluid accelerations must also be considered, usually requiring a more elaborate dynamic analysis. Wave action can be divided into primary forces that are proportional to the wave height (H) where the vessel responds dynamically at the wave frequency and secondary "drift forces" that are proportional to H squared. The drift force is somewhat small in magnitude but can vary slowly over time and, in some circumstances, may excite a dynamic response of the mooring system due to subharmonic resonance with the mooring system stiffness, hence also requiring dynamic analysis. Hydrodynamic and aerodynamic forces in general result from the difference in pressure distribution around the

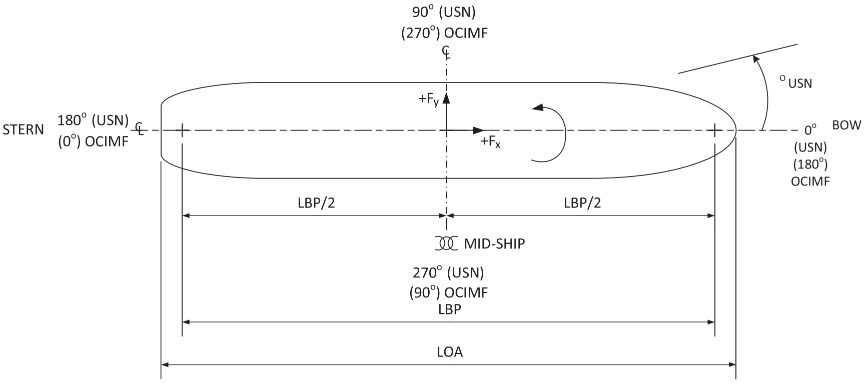


Fig. 4-1. Wind and current forces and moment coordinate systems and sign conventions

entrained body, or moored vessel, due to flow separation and surface friction in the case of velocity forces and inertial effects in the case of acceleration forces. Wave-making resistance at the air-water interface may also be a factor under certain circumstances. The resulting forces acting on the vessel are normally resolved into lateral and longitudinal directional components plus a yaw moment typically assumed to act about the vessel's center of gravity. Alternatively, the yaw moment can be accounted for by applying component lateral forces at the vessel's fore and aft perpendiculars. Fig. 4-1 illustrates the coordinate systems and sign conventions normally used in mooring analysis. Care should always be taken to verify the reference direction for 0° as it may start at bow or stern depending on the source, and the moment may be positive clockwise or counterclockwise. Always keep in mind that for a freely floating, unrestrained body, these forces are mostly inconsequential. Mooring forces are hence the result of the mooring system restraint. Accordingly, the vessel's motions or the movements that would occur in the absence of mooring system restraint are central to resolving the forces. This is also true for water level and draft changes and the resulting change in mooring line geometry as the vessel moves vertically relative to the fixed berth structure.

A free-floating vessel has six degrees of motional freedom: three translational and three rotational. Movement in the fore and aft direction along the vessel's longitudinal centerline is termed "surge," in the lateral side-to-side direction as "sway," and vertically as "heave" (Fig. 4-2). Rotation about a vertical z-axis through the vessel's center of gravity, cg, is termed "yaw," about its longitudinal y-axis as "roll," and about its lateral y-axis as "pitch." Heave, pitch, and roll motions have gravity as a restoring force and have natural periods associated with buoyancy. Surge, sway, and yaw have no natural restoring forces and hence have periods associated with the "stiffness" of the mooring system and are of primary

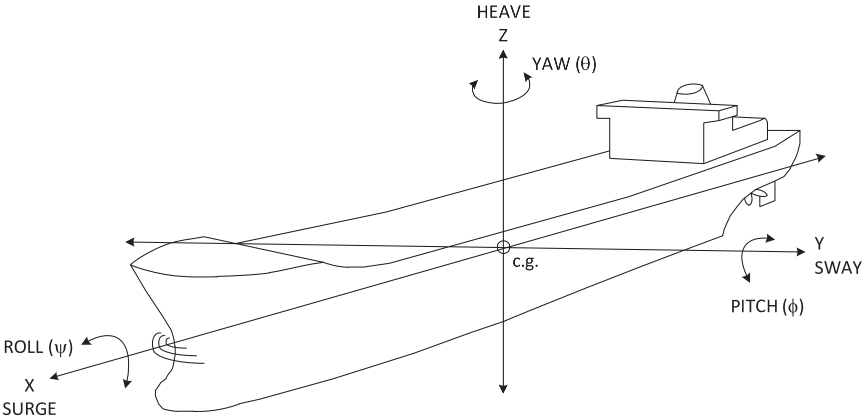


Fig. 4-2. Vessel motion definitions

importance in mooring system analysis and design. Environmental disturbing forces occur over a broad spectrum of frequencies and may excite any of the described responses selectively or in a "coupled" mode. For a freely floating vessel surge, sway, and yaw and heave, pitch, and roll may be coupled separately, whereas for a moored vessel all modes are coupled to some degree. A static or quasistatic mooring analysis typically considers only three degree of freedom (DOF)—surge, sway, and yaw—whereas dynamic analysis necessarily considers all six DOF and coupling. An in-depth treatment of hydrodynamic forces on ships and floating structures can be found in Faltinsen (1990) and Newman (1977).

4.1.2 Traditional Approach to Pier Mooring Design

The traditional approach to designing piers and wharves for vessel mooring forces and sizing and locating mooring hardware has been to apply minimum presumptive loads and bollards, bitts, and cleats of prescribed capacity at given spacing. This approach has some merit when the range of sizes and types of vessels to be accommodated is uncertain, and the largest vessels expected are generally less than around 20,000 mt displacement. Earlier editions of the U.S. Navy design manuals, NAVFAC (1971) for example, required minimum presumptive mooring loads ranging from 1 kilo-pound per lineal foot (klf) for destroyer piers up to 2.5 klf for aircraft carrier facilities to be applied horizontally at deck level. BSI (1994, 2000) provide tabulated values of minimum bollard capacities to be spaced at 15 to 30 m along the pier face from 10.2 up to 102 mt for vessels from 2,000 to 20,000 mt loaded displacement. For vessels with a loaded displacement greater than 20,000 mt a mooring analysis is required. Another simplified approach is to calculate the sum of the environmental forces and assume an unequal distribution to the mooring fixtures. According to BSI (1994), for a vessel moored to four points one-half of the total should be assumed to act at any single point, and for a vessel moored at six points one-third of the total should be assumed to act at any single point. Whereas the aforementioned rules of thumb are perhaps useful for preliminary estimates and quick checks, contemporary practice is to determine the maximum environmental loads likely to occur with the design vessel at berth and to conduct a mooring analysis to determine the load distribution to mooring points and overall pier structure.

4.2 WIND FORCES

Wind is omnipresent and an important source of mooring forces at virtually all marine facilities. Hence, it is essential to understand the nature of wind loads on moored vessels and how to calculate and apply such forces in a mooring analysis.

4.2.1 Wind Forces and Moments

Wind is an important factor in virtually all mooring force analyses. Wind is commonly treated as steady-state static force and calculated using the well-known drag force equation:

$$F_w = \frac{\rho}{2} C_d V_w^2 A \tag{4-1}$$

where
F_w = wind force,
ρ = mass density,
C_d = drag coefficient assumed to account for both friction and form drag,
V_w = the wind speed, and
A = the projected area normal to the wind direction.

For air at standard temperature of 59° F and sea-level pressure of 1,013.2 mbar, the unit weight = 0.0765 pcf and for V_w in knots Eq. (4-1) reduces to

$$F_w = 0.0034 C_d V_w^2 A$$

Note that air density increases linearly with decreasing temperature with a resulting increase of nearly 13% at 0° F, which should be accounted for at cold region sites. The problem of calculating the wind force then reduces to one of determining the proper drag force coefficient and of applying appropriate corrections to V_w for duration and height.

Wind force calculations are normally carried out by resolving the force into lateral and longitudinal components plus a yaw moment, all of which vary with the angle of attack θ relative to the vessel's longitudinal axis.

The longitudinal and lateral force components are determined by applying an overall drag force coefficient, C_{dx} and C_{dy} respectively, to the general drag force formula. The yaw moment is determined by applying a yaw moment coefficient, C_{ym}, to the lateral force, F_{wy}, times the vessel's length, which may be either LOA, LWL, or most usually LBP depending on how the coefficients were determined. Note that $C_{ym} \times \text{LBP}$ represents an eccentricity, e, about the vessel's center of rotation times the lateral force. The following equations then can be used to determine the total wind force and moment acting on a moored vessel:

$$F_{wx} = 0.0034 C_{dx} V_w^2 A_x \tag{4-2}$$

$$F_{wy} = 0.0034 C_{dy} V_w^2 A_y \tag{4-3}$$

$$M_{whm} = F_{wy} C_{wym} \text{LBP} \tag{4-4}$$

Drag coefficients depend on the vessel's shape, orientation to flow, surface roughness, and boundary conditions, and to a lesser degree on the nondimensional Reynolds number (R) as in most all cases of interest R remains soundly within the turbulent flow regime. The Reynolds number expresses the ratio of inertia to friction forces and is defined in any fluid mechanics text. Wind force drag coefficients have been determined experimentally for many representative vessel types and can be found in the referenced literature for selected vessel types. Figure 4-3 shows a generic plot of wind force and moment coefficients for a representative but hypothetical vessel. Note that care must be taken in applying coefficients as to the sign convention and coordinate system used. Also note that the maximum lateral and longitudinal forces may not occur exactly at 90° and 0/180°, respectively, for a given vessel. Typical ranges of C_{wx}, wind ahead or wind from astern, are approximately 0.4–1.2 with 0.7 to 0.9 being most representative. Note that variation typically exists between wind ahead and astern conditions, and in particular for vessels such as tankers and bulk carriers with accommodations aft the wind force from ahead is typically greater than from astern. Another curious phenomenon that can be noted from the OCIMF 2008 is that for tankers with cylindrical bows and for wind angles of around 60 to 80° from the bow a forward (directed toward the wind) force component also acts to pull the bow laterally away from the wind. A typical range of C_{wy}, wind abeam, is approximately 0.6–1.4, with 0.8 to 1.0 being most representative (Gaythwaite 2004). For typical vessels the maxima occurs at $\theta = 90\,\text{deg}$. However, for box-like vessels, such as ferries and car carriers and floating dry docks, two maxima typically occur at around $\theta = 45$–60 and 120–135°. Values of M_{ym} typically range from 0.05 to 0.15 with maxima between approximately $\theta = 30$–60 and 120–150°. OCIMF (2008) gives wind and current force coefficients for tankers

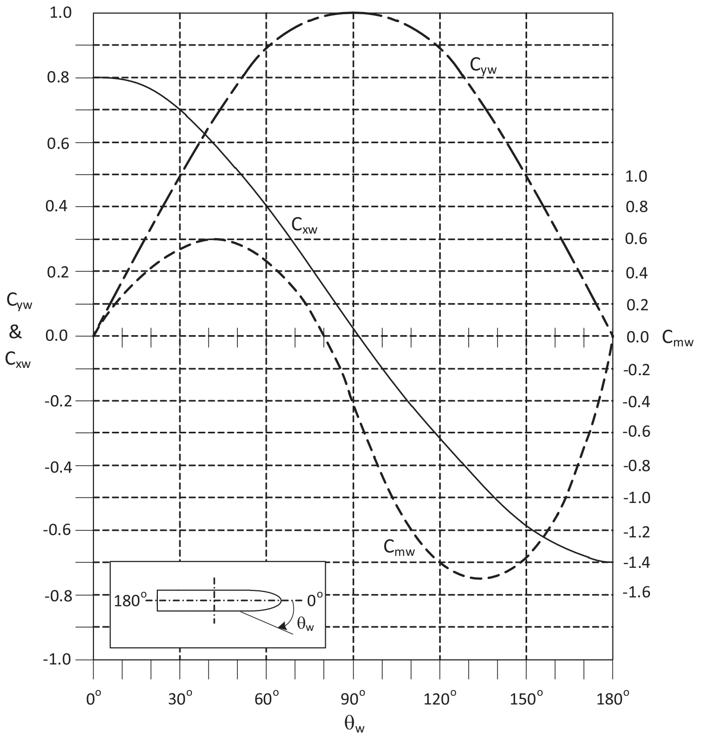


Fig. 4-3. Generic wind force and moment coefficients for a hypothetical vessel. Note that for any given vessel the peak values and locations of zero crossings may vary as described in the text

(also applicable to many large bulk carriers) and for LNG vessels and provides guidance for mooring load calculations and recommended design criteria for shipboard equipment as introduced in Chapter 2. *UFC 4-159* gives wind and current force coefficients for many U.S. naval vessels that may apply to many commercial vessels as well. This document also provides detailed design guidance for mooring load analysis. BSI (2000) provides generic wind and current coefficients for containerships, dry cargo vessels, and tankers, and Rice and Seelig (2010) report recent wind tunnel–derived coefficients for cruise ships of various configurations. Additional references and sources of wind and current coefficients can be found in Gaythwaite (2004).

Fig. 4-4 shows an example of wind forces and moments versus wind direction for a moored floating dry dock (FDD) with a Navy auxiliary vessel in dock calculated using the *UFC 4-159-03* methodology. NAVFAC requires that force coefficients appropriate for the docked vessel be used when docked

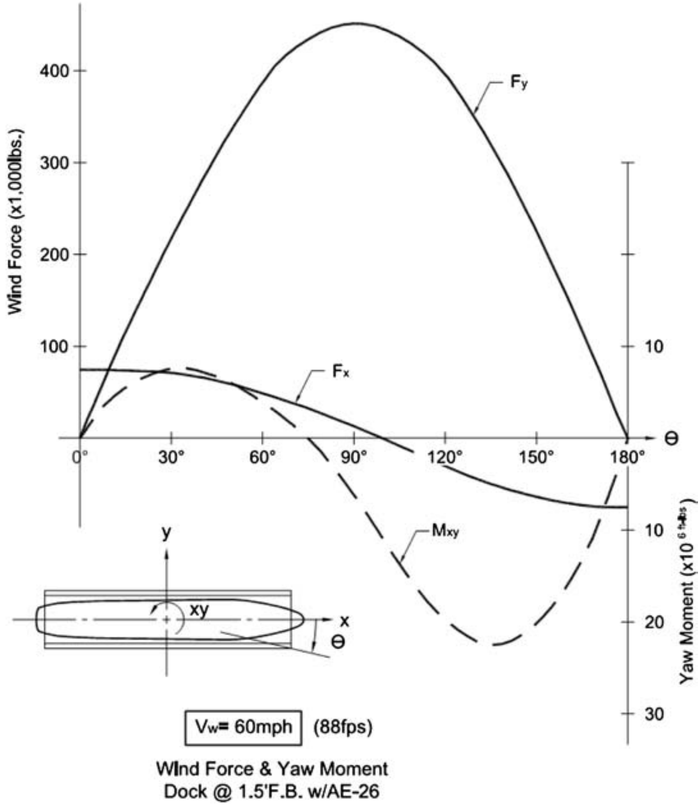


Fig. 4-4. Example wind force and moment on moored floating dry dock with naval auxiliary versus angle of attack

inside an FDD. Fig. 4-5 shows a plan and elevation of this arrangement. As the entire vessel is elevated above the water level, the exposed area of the vessel above and outside of the FDD walls must be added to the FDD area and corrected for elevation as described in Section 4.2.2.

Fig. 4-6 shows an example plot of wind forces on a representative tanker in ballast condition. In this example the yaw moment is accounted for by presenting component forces at the forward and aft perpendiculars. The relationship of these forces to the yaw moment is given by

$$Ffp \text{ and } Fap = F_y/2 \pm M_{ym}/\text{LBP} \tag{4-5}$$

Information on projected areas for specific vessels may be difficult to find and may be estimated from general arrangement plans when available. PIANC (2002) provides tables with wind areas for generic vessel types of varying size ranges within specified confidence limits useful for design of

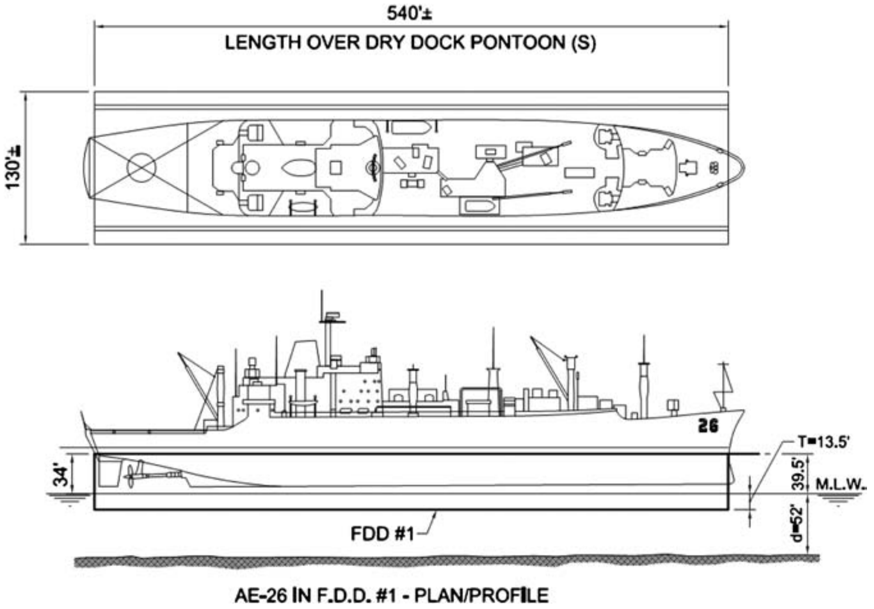


Fig. 4-5. Auxiliary vessel in floating dry dock for example wind and current forces

facilities that must accommodate many vessel sizes and/or types, and Gaythwaite (2004) and Thoreson (2004) provide information for representative vessel types. Wind forces and moments may also be determined directly from scale model tests, an example of which is shown in Figure 4-7 for a 1:198 scale model aircraft carrier. Care must be taken to carefully observe scaling laws (see Section 5.4) when applying such results to similar vessel types of different size.

For multiple rafted vessels and vessels moored on opposite sides of a somewhat narrow pier shielding effects may reduce the wind forces on the downwind-shielded vessel. Although traditionally reduction factors of 20 to 50% have been applied somewhat arbitrarily, the relative sizes of the vessels and their separation distance may have a profound and sometimes counterintuitive effect that can be best predicted by physical model tests or fluid dynamic modeling. Seelig (1997) provides design guidance for various cases of two to four rafted vessels and for two vessels on opposite sides of a pier with varying separation distance. One interesting result is that for the case of two closely moored similar vessels subject to a beam wind the lateral force is actually less than for a single vessel. The force increases rapidly, however, as does the yaw moment with angle of attack to the vessels beyond normal. The longitudinal force

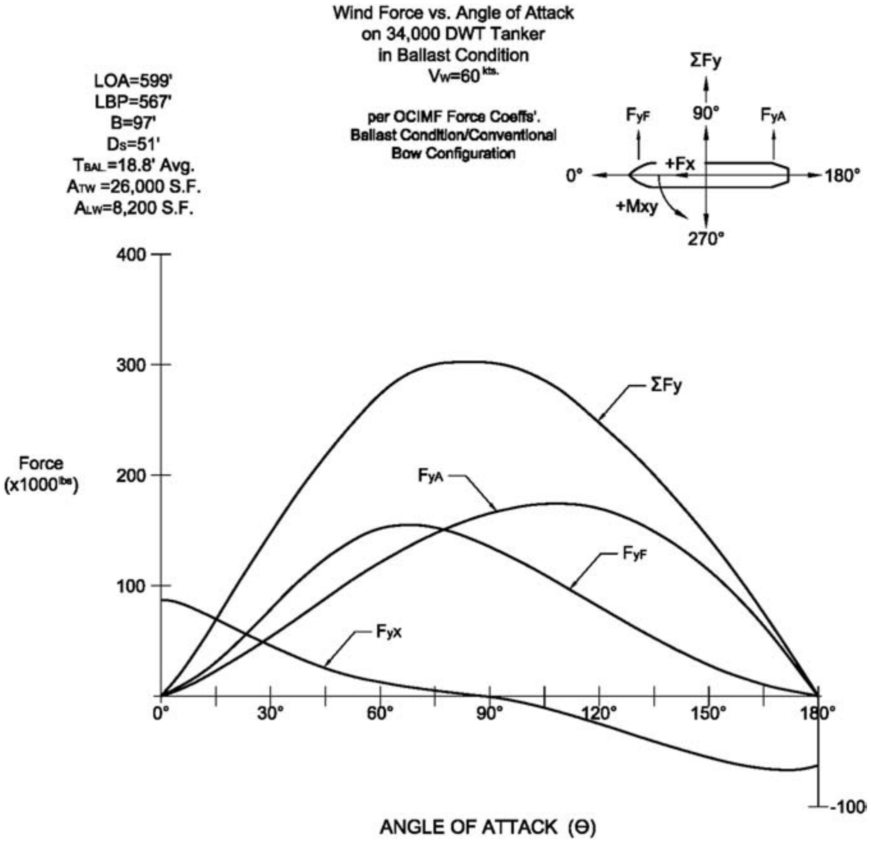


Fig. 4-6. Example wind force versus angle of attack on ballasted 34 kDWT tanker with forces reported at fore and aft perpendiculars instead of yaw moment

on nested multiple vessels can safely be taken as the sum of the individual vessels.

The lateral wind force causes a vessel to list away from the wind direction by inducing a heeling moment related to the restoring moment, M_{whm}, as given by

$$M_{whm} = F_{wy}h = \Delta GM \mathrm{Sin}\psi \tag{4-6}$$

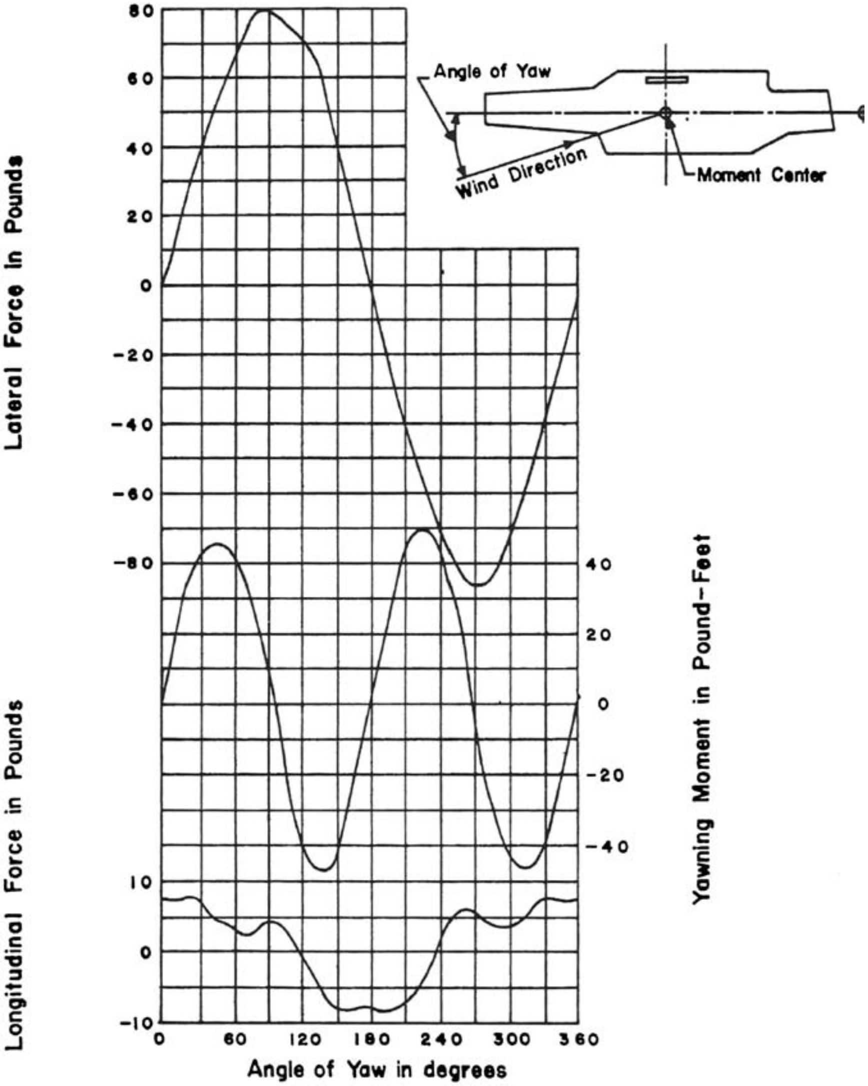
where

h = the vertical distance from the center of lateral resistance below the waterline to the center of wind pressure on the superstructure,

Δ = the vessel displacement,

GM = the transverse metacentric height, and

ψ = the angle of heel.



GRAPH 39

Variation of lateral force, yawing moment and longitudinal force with angle of yaw for a single 1:198-scale model Forrestal class aircraft-CVA 59: wind speed 126 knots; moment center at center of model.

Fig. 4-7. Wind forces and moments on aircraft carrier from wind tunnel scaled model test results
Source: NAVFAC (1968)

GM is a measure of a vessel's stability in terms of its righting moment arm at small angles of heel, as described in any naval architecture text, and must be obtained from the vessel's designers. The moment to trim or list 1 in. (MTI and MLI respectively) at a given draft can also be provided by the designer when required. They are usually presented on hydrostatic stability curves.

Although the heeling moment is not normally included in most mooring analyses, it may be important for vessels with high superstructures and can be readily included in computer programs.

4.2.2 Wind Speed Corrections

Wind speed data must often be corrected for duration. As long-term maximum wind speed data are often presented as short-duration gusts, such as the 3-s gust in ASCE (2010) as adopted by most building codes, the data must be corrected to a minimum gust length and duration capable of overcoming the vessel's inertia and fully mobilizing the drag force. Minimum gust durations of 20 to 60 s are required to develop design level forces on larger tankers. BSI 2000 recommends a 60-s gust duration, which it gives as 85% of the 3-s gust. The EAU 2004 calls for a typical 30-s gust and for 60 s for vessels >50 kDWT. The Spanish ROM 1990 standard recommends a 15-s gust duration for vessels <25 m LOA and a 60-s gust for LOA > 25 m and provides criteria for converting from a 10-min sustained wind speed. The industry consensus in the United States seems to be 30 s as adopted by *UFC 4-159*, OCIMF (2008), and MOTEMS (2011).

Wind speed increases exponentially with height within the atmospheric boundary layer in accordance with the following relationship:

$$V_w(z) = V_{(\mathrm{ref})}\left(\frac{z}{h}\right)^n \tag{4-7}$$

where

$V(z)$ = the wind speed at elevation z above the surface;

$V_{(\mathrm{ref})}$ = the reference elevation or anemometer height h at which the design wind speed was reported, usually taken as 10 m = 33 ft; and

n = an exponent usually taken as $1/7$ (typical for open terrain near the ocean) but may vary from $1/9$ to $1/10$ over the open ocean.

The wind speed at the 33-ft reference height is often applied as the average over the height of the superstructure and can be considered as conservative when superstructure heights do not exceed approximately 50 to 60 ft above the waterline. However, for vessels such as cruise ships and others with very high superstructures, this correction can be important. *UFC 4-159* includes a methodology to account for the vertical distribution of wind with height over vessels with nonuniform superstructure heights. At many inland and highly developed port locations the proximity of buildings and local terrain effects may be important, especially for winds from a particular direction. ASCE (2010) provides guidance for such cases.

4.2.3 Dynamic Wind Loads

Although in most instances wind can be treated as a static or quasistatic load, under certain conditions the unsteady nature of the wind, i.e., turbulence or "gustiness," may generate dynamic loads that greatly exceed those of a steady wind speed. Dynamic analysis is essential for free-swinging, buoy type moorings and is typically called for at fixed moorings subject to extreme winds such as hurricanes and erratic sudden winds such as thunderstorm "gust fronts" and at high-risk exposed sites such as LNG terminals. Wind speed variations may excite the low-frequency motions of large moored vessels similar to the low-frequency response to wave drift forces (Feikema and Wichers 1991) as described in Section 4.5. Wind gusts and turbulence are accounted for by wind energy density spectra normally applied in concert with some mean wind speed such as the mean hourly wind. Various spectral formats are available. The Davenport spectrum, originally developed for building structures and modified by Harris (1971), may be suitable for in-harbor applications. The Ochi-Shin spectrum (1988) was developed for offshore structures and may be more suitable at exposed locations. It gives higher energy at lower frequencies within the range of natural periods of large moored vessels. Many other spectral formats may be more suitable for specific applications. Further description of wind spectra is beyond the scope of this manual. The reader is referred to Simiu and Scanlan (1996) for in-depth treatment of wind spectra and Feikema and Wichers (1991), de Kat and Wichers (1991), and Forristal (1988) for their application to moored vessels. Section 5.2.3 includes an example dynamic analysis of an LNG vessel moored pier side including wind spectra.

4.3 CURRENT FORCES

Current, the horizontal flow of water, is present at many sites, and current forces are additive to wind forces and may exceed wind forces in some instances. Current forces are dramatically affected by vessel draft to water depth ratio and may create vessel "standoff" forces and other local effects that must be understood to conduct a proper mooring analysis.

4.3.1 Current Forces and Moments

Current forces are normally calculated using the drag force equation, Eq. (4-1), similar to wind forces in most instances. The unit weight of water, however, is 840 times greater than air, and is 62.4 pcf for freshwater and around 64 pcf for sea water depending on salinity and temperature.

Accordingly, for a steady current speed in knots, Eqs. (4-2) through (4-4) become in foot pound units

$$F_{cx} = 2.85C_{cx}U_c^2A_x \tag{4-8}$$

$$F_{cy} = 2.85C_{cy}U_c^2A_y \tag{4-9}$$

$$M_{cym} = F_{cym}C_{cym}\mathrm{LBP} \tag{4-10}$$

In these equations, U_c is the average current over the vessel's draft and the coefficients are a function of the water depth to draft (d/T) ratio. Force and moment coefficients for currents are less certain than for wind because, although generally still within the turbulent flow regime, the Reynolds number is near the transition zone, especially for the largest vessels at low current velocities, resulting in a wider scatter in the experimental data. In deep water the longitudinal force coefficient, C_{cx}, ranges from 0.1 to 0.6 with 0.15–0.4 being more typical. The lateral force coefficient, C_{cy}, is typically in the range of 0.8 to 1.0 with an extreme range of 0.5–1.5. The yaw moment coefficient, C_{cym}, is typically within the range of 0.05–0.10. Typical deep water ranges of the current force and moment coefficients are similar in shape to the wind coefficients shown in Fig. 4-3; however, the effects of d/T are highly variable and in some cases extreme so that relying on generic data or an assumed curve shape is generally not advisable. Fig. 4-8 shows an example current force on the moored FDD shown in Fig. 4-5 and used in the wind force example. Note that, as for wind, the maximum longitudinal and lateral force may not occur exactly for currents directly from ahead, from astern, or from abeam. In fact, the maximum longitudinal force typically occurs with currents from around 25° from the bow. Current forces are also affected by the vessel's trim and load condition. Yaw moments in particular increase for tankers in ballast condition, typically with a large amount of trim. OCIMF 1994 are based on model tests at 0.8 deg trim and may need correction if actual trim exceeds around 1°. These tests were also conducted with models having length to beam ratios, LBP/B, of 6.3 to 6.5 and may need correction for vessels much outside this range. Note that some contemporary tankers may have an LBP/B as low as 5.0, which may result in an increase of longitudinal force of 25 to 30% at angles of attack up to 15° or more. For a fully loaded tanker with a bulbous bow in shallow water, $d/T = 1.1$, and currents between 10 to 33° from the bow, the OCIMF 1994 show a forward-directed component of longitudinal force, due to low pressure in the vicinity of the bulbous bow.

The lateral force is especially sensitive to d/T, ranging from a minimum value of $d/T \geq 6$ for "deep water" to approximately five times the minimum value at $d/T = 1.1$. Figure 4-9 illustrates this effect. It is very important to note from these curves the very steep rise in lateral force, even with the current nearly end on, which is especially acute at low d/T. For this reason the designer should never assume that the current is

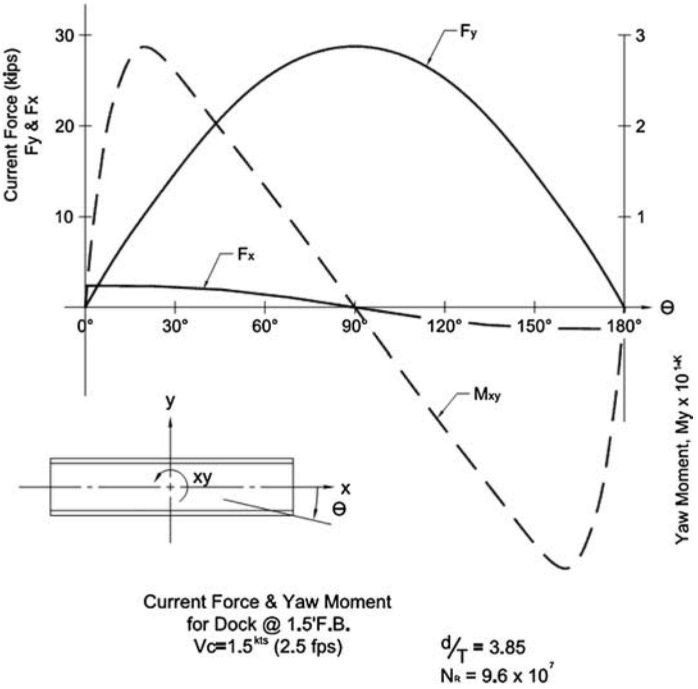


Fig. 4-8. Example current forces and moment on moored floating dry dock

exactly end on and that the lateral component is zero. A margin of at least 15° is generally recommended to allow for current variability and uncertainty. The curves in this figure were based in part on model tests conducted under the auspices of the OCIMF between 1968 and 1977 and later drawn and published by NAVSEA (1987). Full-scale measurements conducted on a moored tanker and destroyer as reported by Palo (1983) showed that lateral force coefficients are somewhat insensitive to hull shape but show a significant dependence on the vertical distribution of current velocity or "current shear." Seelig et al. (1992) provide a simplified method for calculating the lateral force coefficient based on model test data from the U.S. Naval Academy and adopted by the *UFC 4-159*.

Tidal currents generally exhibit a typical boundary layer-type flow profile, and assuming a 1/7 law, vertical velocity profile similar to wind is common practice so that the current velocity at any depth is given by

$$U_{(z)} = U_s\left(\frac{z}{d}\right)^{1/7} \tag{4-11}$$

where z is measured upward from the bottom and U_s = the maximum current at the surface. Therefore, assuming the maximum value of the

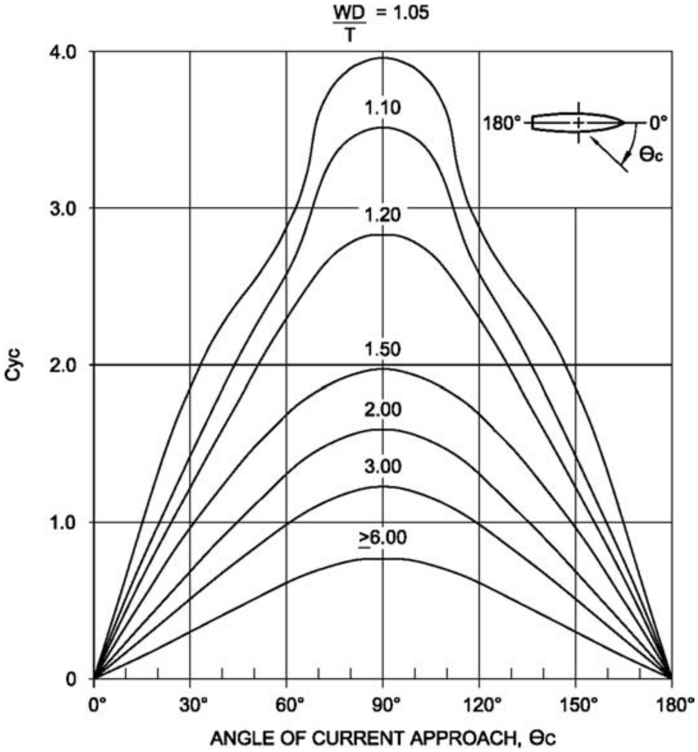


Fig. 4-9. Lateral current force coefficient for varying d/T
Source: NAVSEA (1987)

current is uniformly distributed over the vessel's draft is generally conservative, if the current is confirmed as the surface/maximum value. The actual vertical and horizontal distribution may vary at a given site and among sites. The velocity can be affected by wind, and in general it varies in strength in rough proportion to the tide range.

The averaged squared velocity of the current over a vessel's draft can be found from

$$U_c^2 = \frac{1}{T}\int_o^T (U_z^2) d_z \tag{4-12}$$

where U_z is the current velocity at depth z. In this case, z is measured upward from the ship's keel. Refer to Fig. 4-10.

The longitudinal force component is primarily due to surface friction drag, and although many sources still apply, a single overall form drag coefficient the surface drag or "skin friction" can be calculated separately as well. The U.S. Navy per *UFC 4-159* adds the form drag and friction drag

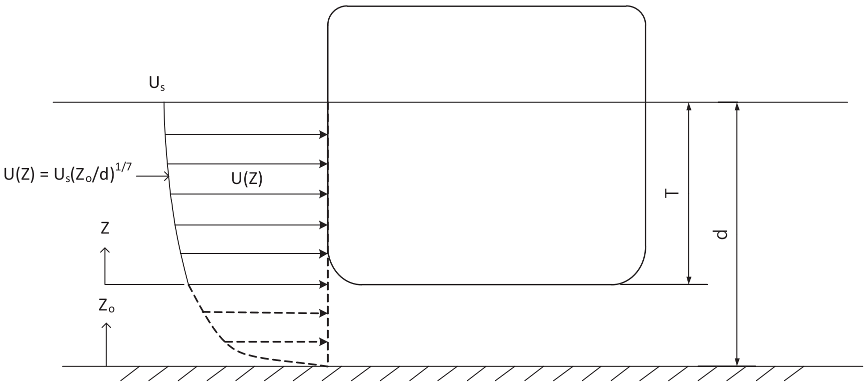


Fig. 4-10. Vertical distribution of current velocity (U_c) over vessel's draft

components and an additional term for appendages and propeller drag to the longitudinal force component, separately. The drag of locked propellers on military vessels can exceed the longitudinal drag force on the hull itself. The longitudinal force due to skin friction alone (F_{cst}) is calculated from

$$F_{cst} = \frac{\rho}{2} Ccsf U_c^2 A_{ws} \tag{4-13}$$

where C_{csf} is the skin friction coefficient, which is a function of R, and A_{ws} is the immersed wetted surface area, which is a function of the vessel's geometry. The skin friction coefficient is normally within the range of 0.001–0.006 for laminar to turbulent flow conditions. *UFC 4-159* provides formulas for estimating C_{csf} and A_{ws}.

The added drag due to fixed propellers (F_{cp}) is determined from

$$F_{cp} = \frac{\rho}{2} C_{cp} U_c^2 A_{cp} \tag{4-14}$$

where C_{cp} is the propeller coefficient, usually taken as equal to 1.0, and A_{cp} is the expanded propeller blade area, which is a function of the total projected blade area and the propeller pitch. Again, *UFC 4-159* provides a methodology for calculating C_{cp} and A_{cp}.

4.3.2 Local Current Effects

For vessels moored alongside in rivers and narrow channels, the presence of the vessel may obstruct enough water flow to accelerate the flow around the vessel and within the channel in general, thus increasing the forces on the moored vessel. This effect, greatest in shallow water, normally needs to be taken into account when the channel width (W) to vessel beam ratio $W/B < 5$. A blockage coefficient can be defined as BT/Wd

where d is the average water depth. Also, in somewhat shallow water, the current flow below the vessel may increase, causing the vessel to sink slightly due to higher pressure at the bow and stern resulting in a wave trough below most of the vessel's mid length. The resulting sinkage is known as "squat" and is generally small, less than 1 ft, for a moored vessel, but can be much greater for vessels underway at speed in constricted channels. Squat effects increase with the square of the current velocity, with decreasing d/T and W/B, and with a vessel's block coefficient.

Tidal flows typically exhibit changes in speed and direction over a period of hours with minor fluctuations on the time scale of minutes. In certain stratified estuaries and river mouths where fresh water and sea water mix, a current shear may be created with pronounced changes in speed and direction with depth such that at some locations surface and bottom currents may flow in opposite directions at certain stages of the tide. Wind stress and peaks in river discharge may significantly alter the normal flow profile. Downstream of islands or obstructions and/or along irregular shorelines turbulent eddies may be formed that result in more dramatic changes of speed and direction over shorter time scales. In such situations dynamic analysis may be required, especially if the eddies are on the order of the vessel size.

4.3.3 Current Standoff Forces

A vessel moored alongside in a strong current such that the flow of water along the shore side is greatly reduced by the presence of a quay wall or even a densely spaced pile foundation may be subjected to a "standoff" force directed away from the shore. This is due to the Bernoulli effect of the higher water velocity along the outshore side of the vessel creating a pressure differential with resultant higher water elevation along the inshore side pushing the vessel away from the dock. This head difference (h_{so}) can be expressed as the velocity head times some empirical coefficient, C_{so}, and is thus given by

$$h_{so} = \frac{C_{so} U_c^2}{2g} \tag{4-15}$$

As the current velocity and associated head difference will likely vary along the vessel length the velocity head term must be integrated along the vessel's LBP. Also, as the pressure head applies over the vessel's draft this can result in very substantial forces on fully loaded/deep draft vessels even for somewhat low values of C_{so}. No generally accepted value for C_{so} exists. Early field measurements by Jackson (1973) indicated values of C_{so} as high as 0.42. Later studies based on model experiments of a design case history (Khanna and Sorenson 1980) for a scaled current velocity of 5 knots indicate C_{so} on the order of 0.10–0.15.

4.3.4 Combined Wind and Current Forces

Wind and current forces and moments calculated in accordance with the foregoing methods can be readily resolved into components about the vessel's cg and combined directly to obtain the resultant sum of forces. It is, however, important to note that a series of calculations may be required to obtain the worst case combinations with regard to water level, vessel draft, and relative wind and current directions. Although in most cases the current will ebb and flood in somewhat fixed directions, the peak current velocities usually occur at near mid tide and may differ considerably between flood and ebb. Typically the current is nearly still or "slack" at high and low tide so that at locations with somewhat large tide ranges applying the maximum design current may not be necessary at these times. Obviously, current forces are at maximum for loaded, deep draft conditions at low tide, whereas wind forces are higher in ballast condition, typically at high tide, for cases of offshore wind where pier shielding is less.

4.4 PASSING VESSEL FORCES

Moored vessels may be subjected to substantial dynamic forces due to the nearby passage of other vessels especially in narrow restricted waterways with large vessel traffic. Passing vessel forces have caused many mooring incidents, including some tragic breakaways as reported in Section 6.3.3. This section provides an overview of passing vessel forces and methods available to calculate them.

4.4.1 Force Generation Mechanism

Moving vessels in narrow waterways generate pressure differentials (pressure fields) in the surrounding body of water. High-pressure zones form at the bow and stern of the vessel, whereas low-pressure zones form along the sides of the vessel. The pressure differentials generate long-period waves typically known as drawdown, the Bernoulli effect, or the pressure field effect. For consistency with most recent technical publications, this effect is herein referred to as the "pressure field effect" or "pressure field wave." Fig. 4-11 shows a typical passing vessel situation in the Port of Oakland Inner Harbor Waterway. Fig. 4-12 shows a conceptual pressure field distribution surrounding a vessel entering a narrow waterway. Areas on the sides of the vessel represent zones of below-static pressure and areas in front and behind the vessel represent zones of above-static pressure.

In the case of high speeds and narrow channels, the hydrodynamic forces due to the pressure field are significant and may result in serious damage to port infrastructure and impose life safety risks. Pressure field waves and hydrodynamic forces generated by pressure fields should be

Fig. 4-11. *Inner harbor waterway, Port of Oakland, CA*

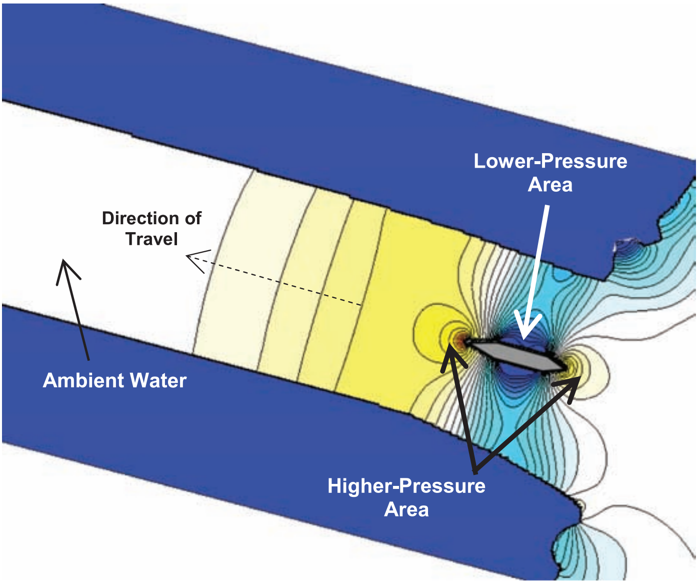


Fig. 4-12. *Pressure field surrounding passing vessel entering narrow waterway*

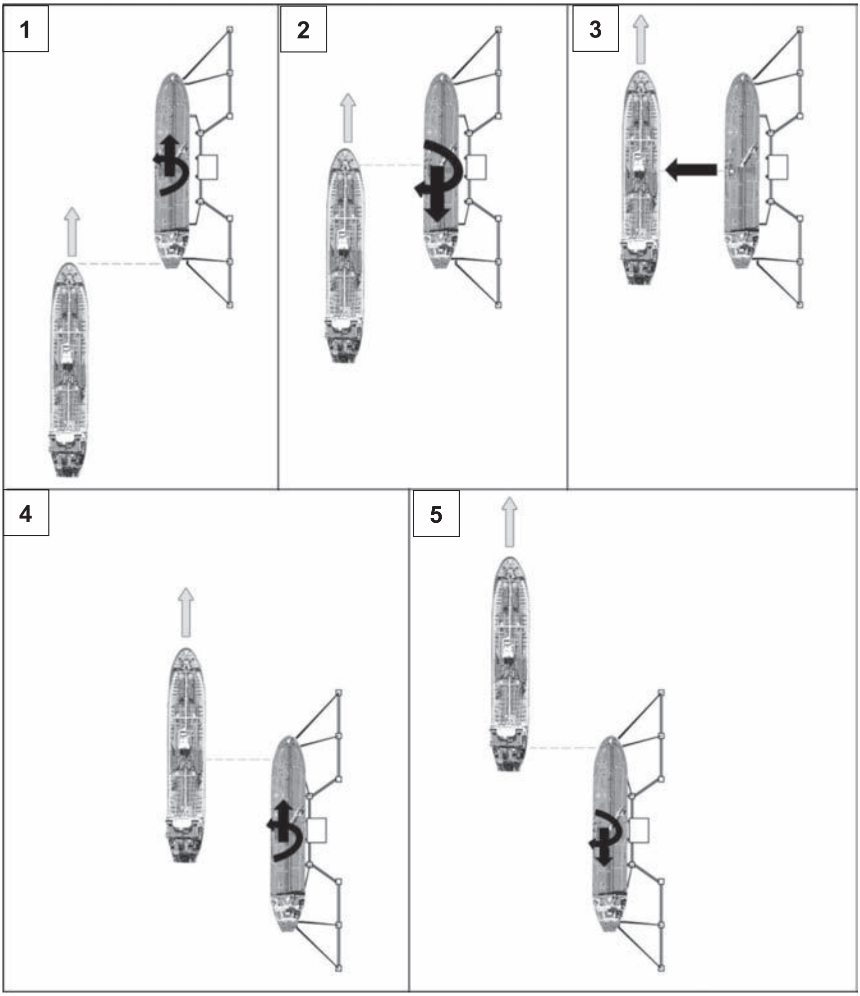


Fig. 4-13. *Ship passing berthed ship moored alongside terminal*

taken into consideration during design and operation in narrow waterways and navigation channels. Figure 4-13 shows a ship passing a berthed ship in a series of frames, during which the dynamic forces and moments evolve as follows:

1. Passing ship bow reaches stern of berthed ship, inducing primarily a small surge force in passing ship direction and small CCW yaw moment.
2. Passing ship bow reaches amidships of berthed ship, inducing primarily a large surge force counter to passing ship direction and large CW yaw moment.

3. Passing ship aligned amidships with berthed ship, inducing primarily a large sway force toward passing ship.
4. Passing ship stern reaches berthed ship amidships, inducing primarily a large surge force in passing ship direction and large CCW yaw moment.
5. Passing ship stern reaches berthed ship bow, inducing primarily a small surge force counter to passing ship direction and small CW yaw moment.

4.4.2 Passing Vessel Force Analysis Techniques

4.4.2.1 Passing Vessel Hydrodynamics Pressure field effects should be evaluated to determine impacts to berthed vessels, passing vessels, waterfront structures, and protected (or unprotected) shorelines. Engineering practice has developed several levels of hydrodynamic analysis for evaluation of pressure field effects, including steady-state analytical methods, time-dependent two-dimensional (2-D) methods (depth-averaged finite difference or finite element), time-dependent three-dimensional (3-D) methods, and Reynolds Averaged Navier Stokes (RANS) panel methods. In design practice, the engineer may apply different levels of hydrodynamic evaluations depending on the complexity and scope of the project.

Steady-state vessel hydrodynamics models can be used to evaluate pressure field effects and water level fluctuations in narrow waterways as an initial approximation. The use of these types of methods and models can typically be justified only for waterways with simple geometry. Analysis approaches (Muga and Fang 1975, Shepsis et al. 2001) include the method of images, slender body theory approximations, and others. These methods can be used in some cases to determine the need for higher-level analysis with time-dependent numerical modeling tools. Several modeling tools have been developed recently based on finite-difference codes (Nwogu 2001, Fenical et al. 2006) and finite-element codes (Stockstill and Berger 1999) to simulate relevant hydrodynamic processes.

Deep-draft vessel hydrodynamic effects under consideration include water level fluctuations and velocities in the channel generated by the moving vessel's pressure field. The use of two-dimensional (depth-averaged) modeling tools typically is adequate as long as the hydrostatic pressure assumption is valid, and results of analysis using two–dimensional modeling tools have shown good correlation with laboratory and field measurements. Time-dependent two-dimensional (depth-averaged, hydrostatic) models can simulate vessels moving through modeling domains using finite–difference or mesh vessel hull shape approximations. Finite element models have also been used with similar shallow water equations to evaluate water level and velocity fluctuations.

Recent developments have also provided industry with fully three-dimensional hydrodynamic codes using RANS equations (Chen et al. 2002) and coupled codes with three-dimensional hydrodynamics in the near field and two-dimensional hydrodynamics in the far field (Kofoed–Hansen et al. 1999, Nwogu 2007). These codes are used to evaluate more detailed effects of moving vessels, particularly for vessels moving with high Froude numbers and for evaluation of high-frequency wakes. These types of studies require a high level of detail on vessel hull information and hydrodynamic predictions and are computationally expensive. Physical modeling (laboratory tests) can also be used for specific studies when the study scope requires the highest level of analysis, provided that the experiments are of sufficient scale. It should be noted that in practice the expense associated with most three-dimensional methods and physical modeling are rarely warranted for pressure field analysis on engineering projects.

4.4.2.2 Passing Vessel Force Calculations Passing vessel load calculations can typically be made using either of two methods: empirical load formulations or direct application of vessel hydrodynamic calculations from pressure field models.

Empirical Methods Several empirical methods have been developed for calculating passing vessel loads and moments using analysis of forces measured in the laboratory (Flory 2002, Seelig 2001, Kriebel 2005). Input to these methods includes channel and vessel dimensions, passing distance vessel locations, and passing speed. These methods represent a first approximation of loads and moments on passing vessels. However, only a few laboratory data sets were available for development of these methods (Remery 1974, Lean and Price 1977, Kriebel 2005), and the laboratory tests do not include significant geometric features such as channel banks and variable bathymetry; therefore, these methods should be used with caution and only as a first approximation.

In cases where vessel hull shapes, channels, or navigation conditions are more complex, passing vessel hydrodynamic forces and moments should be evaluated with time-dependent modeling tools. Passing vessel forces are strongly affected by the presence of confinement features such as channel side slopes and nearby wharf structures such as quaywalls. Within confined channels, passing vessel sway forces are likely to be less than in open water conditions, whereas surge forces are likely to be significantly greater than predicted by methods using the open sea condition. Passing vessel forces and moments are also strongly affected by the presence of ambient tidal/river currents. The simple approach of adding or subtracting ambient current speed and passing ship speed to approximate the effects of current should not be performed in confined harbor conditions.

Direct Application of Hydrodynamic Results Recently the direct application of hydrodynamics results to pressure field modeling tools or to external load calculation tools (Chen et al. 2002, Fenical 2007) has been successfully performed. This methodology allows inclusion of project-specific details in passing vessel load calculations, such as complex channel and bank configurations, complex ambient conditions, and hull shapes that differ significantly from those used in development of empirical methods. Therefore, this approach removes many significant assumptions and simplifications associated with empirical formulations.

Time histories of loads and moments on the berthed vessel calculated using either of these two force calculation methods can then be used as input into dynamic mooring analysis packages to obtain berthed vessel response and loads in the mooring lines, bollards, and fenders.

4.5 WAVE FORCES

Although most piers and wharves are located at sites that are relatively well sheltered from waves, wave action may become important when wave conditions exceed certain threshold values. Wave forces are essentially dynamic in nature and it is important to understand the nature of wave loading and vessel motion response and when a more rigorous dynamic analysis may be required. This section provides an overview of the nature of wave forces and conditions that may result in large forces and/or unacceptable vessel motions.

4.5.1 General Considerations

Wave forces on moored vessels arise from a complex interaction of water particle kinematics, vessel body motions, and mooring system response. Determination of the hydrodynamic coefficients for added mass, and damping and higher order nonlinear effects further complicates the problem. Hence, no simplified standard procedure exists for calculating the general case, even for regular waves. Despite this fact, the Spanish *ROM 0.2-90* presents equations for preliminary evaluation purposes that give static longitudinal and lateral component wave forces. Graphs are provided to determine correction coefficients that account for draft and water depth effects relative to the incident wave length. McConnell et al. (2004) present a series of nondimensional graphs to determine quasistatic wave loads on tankers up to 120 kDWT moored with 12 lines at a sea island type berth for head, beam, and quartering sea conditions.

The graphs include nondimensional mooring line and fender stiffness factors for variable LBP-to-wave-length and wave-height-to-wave-length ratios and yield mooring line and fender forces and vessel motions. The authors emphasize that the graphs are not intended for design purposes but for preliminary and planning purposes. The reader is advised to use these or any similar formulations with caution, even for preliminary evaluation purposes. The intent herein of this and the following section is to describe the nature of the problem of and approaches to dealing with wave forces. Furthermore, in-depth treatment of the evaluation of wave forces requires that the reader have a firm understanding of wave theory and kinematics, which is beyond the scope of this manual. The reader is referred to the general literature on wave mechanics to obtain such background. In general wave action may result in unacceptable vessel motions and significant mooring forces under the following conditions for large vessels of interest:

- Wave periods > approximately 4 s and heights > approximately 4 ft;
- Beam to sea orientation;
- Vessel in light/ballast condition vs. fully loaded;
- Long waves (even of low height) at resonant periods (slow varying drift forces);
- Slack lines resulting in excessive movements and potential "snap loads"; and
- Vessel motions may be deemed unacceptable based on:
  - Safety limits: excessive motions that could result in line breakage, damage to the vessel;
  - Pier or other nearby vessels and/or personal injury;
  - Operating limits: excessive motions that may result in cessation of or reduction of cargo;
  - Transfer rates and/or possible damage to equipment; and
  - Prescribed limits: limiting motions mandated by vessel and/or terminal owner/operators or local governing authorities.

Further discussion of acceptable vessel movements is provided in Section 6.2. Properly defining the wave climate with regard to when the vessel is likely to be in the berth and as to whether long-wave effects are present versus sea and/or swell is very important.

4.5.2 Oscillatory and Drift Forces

In general, wave forces can be categorized as primary and secondary forces. Primary forces, to which a moored vessel responds dynamically at the wave frequency in direct proportion to the wave height, result from pressure differences developed around a vessel as diffraction and reflection scatter incident waves and the oscillating vessel radiates waves. Secondary forces have lower magnitude and result from the excess momentum flux and radiation stress of wave trains and irregular seas, referred to as "drift forces," which are proportional to the square of the incident/reflected wave height. Primary forces are greatest at longer wave periods, and secondary forces are greatest at shorter wave periods. Wave forces in general are profoundly affected by water depth to draft ratio, d/T; water depth to wave length ratio, d/L, where L is the local wave length; the surrounding bathymetry; and proximity effects, such as solid versus open pier construction and wave/current interactions. The mooring system restoring forces exhibit a nonlinear response due to the nonlinearity of mooring lines and fenders and the differences in stiffness among them. Resonant responses may develop, especially at low frequencies where damping is low, when the natural period (T_n) of the moored vessel is near that of some exciting environmental force. Moored vessels typically have natural periods around 20 s for vessels of about 3 kDT to 60 s and longer for vessels of 100 kDT and larger. The natural period in surge (T_{nx}) can be estimated from the following formula, assuming that it is not coupled with other modes and that fender friction can be neglected:

$$T_{nx} = 2\pi\sqrt{\frac{M_s + M'}{K_{sx}}} \qquad (4\text{-}16)$$

where

M_s = vessel mass, (DT/g);

M' = added mass of water in surge, which is ordinarily around 15% M_s; and

K_{sx} = the spring constant associated with the longitudinal restraint of the mooring lines, which is assumed to be equal in the fore and aft directions.

The natural period in sway (T_{ny}) cannot be so readily calculated due to the nonlinearity between the fenders and mooring lines and the fact that the added mass in sway is more greatly affected by the water depth to draft ratio or under-keel clearance.

The vessel's response is also very much affected by the wave length in relation to the vessel's length or beam. For example, for a vessel moored in a head- or stern-to-sea condition, the heave and pitch response approaches unity, i.e., the vessel moves in concert with the wave profile, when the wave length exceeds about two times the vessel LBP, whereas when the wave length is less than three-fourths of LBP, response is minimal. Therefore, in somewhat long waves in the head-to-sea orientation, the vessel's chocks follow a roughly circular or elliptical path as the wave form passes, and as a first approximation the associated change in lengths of the mooring lines can be used to estimate their loadings. In long regular waves the theoretical upper bound of the surge force is the equivalent of the vessel's mass sliding down the sea surface slope or $\pi H/L$ times the vessel's mass (Dean and Dalrymple 1991). The beam sea condition is again, however, more complicated and requires numerical models.

Actual field measurements conducted in the ports of Long Beach and Los Angeles as reported by McGehee (1991) highlight the importance of resonant response of moored vessels. Fig. 4-14 presents normalized energy spectra (the percentage of measured energy to the total energy at the given frequency or period) for ambient wave conditions and the

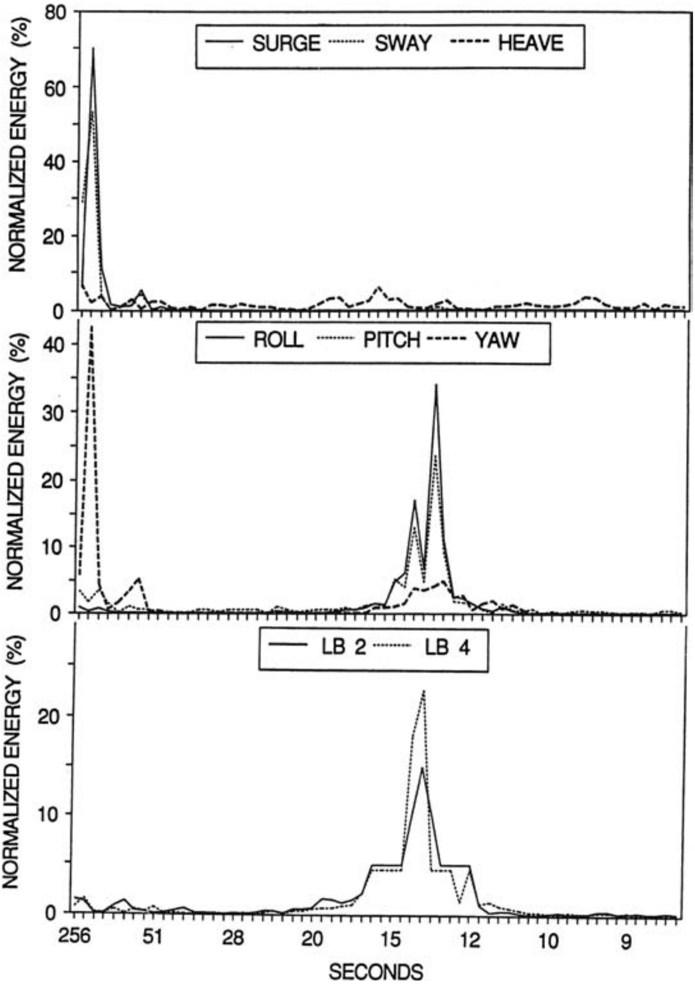


Fig. 4-14. Energy spectra of waves for total energy >8 s in S.E. Basin of Long Beach Harbor and resulting motion spectra of containership M/V Hui He, March 1989
Source: McGehee (1991)

corresponding response of a moored containership in six degrees of freedom. The vessel was moored with nine lines fitted with tension links to measure and record mooring line tensions. The wave energy peaks at around 14 s with a corresponding peak in mostly roll motion at the vessel's natural period of roll and a slight subharmonic at around 64 s. The vessel exhibits a sharp peak in surge, sway, and yaw, however, at around 172 s where there is little input wave energy (about 1% of total). This is due to a "slow drift" nonlinear harmonic response. Prototype measurements of mooring line loads of a berthed LNG vessel under various environmental conditions were used to verify the six degrees of freedom computer model, TERMSIM (see Section 5.3; Van der Molen et al. 2003). For the studied berth situation, yaw motions due to swell waves were dominant and resulted in large breast line forces. An empirical expression was derived to calculate the LNG yaw motions in swell that could be applied to preliminary design of similar facilities under similar swell conditions. The "drift force" refers to a constant component of the wave force that tends to move the vessel in the direction of wave propagation. It is related to wave train momentum flux or radiation stress. The drift force is a steady force in regular waves and a slow, varying unsteady force in irregular waves. The steady drift force in regular waves can be added to the static wind and current forces, whereas the dynamic slow varying drift force in irregular waves can incite a resonant response at or near any of the moored vessels' natural periods and subharmonics (Loken and Olsen 1979). For the case of no energy dissipation, the steady drift force, F_{dr}, as derived from linear wave theory (Sarpkaya and Isaacson 1981) is given by

$$F_{dr} = \frac{1}{8}\rho g H_r^2 \left(1 + \frac{2kd}{\sin h2kd}\right) \tag{4-17}$$

where

H_r = the incident reflected wave height, which should be taken as the RMS value of the irregular wave heights times a reflection coefficient; and

k = the wave number = $2\pi/L$ and L = wave length.

This equation applies primarily to "slender" bodies in beam seas normal or nearly normal to the vessel's side. Chakrabarti (1980) provides a comprehensive overview of steady and oscillating drift forces on floating objects.

Where wave-induced vessel motions and resulting mooring forces can be assumed to be linear and frequency dependent, response spectrum techniques or "frequency domain" analysis can be applied to the wave energy spectrum to derive the vessel motion and force spectra. This requires determining a transfer function referred to as a response amplitude operator (RAO), which must be determined from the hydrodynamic equations and defines the vessel's unit response at a given frequency in a given mode. Gaythwaite (2004) introduces this technique, and Michel (1968, 1999) provides a more in-depth description of wave spectra applications. Frequency domain analysis reduces computational effort and is especially useful for comparative studies such as berth down time analysis. Hwang and Bando (1987) present a comparison of results of frequency domain and time domain analyses carried out for a container ship berth. Time domain analysis is essential to fully represent nonlinear effects and time varying excitation forces. See Section 5.2 for further discussion of this topic.

4.5.3 Maximum Probable Wave Height

In evaluating extreme vessel motions and associated high mooring line loads determining the most probable maximum wave height or amplitude, A, may be useful. The maximum significant wave height, H_s, must first be determined for the design storm conditions. Determining H for a 3-h duration and applying the average wave period to determine the total number of waves, N, that will pass during that interval is common practice (OCIMF 2008). The maximum probable wave height can then be determined from

$$H_{mpw} = 0.707 H_s \sqrt{\ln N} \tag{4-18}$$

If both longer period swell and locally generated wind wave seas are present with well-defined component heights, then the value of H_s in Eq. (4-18) can be taken as the RMS value of the combined sea state as given by

$$H_{rms} = \sqrt{H_{ww}^2 + H_{sw}^2} \tag{4-19}$$

4.6 SEICHE AND LONG WAVE EFFECTS

Periodic water level oscillations known as "seiche" and long period waves, even of very low height, may excite large motions in moored vessels with resulting high mooring forces. Seismically generated sea waves known as "tsunamis" are also a form of long period wave that may threaten certain sites. This section provides an overview of long wave effects and their potential for causing mooring problems in certain harbors.

4.6.1 Seiche

Certain enclosed and semienclosed harbors and bays may be subject to periodic oscillations of water level known as seiche. The harbor basin will slosh back and forth about some nodal point or even multiple nodal points at a given natural period. The seiche period is a function of water depth, plan dimensions, and overall basin shape or configuration. Seiche periods range from 25 s up to several hours but most typically range from 30 s to 10 min with typical heights of 0.1–0.4 ft (USACE 2006), although they can be higher. Seiching may be initiated by input wave energy, in particular infragravity waves of long wave lengths that are themselves the result of wave grouping of offshore storm waves. Seiching may also be initiated by wind forcing and the movement of atmospheric low pressure systems, especially for lakes and shallow enclosed water bodies. A sudden change of water level, such as may occur in canals near locks or extreme storm water runoff, may also induce seiching. The seiche wave form travels at the shallow water wave speed or "celerity," $C_{sw} = \sqrt{gd}$, and for the simple case of a narrow enclosed rectangular basin of constant depth, the natural period of the fundamental mode is given by

$$T_b = \frac{2L_B}{\sqrt{gd}} \tag{4-20}$$

where Lb = length of basin. For an open-ended basin the natural period is twice the value of an enclosed basin. The corresponding maximum horizontal water particle velocity and displacements are given by

$$V_h = \frac{H}{2}\sqrt{\frac{g}{d}} \tag{4-21}$$

$$X_h = \frac{HT_b}{2\pi}\sqrt{\frac{g}{d}} \tag{4-22}$$

Fig. 4-15 shows a cross section for these simple cases that illustrates the water level changes and node locations about which no water level change occurs. Note that the horizontal water velocities and displacements are greatest at the nodal points, and the vertical rise is greatest at the basin ends. Although the water velocity may be somewhat low, the displacement may be quite large and therefore vessels located at or near nodal points may be subject to large surge forces and motions. Field observations have noted that vessels tend to move horizontally at longer periods, on the order of 20 s to several minutes, and move vertically in synchrony with the primary wave period. At steep-sided basins or solid vertical quay walls the water level oscillates vertically as a "standing wave" and can attain a height of twice the incident wave height. Closed form solutions for basins of various geometries can be found in Bruun (1989).

4.6.2 Long-Period Waves

Long-period waves, generally known as infragravity (IFG) waves, with periods typically ranging over 25 to 300 s, may force seiching. Such low-frequency waves may also result in significant excitation of vessel motions

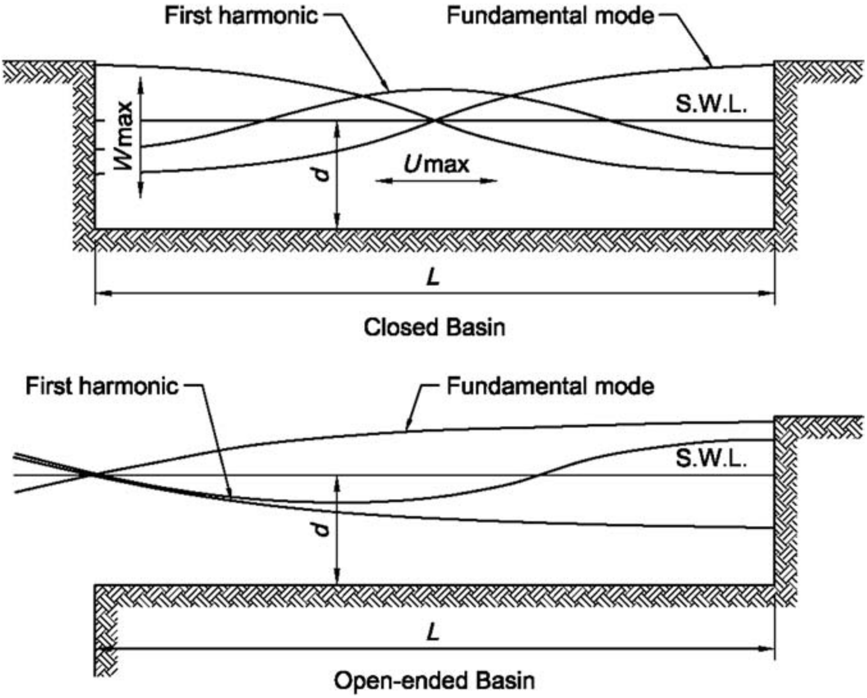


Fig. 4-15. Free oscillations of narrow rectangular basins

due to "set-down" effects, especially in shallow water, and the fact that damping is typically very small for low-frequency excitations. IFG waves may be "bound" or "free" in nature. Bound waves are nonlinearly coupled to wave groups traveling at the group velocity and are phase locked to sea and swell waves. Free IFG waves radiate to and from deep water after being reflected from the shoreline and may be associated with surf beats and edge waves that travel in the alongshore direction. The energy of both bound and free waves increases with increasing swell energy and decreasing water depth. Far infragravity waves also exist and have even longer periods of 2 to 64 min. Long waves are highly reflective, and their energy may penetrate rubble mound structures, which greatly enhances their potential to cause disturbances within artificial and exposed harbors. All of the aforementioned types of long waves may initiate seiching or resonant response of a moored vessel directly without the presence of harbor oscillations. Early investigations of vessel surging problems due to long waves were carried out by Wilson (1959) and O'Brien and Kuchenreuther (1958). Numerical modeling of long-wave problems in Long Beach Harbor has been reported by Headland and

Poon (1998). Goda (2000) provides a useful discussion of the effects of wave action within harbors and remarks on moored vessels.

4.6.3 Tsunamis

Tsunamis are impulsively generated dispersive waves of long period and low height usually caused by sudden large-scale vertical sea floor movements, or sometimes by submarine landslides. Typical periods range from a few minutes to several hours with open ocean deep water heights generally less than 1 m. Such waves travel at very high speed in the deep sea governed by the shallow water wave speed, C_{sw}, that often results in very high run-up heights and bore formation as they enter shallow nearshore waters. The tsunami may manifest itself in a series of surges persisting over a period of several hours. PIANC (2010) presents an excellent overview of tsunami problems in ports including case studies and an example mooring analysis. Moored vessels are subject to three basic physical phenomena during a tsunami:

1. Vertical movement due to rise in water level;
2. Horizontal forces due to accelerated currents, which can be quasistatic or dynamic in nature; and
3. Horizontal dynamic forces due to the leading tsunami waves.

PIANC (2010) concludes in part that approximating tsunami forces on moored vessels is possible using current state-of-practice numerical models and that a static analysis of the vertical movement of the moored vessel can be applied as a simple means of first-order assessment of the vulnerability of a moored vessel to given tsunami conditions. The effects of tsunamis on moored and maneuvering vessels have been described by Headland et al. (2006), and Dykstra and Jin (2006) describe detailed modeling of locally generated tsunami propagation within the ports of Los Angeles and Long Beach. Section 6.3 includes a case history of a tsunami-related mooring incident.

4.7 TIDE AND DRAFT CHANGES AND VESSEL MOVEMENTS AT BERTH

Moored vessels may subject to very large changes in water levels primarily because of tides and vessel draft due to transfer of cargo. As a result, significant change may occur in the height of the vessel's mooring chocks above and/or below the pier deck and mooring hardware. This in turn could lead to dramatic changes in mooring line tensions without proper line tending. Many large vessels are equipped with constant tension winches to reduce the line tending manpower requirements and risk of overloads. Nevertheless, some change in mooring line geometry

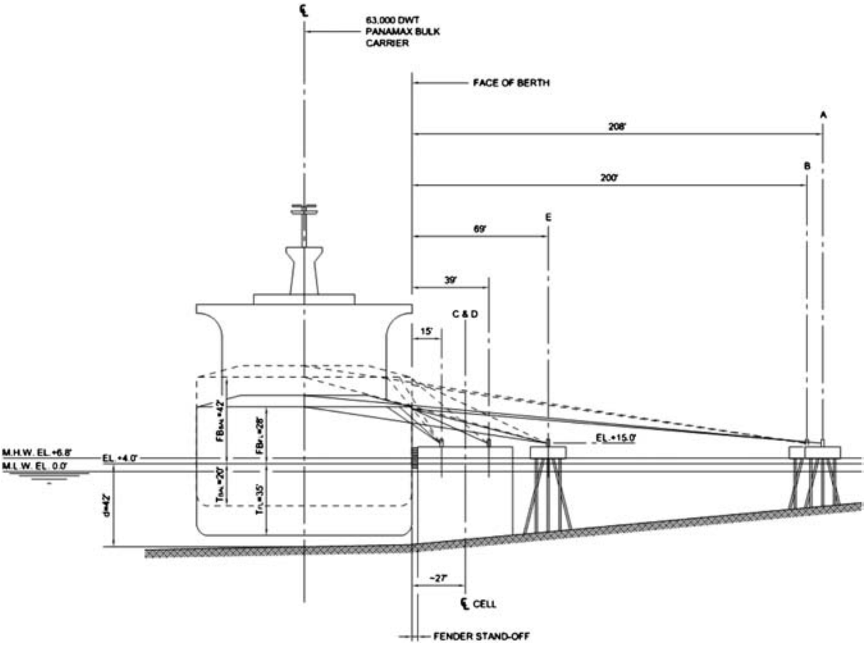


Fig. 4-16. Effects of tide and draft changes on moored vessel

must typically be accounted for in a mooring analysis. Figure 4-16 illustrates the change in mooring line angles between a ship and berthing and mooring dolphins with water level and draft changes. Other difficulties arising from water level and draft changes include the chafing of mooring lines leading over the edge of a pier down to the deck of a fully laden vessel at low water, fouling of lines on fender units or other pier face and deck features, and uplift on mooring hardware for unloaded vessels at high water.

4.7.1 Water Level and Draft Changes

Tides naturally tend to be semidiurnal with two lows and two highs per day. At some locations resonant type response due to the local bathymetry may diminish and/or cancel out completely one of the high/low cycles resulting in a diurnal type tide. Tides anywhere between these extremes are known as mixed tides and characterize many port locations. Tides also undergo many other variations over periods of days, months, and years (Section 2.2.4). Tide height ranges vary from nearly zero at some open ocean island sites to extremes of 30 to 50 ft under certain circumstances near the heads of narrow bays and estuaries. Tides and associated currents are well covered elsewhere in the literature, refer to

Gaythwaite (2004) for an introductory treatment and further references. The important point is that water levels constantly change over periods of hours and, along with vessel draft changes associated with loading/unloading, can result in significant changes in mooring line geometry. The tidal current velocity of a typical reversing type current, i.e., flood and ebb in opposite directions, within rivers and estuaries is typically at maximum near mid tide with a brief period of stand near high and low water as the current changes direction. The rate of rise and fall of the water level is also greatest near mid tide, which has contributed to breakaway incidents such as the example in Section 6.3.

Tankers and bulk carriers in particular undergo large changes in draft between loaded and unloaded conditions and, in fact, must take on water ballast to maintain stability in the light condition. The mean ballasted draft for a 16 kDWT tanker and larger can be estimated from the following International Maritime Organization (IMO) formula:

$$T_{\mathrm{bal}} = 2m + 0.02\mathrm{LBP} \tag{4-23}$$

where $m =$ meters.

Note that the maximum draft aft may be much greater than above average as vessels in ballast typically have a large amount of trim. Similarly, changes in trim and/or list may result from the shifting of onboard weights during cargo transfer and also due to wind-heeling moment as discussed in Section 4.2. The ballasted draft may alternatively be conservatively estimated at about 40% T where T is the full load draft. Note that vessels in fully lightship condition can have even shallower drafts, perhaps as low as 25% T for large tanker and bulk carrier types.

4.7.2 Berthing and Movements at Berth

In addition to fender impacts, mooring lines may be passed to the pier to aid in slowing and/or bringing the vessel into position during berthing operations. This can result in very high bollard loads. In addition, vessels may be relocated at berth using mooring lines and in some cases turned around by tugs so that the opposite side of the vessel is alongside the pier, a process called “winding ship.” In some cases the end corners of the pier may be used for “warping” to rotate the vessel. Occasionally ships may drop or carry out anchors to hold them off of the pier face or for added security in strong currents. Tugs can have an important impact on mooring forces at berth as discussed in Section 4.7.3. Vessel berthing maneuvers and movements in berth are described in detail by Clark (2009).

A vessel may heel or “list” during cargo transfer at berth, resulting in a significant change in mooring line tensions as it raises or lowers and moves the vessel's chocks toward or away from the berth face. Longitudinal "trim" may have a similar effect and is typically associated with overall change in draft as discussed previously.

4.7.3 Tug Assistance

After the berthing operation of a ship has been completed and the mooring lines are secure, tugs are seldom needed while the ship is at berth. However, occasionally a tug is required to hold the ship in place during unusual circumstances, such as replacing broken lines or repairing dock structure, dolphins, or fenders. If the mooring lines are too tight due to wind or tide variations, pushing the ship in to adjust the lines may be necessary. Contemporary tugs can be quite powerful and, in fact, may have sufficient power to fully compress or even damage a fender system. Under some circumstances, the propeller wash from tugs operating at an adjacent pier can affect a moored ship.

The force applied on the ship by a tug can be included in the mooring analysis as a concentrated load applied to the hull at some assumed or known location. Large ships have the safe location for tugs to contact the ship painted on the hull. The pulling power delivered by a tug is referred to as brake horsepower (bhp) or shaft horsepower (shp). Bollard pull or towline pull is determined at zero speed or 100% slip of the propeller. The bollard pull can be roughly determined as 25 lbs per bhp for conventional propellers and 30 to 35 lbs per bhp for tugs with Kort nozzles. Based on a comparison of the force required to keep a ship in place and the capacity of the tug, the size and number of tugs required can be determined. Usually, however, this decision is made through experience and local practice. Contemporary harbor tugs have bollard pulls typically in the 50–80 ton range, which approaches and may exceed the capacity of the vessel's mooring hardware and thus may be a practical upper limit for most harbor berthing and mooring work.

Some vessels, including most cruise ships, are equipped with built-in thrusters, typically located near the bow and stern, that can propel the ship sideways. This allows the vessel to berth without tug assistance and usually results in softer impacts as the vessel is very slowly maneuvered sideways under its own power. This may not always be the case, however, such as in strong beam winds where the thrusters may have insufficient thrust to compensate for the wind force.

4.8 ICE

Vessels moored in static ice of nominal thickness do not normally experience difficulty (see Fig. 4-17). Moving ice as driven by wind or

Fig. 4-17. Vessel moored alongside in ice of moderate thickness
Source: Photo reproduced courtesy of Appledore Marine Engineering

currents and pile up of ice, or “rafting,” against a vessel may result in very large forces as evidenced by the breakaway incident discussed in Section 6.3. Pertinent properties of ice include thickness; compressive strength; consistency; and nature of ice action, such as impact or pile up of ice floes versus expansive ice sheets driven against a vessel by wind and/or currents, etc. The force of an ice sheet acting on a fixed vessel is most often limited by the driving force of wind and/or current acting on the ice sheet. This force in turn is limited by the frictional drag of the wind or current, which varies with the square of the speed and the surface area of the ice upon which it acts. If sufficient driving force exists, then the ice force may be limited by ice crushing, bending, buckling, and splitting, or any combination thereof. The compressive, crushing strength of ice is often taken to be in the range of 100 to 400 psi depending on its temperature and consistency. Fresh water ice is typically stronger than sea water ice. The effective crushing pressure is further modified by strain rate, overall plan shape factor, contact area aspect ratio, etc. As can be readily surmised, there are many variables to be assumed and hence large uncertainty in the calculation of ice forces. The calculation of ice forces on structures is covered in detail in USACE (2002, 2006), and the USACE Cold Regions Research and Engineering Laboratory (CRREL) has many publications on ice formation and forces. Useful information on ice sheet formation and problems in ship channels is provided by PIANC (2004).

Ice may be driven against moored vessels by passing vessels resulting in large lateral forces, and sites exposed to regular vessel traffic may be subject to vessel track ice buildup (Tsinker 1995) due to the repeated break up and refreezing of ice in the channel adjacent to the pier or wharf. Similarly, a berthing vessel may force ice against the pier and fender system resulting in damage. Fenders stiffen at low temperatures, and ice may collect around fender units, effectively jamming them.

CHAPTER 5

MOORING ANALYSIS METHODS

5.1 STATIC MOORING ANALYSIS

Static mooring analysis is the most fundamental mode of mooring analysis generally applicable to most cases of wind and current loading where vessel motions are not important. Static analysis may be employed to optimize mooring line arrangements and the size and locations of mooring hardware, as well as the determination of individual mooring line loads.

5.1.1 Introduction and Principles

In terminal design, mooring analysis is performed to ensure that the general arrangement of mooring points and fenders is adequate for the intended types and sizes of vessels in the most extreme mooring environment at the location.

This is important to

- Provide sufficient mooring points and fenders and ensure that these have sufficient strengths and suitable locations for all vessel sizes; and
- Ensure that vessel motions are not excessive, especially at manifolds, gangways, and ramps.

During terminal design, mooring analyses should generally be done not only for the largest expected vessel but also for the smallest and, where a large range of vessels is expected, for representative intermediate size vessels.

The vessel mooring lines are beyond the control of the terminal designer and operator, except in the case of a terminal serving "dedicated" vessels. Mooring analysis should be done not only for the strongest available mooring lines and for the optimum number and arrangement of mooring lines on the vessel but also for typical and even "worst-case" numbers, strengths, and arrangements of mooring lines.

For oil and gas terminals, the concern is to avoid exceeding the loading arm or hose system operating envelope. Similar concerns exist at terminals serving passenger vessels, ferries, RO-RO ships, and container ships.

During terminal operations, mooring analysis is sometimes conducted to ensure that a particular vessel can remain moored in the expected environment. Where large changes in vessel freeboard, tide elevation, or current flow are expected, a mooring analysis can determine when mooring lines need to be tended. For more in-depth treatment see Flory and Ractliffe (1994) and Flory (1998a and 1998b).

Mooring analysis is also conducted in vessel design to ensure that the vessel has an adequate number of mooring lines, that these are of sufficient strength, and that they are properly arranged so that the vessel can safely moor at various terminals. Several organizations publish guidelines for this purpose (OCIMF 2008, Clark 2009).

Static mooring analysis is usually adequate to verify that a vessel can safely moor at a particular terminal or can remain moored in a predicted environment. But in some cases, for example when high waves or swell, seiche, or passing ships are a concern, a full dynamic analysis should be conducted.

The following basic principles of good mooring arrangement should be followed to the extent possible:

- Mooring lines should be arranged symmetrically about midship.
- Breast lines should be oriented nearly perpendicular to the longitudinal centerline and far forward and aft from midship.
- Spring lines should be oriented nearly parallel to the longitudinal centerline.
- Vertical angles of mooring lines should be minimized.
- Mooring lines of the same, type, and length should be used for all leads.

For a more in-depth treatment of the effect of mooring line elasticity on line load distribution see Flory (1998b), and for a general discussion of proper mooring practice see Flory (1998a).

If these principals are followed, then the static mooring analysis is somewhat simple. If they are not followed, then more complicated mooring analysis procedures should be used.

Mooring analysis consists of balancing the forces and moments applied to the vessel by the environment and other factors against the reaction forces exerted by the mooring lines and fenders. For the purpose of mooring analysis

- The summation of applied longitudinal forces is represented by a single longitudinal force F_X applied along the vessel's longitudinal centerline;

- The summation of applied transverse forces is represented by a single transverse (lateral) force F_Y applied perpendicular to the longitudinal centerline at midship; and
- The summation of applied moments is represented by a single moment M_{XY} applied about a vertical axis at midship.

Alternatively, the transverse force and moment can be represented by transverse forces F_{YF} and F_{YA} applied at the forward and aft perpendiculars respectively. Or another alternative is to represent the transverse force and moment with a transverse force F_Y applied at a longitudinal distance L_M from midship, representing the moment arm that produces the moment.

The spring lines principally act against the applied longitudinal force, whereas the breast lines principally act against the applied transverse force. The breast lines and the fenders principally act against the applied moment.

5.1.2 Static Mooring Analysis and Special Considerations

5.1.2.1 Elementary Grouped Forces Static Analysis The simplest method of conducting a static mooring analysis assumes that all breast lines are perpendicular to the vessel side and are grouped together at defined distances fore and aft of midship. This is illustrated in Fig. 5-1.

The set of equations for this simple static analysis follows:

$$\sum F_x = F_X - T_X = 0 \tag{5-1}$$

$$\sum F_y = F_Y - T_{YF} - T_{YA} = 0 \tag{5-2}$$

$$\sum M_{xy} = M_{XY} + T_{YF}L_F - T_{YA}L_A = 0 \tag{5-3}$$

where

F_X = applied longitudinal force,
T_X = reaction force of spring line(s),
F_Y = applied transverse force (at transverse centerline),
T_{YF} = reaction force of forward breast line(s),
T_{YA} = reaction force of aft breast line(s),
M_{XY} = applied moment,
L_F = distance from centerline to point of application of forward breast line group, and
L_A = distance from centerline to point of application of aft breast line group.

There are three equations and three unknowns, T_X, T_{YF}, and T_{YA}. This simplified static mooring analysis can be carried out by hand. But it is not very useful or accurate, because it assumes that spring lines are parallel to the vessel's longitudinal axis, ignores the fact that fore and aft spring lines

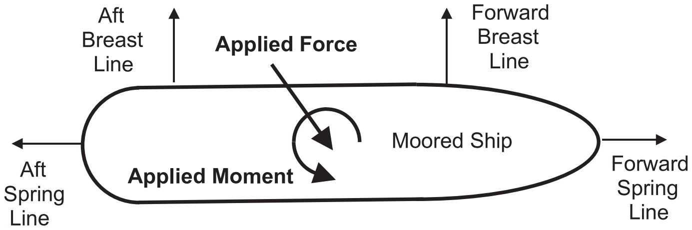


Fig. 5-1. Simple mooring analysis, three equations and three unknowns

act against each other, and assumes that forward and also aft breast lines are grouped together and that they are perpendicular to the longitudinal axis. Furthermore, it ignores any reaction forces of fenders, especially their contribution in reacting against applied moment.

5.1.2.2 More Realistic Vector Forces Static Analysis For all but the simplest mooring arrangement, considering that there are numerous breast lines, that they are not concentrated together near the bow and stern, and that they are not perpendicular to the longitudinal axis and not parallel with each other is important. Also, fender reaction forces are important in restraining yaw motion. This more representative mooring arrangement is illustrated in Fig. 5-2.

Each breast line exerts a longitudinal force, which is a function of the cosine of that angle from the longitudinal centerline. Each spring line exerts a transverse force, which is a function of the sine of its angle to the longitudinal centerline. Thus, an interrelationship exists between the sum of longitudinal forces and the sum of lateral forces.

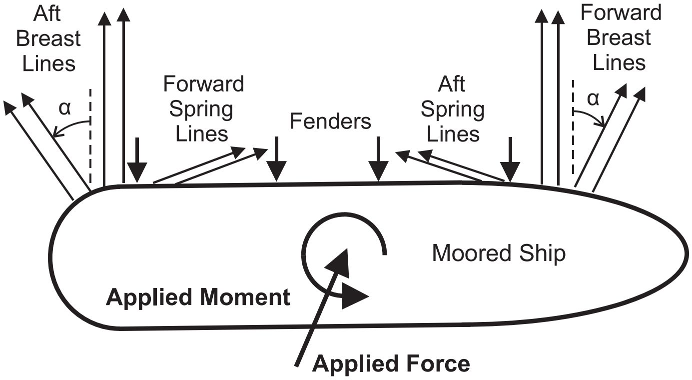


Fig. 5-2. Complex mooring analysis, three equations and many unknowns

The following set of equations considers the effect of each breast and spring line, including the horizontal line angles, and the effect of each fender.

$$\sum F_x = F_X + \sum_1^q (k_q X - P_q)\sin\alpha_q + \sum_1^m k_m(Y + L_m \sin\theta)\cos\alpha_n = 0 \quad (5\text{-}4)$$

$$\sum F_y = F_Y + \sum_1^m k_m(Y + L_m \sin\theta_m)\sin\alpha_m + \sum_1^q k_q X \cos\alpha_q$$
$$- \sum_1^n k_n(Y + L_n \sin\theta) = 0 \quad (5\text{-}5)$$

$$\sum M = M_{XY} + \sum_1^m k_m(Y + L_m \sin\theta_m) L_m \sin\alpha + \sum_1^q k_q L_q \cos\theta_q \cos\alpha$$
$$- \sum_1^n R_n(Y + L_n \sin\theta) L_n = 0 \quad (5\text{-}6)$$

where
m = number of breast lines,
n = number of fenders,
q = number of spring lines,
T_m = reaction force in breast line m,
L_m = distance of breast line m from transverse centerline,
R_n = reaction force in fender n,
L_n = distance of fender n from transverse centerline,
k_m = spring rate of breast line m,
k_n = spring rate of fender n,
k_q = spring rate of spring line q,
α_m = horizontal angle of breast line m from longitudinal centerline,
α_n = horizontal angle of spring line q from longitudinal centerline,
X = surge of vessel,
Y = sway of vessel, and
θ = yaw angle of vessel.

This set of equations is statically indeterminate. There are still only three equations, but there are $m + n + q$ unknowns, representing the many mooring lines and fenders. The unique vessel position, surge, sway, and yaw must be determined such that the force in each mooring line and also in each fender satisfies the aforementioned equations.

For very simple mooring arrangements, this set of equations might be solved algebraically by hand. But if more than a few mooring lines and fenders are used, solving these equations will require a trial-and-error, iterative convergence technique, or matrix analysis technique.

Mooring analysis computer programs specially written to solve these equations and also consider other issues are discussed in Section 5.3. Some spreadsheet programs and advanced math computer programs can directly solve such equations through iteration.

5.1.2.3 Vertical Mooring Line Angles If a mooring line is not essentially horizontal, its vertical angle should be accounted for, as shown in Fig. 5-3. In Eqs. (5-4), (5-5), and (5-6), the tension in each line should be adjusted by sin β, where β is the line angle from horizontal.

Vertical angles of breast lines at container terminals can be very steep. In this case, the vertical angles might change significantly due to vessel sway and yaw movement.

If the vertical line angle is significant, changes in vessel draft and tide can greatly affect tension. Conduct analyses for both the extreme high and low cases. When assessing terminal operations, an analysis for the effect of change between high and low cases can determine if line tending will be necessary.

5.1.2.4 Mooring Line Stiffness and Other Effects Rope and chain properties are discussed in Section 3.1, and Fig. 3-1 shows typical stiffness characteristics for several rope types commonly used as mooring lines.

Small differences in mooring line stiffness usually make little difference in the results of a mooring analysis. Thus, being completely accurate in representing rope stiffness is usually not necessary. But large differences can have large effects. Improperly mixing different types of mooring lines, for example wires and synthetic fiber ropes, can result in bad mooring systems (Flory and Ractliffe 2005).

The stiffnesses of wire rope mooring lines are generally linear. The stiffnesses of high-modulus fiber ropes are generally linear after being pretensioned. The stiffnesses of conventional fiber ropes, especially nylon,

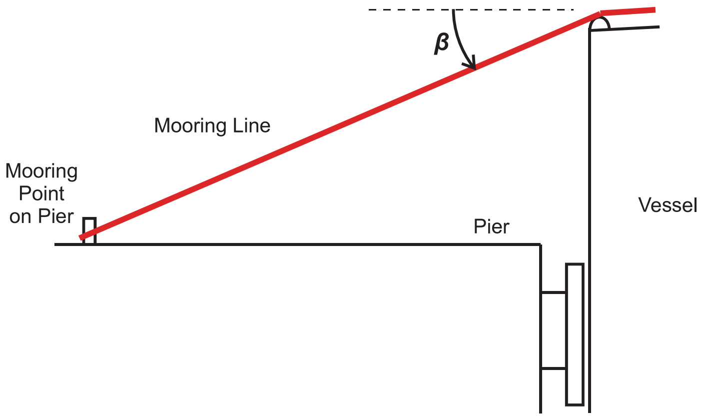


Fig. 5-3. Vertical mooring line angle

are nonlinear; spring rate increases with applied tension. Catenaries in wire and chain mooring lines produce nonlinear stiffness.

If mooring line stiffness is nearly linear, it may be represented by the secant slope from zero to the assumed applied tension. Fore and aft spring lines are pretensioned against each other, and in this case the spring rate may be represented by the slope of the tangent at the pretension.

The spring rate of a mooring line is a function of its total length. Thus, calculating the spring rate of each mooring line based on its length is necessary. The length of the mooring line on the vessel deck between the fairlead and the winch or bitts should be included when calculating mooring line length.

A mooring line is only effective in tension; it cannot exert a pushing force. Thus the mooring line spring rate must be zero in compression.

Conventional fiber ropes are sometimes used as tails on wire rope or high-modus fiber rope mooring lines to decrease line stiffness and thus reduce peak mooring loads. The composite stiffness of the tail and the mooring lines should be represented in the mooring analyses. This can be calculated by the summation of the inverse rates of the mooring line and the tail, accounting for the relative length of each segment.

5.1.2.5 Fender Stiffness and Other Effects Fender spring rate generally does not have a significant effect on the results of mooring analyses. An approximation of fender spring rate is usually sufficient.

But fender spring rate may be of concern when the fenders are somewhat soft and the mooring lines are somewhat stiff. Fender spring rate may also be important when vessel motions are of concern.

Determining the proper fender spring rate to use in mooring analysis is usually difficult. Data on spring rate are available for some fender types in new condition. However, the spring rate can change with age and use. Fender manufacturers may be able to provide some useful data for specific cases.

Fenders are sometimes supported on flexible piles or semirigid dolphins, or the entire pier structure is sometimes somewhat flexible. In these cases the spring rate of both the fender and its supporting structure should be considered. The composite spring rate should be determined by summing the inverse spring rates of both the fender and the supporting structure. The resulting spring rate will be softer than that of the fender alone.

Fender spring rates typically linear over a large deflection, and thus representing the fender by a linear spring rate is usually sufficient. Some fenders have nonlinear spring rates. At very high deflections all fenders become very stiff.

Some fenders reduce to almost zero spring rate and even buckle and have negative spring as they compress. Such soft spring rate characteristics are of concern when accurate calculation of vessel movement is necessary.

The spring constant for a fender is only effective when it is compressed. Thus, the fender spring rate must be zero in tension.

A fender should only exert force perpendicular to the longitudinal centerline, unless fender friction is modeled. Fender friction is complex and is usually of interest only during dynamic analysis. Determining the proper coefficient of friction is difficult. Fender friction is a function not only of the tangential force tending to move the vessel along the fender but also of the perpendicular force of the vessel against the fender.

If the vessel is pushed off the pier, no fender friction exists. The conservative assumption is that there is no fender friction, as this permits the most vessel motion and results in the highest mooring line tensions.

5.1.2.6 Other Static Mooring Analysis Considerations

Wind Direction Sweep A static mooring analysis is sometimes conducted to determine the limiting wind velocity from various directions. The data from such an analysis can be depicted as a polar plot of limiting-wind velocity. This wind-limit plot is then compared against a wind rose plot of historic or predicted wind velocities to determine the adequacy of a mooring system design.

The limiting-wind velocity plot can also be used in conjunction with wind forecasts as a tool during marine terminal operations to determine when cargo transfer should be suspended or when additional mooring lines or tug support should be called for.

Change in Vessel Draft and Trim and Tide Elevation The draft and trim of tankers usually change significantly during cargo operations. The vertical line angles will be different for loaded and ballasted conditions. Draft and trim changes also affect the hull area exposed to wind and current and thus affect the applied forces and moments. Thus, analyzing tanker moorings in both loaded and ballasted conditions is generally necessary.

A change in under-keel clearance also affects current forces and moments. Thus, conducting mooring analyses may be necessary for both low and high tide conditions. The corresponding current velocities and directions should be used.

Effect of Yaw on Mooring Forces and Moment Typical vessel wind and current force and moment coefficients are discussed in Sections 4.2 and 4.3.

A small change in wind or current attack angle from bow on or stern on typically causes a large change in the wind and current force and moment coefficients. This happens in critical angle regions for coefficients for some types of vessels.

Thus, repeating the mooring analysis may be necessary when a small change in vessel angle (yaw) results in a significant increase in the applied force or moment. The applied force or moment should be recalculated based on the new yaw angle.

Mooring Line Failure Sequence Mooring analysis is sometimes conducted to determine the consequences of mooring line failure. The failure of one mooring line can lead to cascading failure of additional mooring lines and progress to a complete breakaway of the vessel from the mooring.

An analysis can be conducted by increasing one or several components of the environment, e.g., wind or current, until a first line is tensioned to or near its breaking strength. That line is "broken" by removing it from the mooring system. The same environment is then applied to find if any other mooring line is loaded to or near its breaking strength.

If sufficient redundancy exists in the mooring system, only one or several mooring lines will fail and the vessel will then remain safely restrained by the remaining mooring lines. The resulting vessel movement in this situation should also be checked.

Superimposition of Wave Motion Effects Vessel motions in response to waves can increase mooring line tensions. This effect can be accounted for even in static analysis.

The vertical wave–induced motions—roll, pitch, and heave—are usually of most concern. These motions, especially roll, might be estimated from observing the actual vessel motion in waves. Or they might be calculated through the use of vessel response amplitude operators (RAO).

The estimated or calculated vessel motion at the fairlead or chock position for a particular mooring line can be added to the mooring line stretch, which was determined through static mooring analysis. The resulting mooring line tension can then be determined by applying this revised stretch to the mooring line load-stretch curve. This procedure is illustrated in Fig. 5-4. Flory and Banfield (2010) discuss this technique in greater detail.

Where wave-frequency vessel motions are of concern, this procedure may be more accurate than conducting a dynamic analysis, especially when the RAO function is used. Dynamic analysis computer programs sometimes calculate only the response to slowly varying second order wave forces. They might not consider the time-varying, first-order wave-frequency forces applied to the vessel and thus not calculate wave-frequency vessel motions.

Passing Ship Evaluation The response of a moored vessel to a passing ship is of concern at many terminals. Flory (2001, 2002) has presented empirical methods of estimating the time-varying forces and moments. The effects of quay wall influence on passing ship–induced mooring loads have been addressed by Flory and Fenical (2010). Seelig (2001) generally addresses passing ship effects on moored ships.

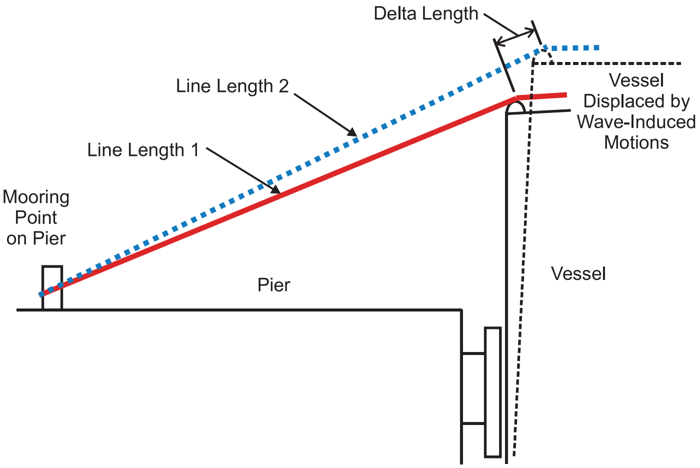


Fig. 5-4. Wave-induced vessel motion increases mooring line length and thus tension

With caution, the peak passing ship–induced forces and moment can be applied in a static mooring analysis. During the passage of a ship, the peak lateral force occurs at a different time than the peak transverse force and the peak moment, but applying them simultaneously is conservative. Nevertheless, this is generally not a conservative analysis.

If the results of such a passing ship analysis indicate that mooring lines become overtensioned by the passing ship effects, the solution might seem to be to reduce initial mooring line pretension. But this is the wrong solution.

During the passage of a ship, it is very important that the mooring lines apply sufficient tension to prevent the moored vessel from being pulled away from the pier. The fenders reacting against the vessel side provide friction forces that inhibit lateral motion along the pier. If the vessel is pulled away from the pier, then large lateral vessel motions may occur and may result in mooring line failure.

Thus, static analysis can only serve as a first evaluation of the severity of passing ship effects. The true time-varying response of the moored vessel can only be calculated by a dynamic analysis computer program.

5.2 DYNAMIC MOORING ANALYSIS

Dynamic analysis is required in cases where vessel motions may significantly contribute to mooring line loads such as due to, most commonly, wave action. As introduced in Section 2.4 dynamic analysis is typically called for under the following approximate threshold conditions: wave heights greater than approximately 4 ft and wave periods greater than approximately 4 s, especially when the vessel is exposed beam to sea, winds greater than approximately 75 knots and currents greater than approximately 3 knots, especially where wind gusts and current eddies or turbulence are expected, exposure to passing vessels as described in Section 4.4, especially in narrow channels, exposure to long period waves and harbor seiche action as described in Section 4.6 and exposure to severe storm conditions, moving ice and/or other site specific conditions that may give rise to vessel motions.

5.2.1 Introduction

Vessels moored to any type of mooring (e.g., single point mooring, multiple buoy mooring, or pier/jetty mooring) will, with enough excitation from environmental conditions (e.g., wind, waves, or currents), experience dynamic loads and vessel motions that exceed those developed from static mooring analyses. A dynamic analysis must be performed to develop a safe and accurate assessment of dynamic loads/motions; there is no substitute. Physical models were used to perform dynamic analysis prior to the development of reliable numerical models (circa 1975–1990). Numerical models are now commonly used for practical design problems. One of the keys to safe mooring design is recognizing the risk of dynamic loading and performing dynamic analyses when those risks exist.

Assessing a priori the risk of important and/or excessive dynamic loading is difficult without performing a proper dynamic analysis. Experience has proven, however, that several factors will usually give rise to dynamic loads. As general approximate guidelines, dynamic loading is likely to occur under the following conditions:

- Somewhat large moored vessels (e.g., Navy, container, auto, coal, and tanker ships, etc.) directly exposed to ocean waves (sea and/or swell conditions) with significant wave heights exceeding 1.0 m with peak wave periods exceeding 6 s.
- Somewhat small moored vessels (e.g., barges, recreational boats, floating breakwaters, tugs, etc.) exposed to ocean and/or local waves with significant wave heights exceeding 0.5 m with peak wave periods exceeding 3 s.
- Moored vessels, especially those at piers and/or jetties, exposed to harbor seiche (i.e., wave periods ranging from 25 s to several minutes); see Headland and Poon (1998).
- Moored ships exposed to swiftly moving vessels of a similar or greater size passing at somewhat close distance (several beams away); see Smith and Headland (2004).
- Somewhat large vessels, especially those with large sail areas, exposed to windspeeds exceeding about 45 knots; see Headland et al. (1989).

> Vessels moored to single point moorings exposed to large winds/currents and those characterized by large and sudden changes in direction. Such wind shifts are possible during squalls, thunderstorms, tropical, and extra-tropical storms (Seelig and Headland 1998). Sudden changes in current direction generally occur in the wake of flow obstructions such as islands or peninsulas (de Kat and Wichers 1991). Specifically, the wake areas can be characterized by large swirling eddies and/or vortices that produce rapid changes in direction of somewhat high speed currents.

The aforementioned general guidelines are approximate and based on experience with dynamic analyses and practical problems encountered in the field. The reader should take from these guidelines that many obvious and not so obvious tell-tales of risk exist. This manual will only address dynamic analysis of vessels moored to piers and wharves. Dynamic analysis of single point moorings (SPMs) and other free or spread moored vessels is beyond the scope of this manual and is covered elsewhere in the literature.

5.2.2 Theoretical Considerations

Dynamic motions of a moored vessel, like all dynamic problems, are governed by Newton's second law (Force = mass × acceleration), which can be summarized as follows:

$$(\textit{ship mass} \times \textit{ship acceleration}) + (\textit{damping coefficient} \times \textit{ship velocity}) + \textit{mooring or buoyancy force} = \textit{applied wind, current, wave or passing ship force on ship}$$

In mathematical terms, this is

$$(m + a)\ddot{x} + b\dot{x} + cx = F(t) \tag{5-7}$$

The mass of the ship is m. Coefficients a, b, and c represent ship added mass, damping coefficient, and restoring force, respectively. $F(t)$ represents a time-varying applied force, e.g., waves.

Application of Eq. (5-7) is difficult in practice owing to many complications. First, a vessel can respond in six modes of motion. These modes have been defined by naval architects as surge, sway, heave, roll, pitch, and yaw. As there are six modes, each mode requires six separate equations. In addition, several of the motions are coupled, which means that motion in one mode (e.g., yaw) will produce motion in another mode (e.g., sway.) This means that the equations must be solved simultaneously.

In addition to the physical mass of the ship, the ship behaves as though it has additional mass inasmuch as the vessel entrains water as it moves dynamically. This added mass (noted as coefficient a in Eq. [5-7]) is different for each mode of motion and varies according to the frequency of ship oscillation. Generally speaking, lower frequency (long period) motions entrain more water and give rise to larger added mass values than high frequency motions. In addition, added mass values increase with decreasing under-keel clearance.

Damping is a term borrowed from structural mechanics and connotes the forces that tend to resist dynamic amplification. In the context of ship mooring problems, damping factors stem from several physical phenomena. One of these is associated with the waves that are created by the vessel moving through the water. This damping force is important for high-frequency motions. Another, often more important factor, is the drag force on a ship hull that arises when the hull moves through the water. This drag force is analogous to the current force on a rigidly held ship hull. The drag damping forces are very important for low-frequency ship motions.

The natural periods of most single point and multiple buoy moorings in surge, sway, and yaw are much longer than the periods of incident sea waves (i.e., <20 s). This is also true of ships moored to piers, especially in the surge mode. In other words, somewhat large moored ships respond to wind, wave, and current excitation at low frequency. As a result, loads on ship moorings (as distinct from smaller vessels such as barges and floating docks) tend to be dominated by low-frequency excitation. Both winds and waves produce low-frequency excitation. Wind speeds vary over time and produce energy at low frequency, particularly for larger wind speeds. Waves produce forces proportional to wave height (i.e., first-order wave forces) with periods equal to the wave period and forces proportional to the square of the wave height (i.e., second-order wave drift forces) with longer periods corresponding to differences in wave frequency. Wave drift forces and low-frequency wind energy often produce energies near the natural periods of moored ships in surge, sway, and yaw. Accordingly, line/fender forces and motions on moored ship are often dictated by low-frequency excitation.

Finally, mooring elements, such as lines, chain, and fender, tend to be nonlinear (i.e., the force-deflection curve of these elements have a hyperbolic shape rather than a straight line). This complication makes solving the equations of motion numerically rather than analytically necessary.

The interested reader should refer to Van Oortmerssen (1976) or Wichers (1988) for a more complete discussion of dynamic mooring analysis. More information on dynamic analysis models can also be found in Headland and Smith (2004a, 2004b). Overall, dynamic mooring analysis involves using a hydrodynamic model and a mooring dynamics model. The former model computes vessel added mass coefficients, damping coefficients, and first/second-order wave forces. The latter model computes vessel motions and mooring line/fender forces. Wind and current loads are computed using methods like those presented earlier for static analysis.

Using results from the hydrodynamics model, the mooring dynamics model solves the equations of motion discussed previously. The equations of motion can be solved in either the frequency or time domains. Linearized versions of the dynamic equations of motion can be solved in the frequency domain in a manner analogous to the mass-spring-dashpot systems of structural dynamics. This linearized simplification is debilitating for most problems inasmuch as the mooring lines and the second-order drift forces are nonlinear. Moreover, frequency domain analysis cannot simulate the complicated motions of SPMs (e.g., fishtailing, motions associated with wind shifts, etc.) where the applied forces are a strong function of vessel heading.

Accordingly, time domain analysis is preferred for practical problems. Time domain analysis involves integrating a time domain version of the aforementioned dynamic equations of motion through time. Typically, time domain simulations are made for periods of 30 min to an hour or more depending on the nature of the problem. Arbitrarily varying wind, wave, and currents can be simulated in the time domain as can the nonlinear behavior of the mooring lines, chains, and fenders.

The following subsections present governing equations for most hydrodynamic models and equations of motion for three mooring types based on derivations published by the Maritime Research Institute Netherlands (MARIN).

5.2.3 Typical Hydrodynamics Models

Most ship hydrodynamic models employ finite element or panel methods to calculate vessel hydrodynamic coefficients of added mass and radiation damping and first- and second-order wave loading as a function of wave frequency. A brief summary of the problem formulation is given below.

Hydrodynamic models solve the wave/ship interaction problem in terms of potential flow theory. The six modes of ship motion are expressed as

$$x_j = x_{aj} e^{-i\omega t}, \quad j = 1, 2, \dots 6$$

where x_j is a displacement for $j = 1, 2, 3$ and a rotation for $j = 4, 5, 6$, and x_{aj} is the corresponding complex amplitude, t is the time, and ω is the radian wave frequency.

The total velocity potential describing the flow field is written as

$$\Phi = \phi_0 e^{-i\omega t} + \sum_{j=1}^{6} \phi_j x_{aj} e^{-i\omega t} + \phi_7 e^{-i\omega t} = \Phi_w + \Phi_f + \Phi_s \tag{5-8}$$

where

Φ_w = potential of the incident wave,

Φ_f = potential of the waves generated by the ship motion, and

Φ_s = potential of the scattered waves.

Each of these velocity potentials also has to satisfy the Laplace equation, i.e.,

$$\nabla^2 \phi_j = 0, \quad j = 0, 1, \ldots, 7 \tag{5-9}$$

Typical hydrodynamic models solve Eqs. (5-8) and (5-9) together with the appropriate boundary conditions. After the velocity potential has been determined, wave loading on the ship and the hydrodynamic coefficients can be calculated by using the pressure equation. The fluid pressure p at any point in the fluid domain can be obtained from the linearized Bernoulli equation:

$$p = -p \frac{\partial}{\partial t} \Phi - \rho g z \tag{5-10}$$

where ρ is the fluid density, g the acceleration due to gravity, and z the depth below water surface.

The total force F_i acting on the ship can then be obtained by integrating the pressure over the surface of the ship. Applying Newton's second law of motion, the pressure equation, and the solution of the velocity potentials, the equations of motion of the ship in matrix form can be written as

$$m_{ij} \ddot{x}_j + K_{ij} x_j = \zeta_a f_{ei} e^{-i\omega t} + f_{ij} x_{aj} e^{-i\omega t} \tag{5-11}$$

where

m_{ij} = six-by-six mass matrix of the ship,
K_{ij} = hydrostatic restoring force (moment) matrix,
x_j = motion vector,
f_{ej} = wave exciting forces and moments per unit wave,
f_{ij} = forces and moments per unit ship motion, and
ζ_a = wave amplitude.

The added mass and damping coefficients can be found upon separation of the real and imaginary parts of Eq. (5-11). In addition to the first-order wave forces, a ship is also subjected to second-order mean and low-frequency wave drift forces. These forces are partially attributable to the velocity-square terms in the Bernoulli equation, partially attributable to the elevation variation of the water surface, and partially attributable to first-order ship motions. The method used to compute these forces is based on the perturbation method developed by Pinkster (1980).

5.2.4 Pier Mooring Exposed to Wind, Currents, and Waves

This section considers an LNG carrier moored at a conventional pier/jetty-type terminal (Fig. 5-5). The following example applications are presented:

- Pier mooring exposed to wind, currents, and waves (Van Oortmerssen 1976);

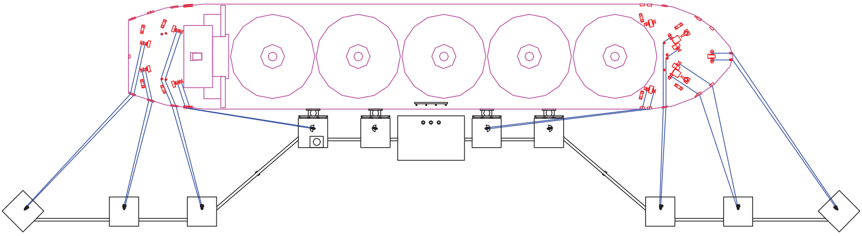


Fig. 5-5. LNG carrier pier/jetty mooring

- Pier mooring exposed to seiche (Headland and Poon 1998); and
- Pier mooring exposed to passing vessels (Headland and Smith 2004, Smith and Headland 2004)

The marine terminal is occupied by a 138,000 m^3 LNG carrier. The length, beam, and draft of this vessel are 290 m, 46 m, and 11.5 m, respectively. The terminal is exposed to winds, waves, and currents. The ship mooring system comprises mooring lines (i.e., wire ropes with nylon tails) and buckling "pi-type" fenders. The allowable safe working load (SWL) in the mooring lines was set at 55% of the minimum breaking load (MBL). The allowable working load in the fenders was the rated reaction at maximum deflection (55%).

A range of wave conditions were evaluated for a ballasted vessel in combination with a 10 knots wind and a 1 knot current. Specifically, wave direction varied +/ − 45° from the ship's bow for significant wave heights of 0.5 m, 1.0 m, and 2.0 m. The maximum allowable wave period for each height/direction combination was then computed. Maximum allowable conditions were based on allowable fender and line loads as described previously. Results of the analyses are presented in Fig. 5-6, which shows that the largest wave periods correspond to waves directly along the bow of the vessel, whereas the smallest wave periods are for wave directions at +/ − 45° from the vessel bow. The allowable wave periods for the 45° cases are less than 10 s for a 2 m significant wave height, less than 12 s for a 1 m significant height, and less than 16 s for a 0.5 m significant height. These results demonstrate that wave loads dominate despite the somewhat large vessel size, even for somewhat small wave conditions.

5.2.5 Pier Mooring Exposed to Seiche

Seiche events experienced at Pier J in Long Beach, California, during the 1990s had wave heights generally less than 10 cm with periods ranging from 25 to 500 s. These wave conditions produced large amplitude surge and sway container ship motions (and attendant large line and fender forces) at the terminal. Investigations were carried out during the late

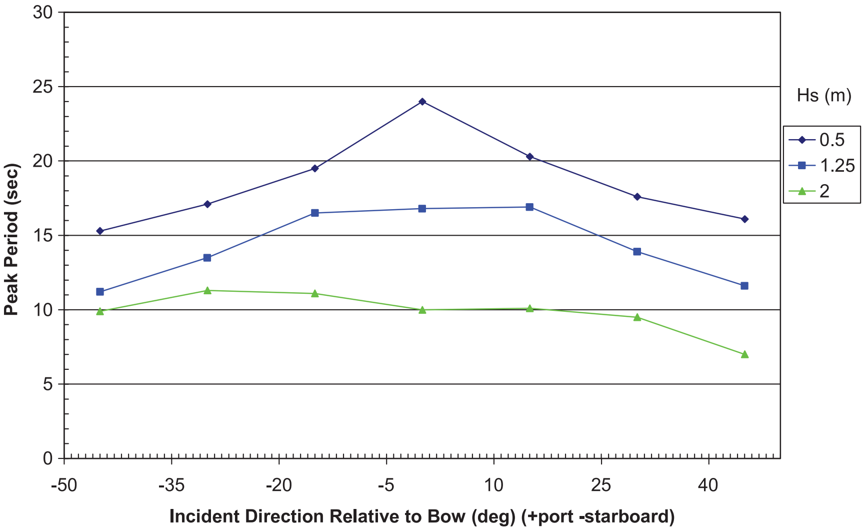


Fig. 5-6. Pier mooring model results

1990s to determine the nature of the problem and evaluate means for correcting or ameliorating seiche-induced problems. The work culminated in the construction of a protective breakwater. This section summarizes the work of Headland and Poon (1998) regarding evaluation of ship motions with and without the breakwater.

Unlike ship motion investigations of short waves in open water, simultaneously evaluating the hydrodynamics of the moored ship and the Pier J basin in a single model was necessary. This need stemmed from the complex interactions of the seiche waves, the moored ships, and the harbor basin. Failure to account for this interaction would lead to inaccurate estimates of added mass, damping coefficients, and first- and second-order wave forces. The two hydrodynamic meshes used for the without and with-breakwater conditions are shown in Figs. 5-7 and 5-8, respectively. The container ships modeled as part of this effort had lengths ranging from 965 to 1,040 ft, beams ranging from 100 to 140 ft, and drafts ranging from 33 to 41 ft.

The ship mooring geometry is presented in Fig. 5-9 and shows that the ship is secured by bow, stern, and breast lines and many fenders.

Two different mooring systems were tested, namely, all nylon lines (mooring 1) and a mixture of steel and nylon lines (mooring 2). The time domain mooring dynamics model was run for several statistically representative wave heights and corresponding seiche wave spectra. Fig. 5-10 presents results of the model runs for a seiche significant wave height of 4.6 cm in terms of vessel surge.

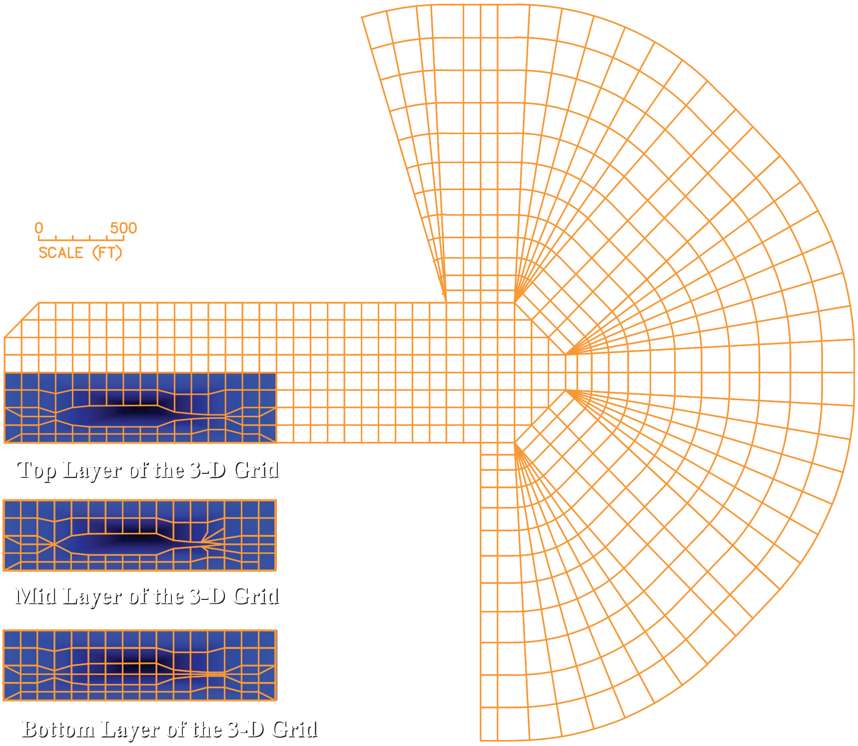


Fig. 5-7. Ship/basin hydrodynamics model

The first conclusion to draw from Fig. 5-10 is that a tremendous amount of surge motion (4.26 ft) is generated by a small wave (4.6 cm). This corresponds to a surge response amplitude operator on the order of 14. The second conclusion is that the breakwater was predicted to reduce vessel motions at the east and west berths of Pier J. Finally, it is clear that seiche vessel motions can be strongly influenced by location in the basin and the type (i.e., stiffness) of the mooring system. Fig. 5-11 shows time histories of motions for a seiche significant wave height of 7.4 cm for a medium-sized container ship using mooring system 1 located at the western end of the basin. The peak-to-peak maximum surge for this simulation was 8 ft.

The breakwater was construction in the late 1990s and has served to ameliorate the problems at the berth. Few incidents of problematic surge motions have occurred in the past 5 years.

5.2.6 Pier Mooring Exposed to Passing Vessels

Several references have emphasized methods for computing hydrodynamic forces imposed on the moored vessels (e.g., Seelig 2001 and

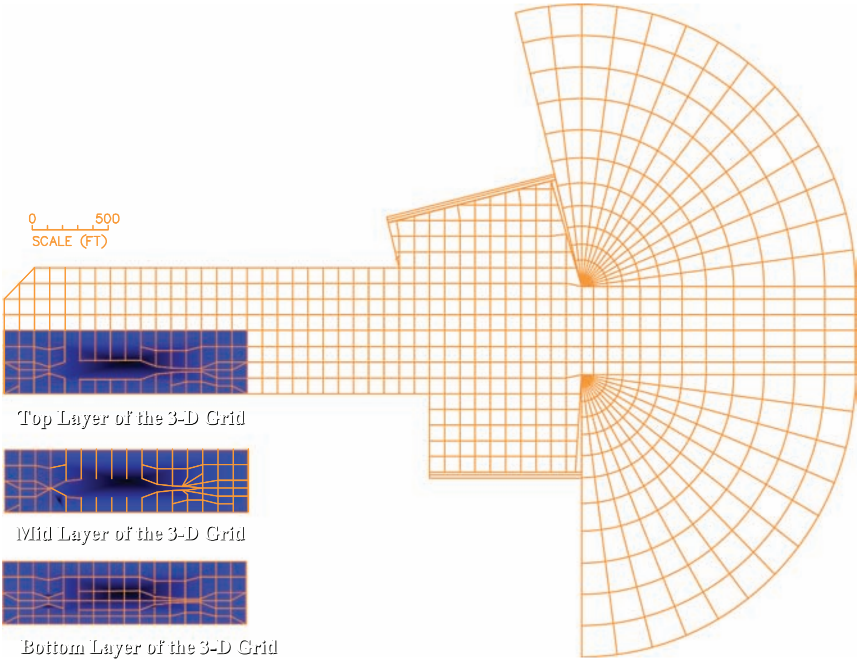


Fig. 5-8. Ship/basin hydrodynamics model with breakwater

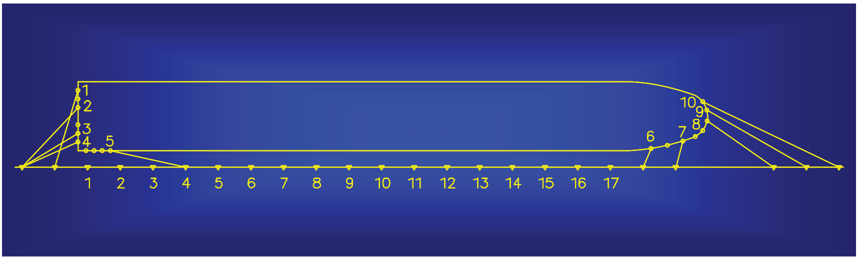


Fig. 5-9. Ship mooring geometry

many others). These forces are an essential element in examination of practical problems. To fully examine practical problems, however, conducting a dynamic analysis that simulates the dynamic response of a moored vessel to the imposed hydrodynamic forces is necessary. The moored vessel may experience loads less than, equal to, or larger than the imposed passing ship forces depending on all the factors that dictate dynamic response (i.e., ship mass, system damping, mooring stiffness, etc.). Given the propensity for vessels to respond dynamically in the case of passing ship problems, the authors have found that

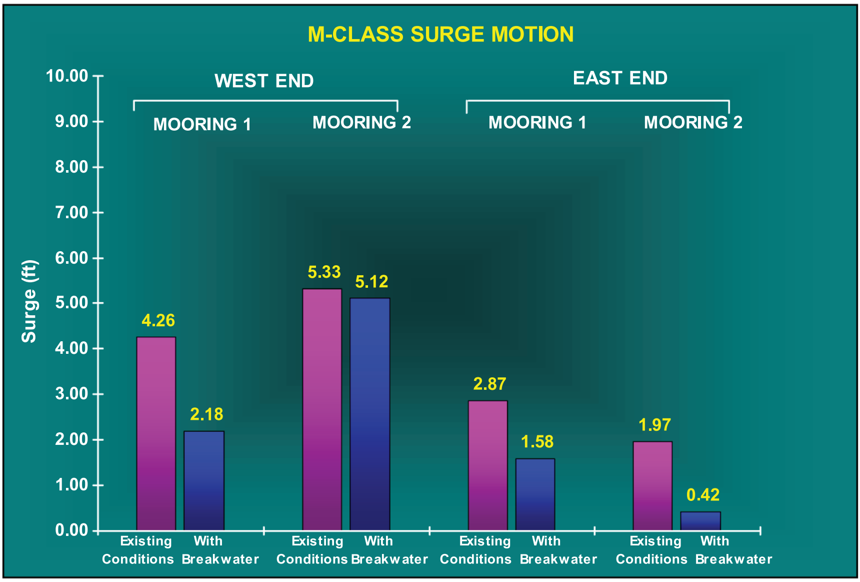


Fig. 5-10. Model results for peak-to-peak surge motion

dynamic analysis is imperative for practical applications (Smith and Headland 2004). The example problem considered here consists of a 138,000 m^3 LNG tanker passing an identical moored LNG tanker.

The mooring lines can be categorized into three groups. Lines 1–2 and 15–16 represent bow and stern lines, respectively. Two lines emanate from each relevant mooring or breasting dolphin as shown in Fig. 5-12.

Lines 3–6 and 11–15 are breast lines used to resist loading in the sway direction (i.e., loads that move the ship off berth to port). Lines 7–8 and 9–10 are spring lines used to resist surge motion (i.e., fore and aft). As is typical of many fixed or jetty mooring arrangements, surge forces tend to be resisted only by two spring mooring lines. The bow and stern lines assume relatively little pure surge and sway load. This mooring arrangement is typical for an LNG berth exposed to waves, strong winds, and/or strong currents.

The example problem was formulated to show the influence of ship speed, separation distance, and mooring line pretension on moored vessel dynamic response. Four cases are presented as follows:

- Case 1: 1.5 × B separation, 4 knots speed, 5% MBL pretension;
- Case 2: 1.5 × B separation, 4 knots speed, 10% MBL pretension;
- Case 3: 1.5 × B separation, 8 knots speed, 5% MBL pretension; and
- Case 4: 1.5 × B separation, 8 knots speed, 10% MBL pretension.

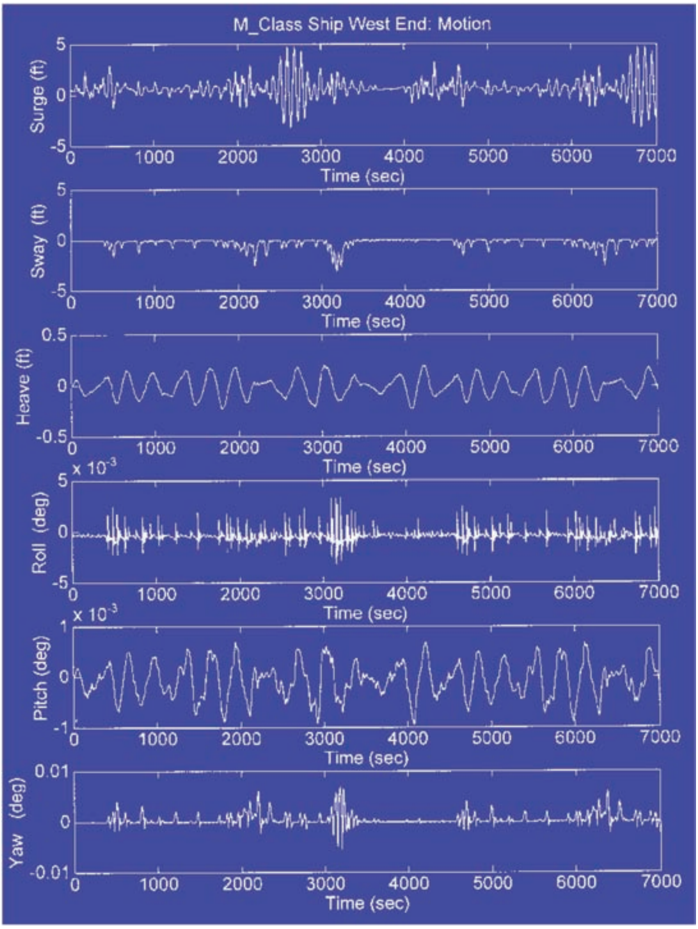


Fig. 5-11. Seiche motion time histories

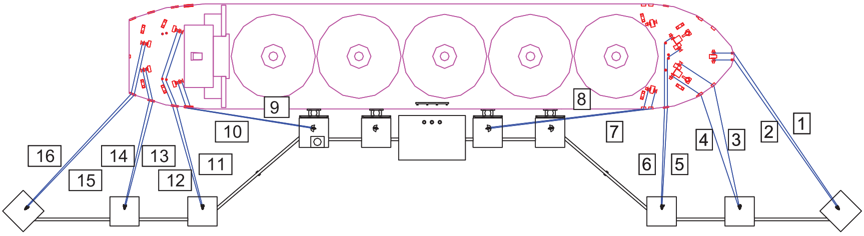


Fig. 5-12. Mooring arrangement for LNG in passing vessel example

The following paragraphs summarize dynamic model results in two ways. The total static and dynamic hull forces on the moored vessel are presented first (Fig. 5-13). The dynamic hull force is the maximum instantaneous sum of all forces on the moored ship hull (hydrodynamic static force, inertial, and damping forces, and mooring forces). This comparison allows for direct comparison of static and dynamic forces. Second, maximum dynamic mooring line forces are compared with static mooring line forces (Fig. 5-14). Mooring lines were grouped into three categories: (1) forward group = lines 1–6, (2) spring group = lines 7–10, and (3) stern group = lines 11–16.

Figure 5-14 shows that an increase in mooring line pretension reduces dynamic response. This is an important principle for managing certain classes of passing ship problems. The authors have found that many passing ship problems, and mooring problems in general, result from poor mooring line management. Typically, mooring lines are not properly laid out or pretensioned during the entire berthing time. Specifically, mooring line geometry (and stiffness/pretension) changes as the vessel draft changes with vessel loading (or unloading) and tidal variations. The lack of mooring line management will not be critical as long as the vessel is not exposed to passing vessels and inclement weather. The typical accident occurs when the mooring lines have not been tended, the vessel is exposed to a passing ship, and a line or two are parted.

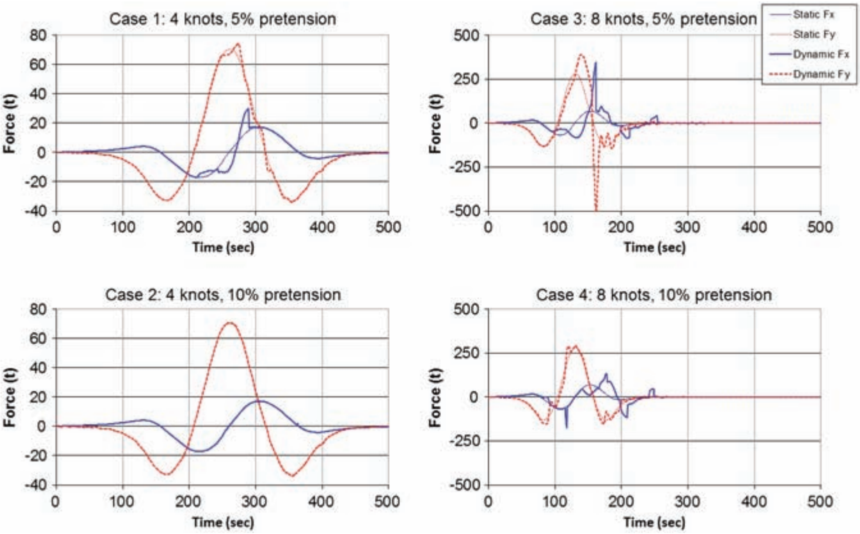


Fig. 5-13. Dynamic versus static force (separation distance 1.5 × beam)

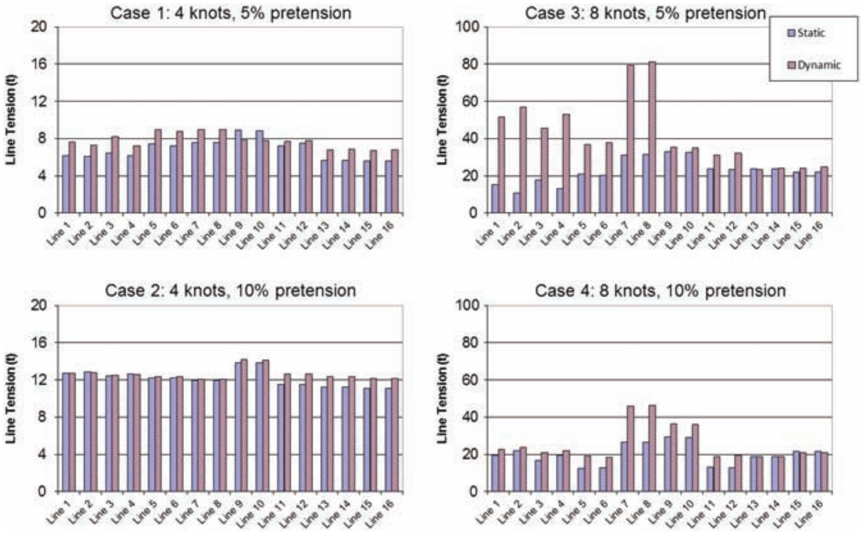


Fig. 5-14. Dynamic versus static line tension (separation distance 1.5 × beam)

Fig. 5-14 shows that the moored ship experiences some dynamic response at the 4 knots speed. The dynamic response is prevented by increasing the pretension in Case 2. The largest dynamic response corresponds to the low pretension, 8 knots speed Case 3. It is worth mentioning that many passing ship problems involve problematic dynamic surge response. One of the reasons for this is that often only a few lines (two in the example problem) resist the surge force. Increasing the mooring pretension tends to limit dynamic response because it (1) acts to keep slack lines from snatching under load, (2) serves to balance applied loads among available mooring lines, and (3) fetches the vessel up against fenders that act to resist surge motion through fender friction. The dynamic amplification is significant in both surge and sway directions. Application of a greater pretension in Case 4 reduces but does not eliminate the dynamic response.

Fig. 5-14 presents the peak mooring line forces for each case in the same format as Fig. 5-13. The results show that the moored vessel responds dynamically for the lower pretension, the dynamic mooring line loads exceed the static loads, and added pretension dampens the dynamic load as indicated earlier. The upper right-hand panel of Fig. 5-14 presents the most dramatic case considered: 1.5 × beam separation, 8 knots passing vessel speed, and 5% MBL pretension. The efficacy of dynamic mooring analysis is clear here. Large dynamic loads are experienced in both the forward and spring line groups. The loads in the spring lines exceed the safe working load. The static analysis does not indicate a mooring line load problem; in fact, loads are less than half of the dynamic loads. This case demonstrates the need for dynamic analysis in practical passing ship problems. Increasing the pretension to 10% substantially reduces the mooring line loads; however, dynamic spring line loads still exceed the static mooring line loads.

Moored vessels can experience large, threatening dynamic loads in excess of static loads when passed at somewhat high speed and narrow separation distances. Stout mooring designs, however, serve to make passing ship problems manageable. From an operator's perspective, many passing ship problems arise owing to poor mooring line management. Tending lines properly, in particular maintaining appropriate pretension, can eliminate many practical problems. Ship speeds may have to be limited or separation distances increased, in some cases.

5.3 AVAILABLE SOFTWARE

Numerical models are necessary for simulations and assessment of dynamic mooring loads and motions. Several commercially available software programs may be applied to the solution of dynamic mooring analysis. The following paragraphs provide a synopsis of such programs and their capabilities and applications. The following list may not be comprehensive and does not include proprietary codes not available for purchase.

5.3.1 TERMSIM II

TERMSIM II is a time domain program, developed by Maritime Research Institute Netherlands (MARIN) as part of a joint industry project. The program was formulated to analyze the dynamic behavior of a moored tanker subject to wind, waves, and current. The mooring system may be an SPM, a multibuoy mooring, or a jetty terminal. The program simulates the mooring loads and vessel motions when the system is exposed to operational environmental conditions.

TERMSIM provides a robust, validated program that can be efficiently set up to simulate mooring configurations of a single tanker (or bulker) shaped vessel. The program cannot simulate multiple floating bodies. For nontanker or bulk carrier vessels, wind, current, and hydrodynamic response characteristics must be calculated outside the program and imported.

The vessel in TERMSIM is a generic tanker of regular dimensions. The hydrodynamic data for the vessel were validated based on the scale model tests of tanker-shaped hulls conducted at the MARIN wave and current basin. A series of tests of various tanker sizes at different loading conditions and water depths were used to populate a database of hydrodynamic response characteristics. Based on the main particulars of the vessel (e.g., length, breadth, draft, water depth, and displacement), the user makes a selection from the database, which is scaled to match the design vessel and site conditions. A user-defined vessel can also be input in the program.

The environmental conditions may include steady currents, steady or irregular wind fields, and/or swell and long-crested irregular waves from arbitrary directions. Several spectral formulations for the wind, waves, and swell are available. The program is capable of simulating vessels in both shallow and deep water. Wind and current loads are calculated based on standard OCIMF (2008) force coefficients for crude and gas carriers. External forces may also be applied to the ship to simulate passing vessel effects, tug forces, or other loads.

The program is populated with several databases of common mooring equipment types and sizes for the user to select. The mooring element database contains particulars of common offshore chains, steel wires, synthetic ropes, and fenders. For synthetic ropes, load-elongation characteristics are included. The load-compression curves for various fender types are included in the database. User-defined characteristics of lines and fenders may also be used.

The output of each simulation consists of a binary file containing all samples of the calculated signals. The signals include tanker motions, velocities, and accelerations and the loads in the mooring lines and fenders and the external forces applied to the vessel. In addition, an output file is produced summarizing the maximum, minimum, and mean forces and motions, as well as factors of safety. A comprehensive data-processing package is delivered with the program to view, plot, and print the results.

5.3.2 AQWA Suite

AQWA is a suite of programs that performs three-dimensional diffraction/radiation analysis and calculates first-order and second-order (nonlinear drift) forces on fixed or floating bodies. The program is useful for mooring problems involving multiple vessels or where the submerged geometry of the vessel hull must be explicitly defined. The program requires more preprocessing and setup than a program like TERMSIM or OPTIMOOR but offers more flexibility in the definition of the vessel and the mooring configuration. For instance, objects such as breakwaters or floating harbor structures may be included to model the interaction and sheltering of wave fields.

The submerged body surface is described by a finite element mesh. The software can resolve multiple floating bodies simultaneously and fixed structures. Time domain mooring analyses can be computed including the influences of nonlinear mooring elements (i.e., catenary chains, synthetic hawsers, winches, and fenders). The model is capable of simulating multiple wave trains with different frequency spectra, gusting winds, and currents. Port structures, such as breakwaters, may be incorporated as fixed structures to model.

The suite of programs comprises modules for computing diffraction/radiation analysis, time domain analysis, and frequency domain analysis. The individual modules are described as follows.

AQWA-LINE: Calculation of wave loading from diffraction and radiation around an arbitrarily shaped floating body. AQWA-LINE performs a three-dimensional diffraction/radiation analysis of wave action around a single floating body, using the classical Green's function approach. The body surface is described by a finite element mesh, and a pulsating source is located on each plate element. The combinations of source strengths required to diffract an incoming regular wave of given period and to allow body oscillation in each degree of freedom are then calculated. From these are obtained the diffraction force, added mass, and radiation damping on the body, which are then stored in the AQWA Suite database for use by other AQWA programs. In addition, AQWA-LINE combines them with the body's motions in all six degrees of freedom and the associated steady wave drift forces.

AQWA-DRIFT: Calculation of the motion and load time histories of an assembly of the floating bodies and mooring systems (mooring lines and fenders) during long irregular wave sequences. AQWA-DRIFT takes from AQWA-LINE the added mass, radiation damping, diffraction force, and drift force on each floating body in an assembly for each of a series of regular wave periods and calculates their motions in an irregular wave train of any given spectrum. The separate bodies can be linked by articulations or mooring lines, which are modeled in a fully nonlinear way. Wind and current loads from any direction are included, and all loading calculations account for the changing headings of the various floating bodies.

Because AQWA-DRIFT models the very long-term slow drift motions and short-term wave frequency motions, it is typically used for producing time histories covering very long periods. No assumption is made that wave frequency motions are independent of mooring forces, so complicated nonlinear mooring snatch phenomena can be accurately simulated. The output of the model includes motions in six degrees of freedom and loads in all mooring components.

AQWA-FER: Frequency domain calculation of the mean and significant linear and second-order motions and loads in the floating structures in irregular waves. AQWA-FER takes from AQWA-LINE the added mass, radiation damping, diffraction force, and drift force on each floating body in an assembly for each of a series of regular wave periods. It also reads data on articulations and mooring lines among the bodies and calculates the effective stiffness and constraint effects at a given equilibrium position. From this information, AQWA-FER computes the RAOs for the motions and loads at any specified points in the assembly and thus deduces the linear response spectra to a given sea spectrum from which the significant and extreme linear response is calculated. In addition, the mean value and spectrum of second-order forces on the assembly are calculated from the wave spectrum and the drift force data; these lead to mean, significant, and extreme second-order responses in a similar way. AQWA-FER can be instructed to perform calculations for several specified wave spectra in turn, producing output in tabular form, showing mean and significant loads and motions over a whole range of sea states.

5.3.3 OPTIMOOR

The OPTIMOOR mooring analysis computer program was developed by Tension Technology International in the early 1990s as a static analysis program. The ability to perform dynamic analysis was incorporated into the program in the early 2000s.

To perform an OPTIMOOR analysis, the user enters data for the vessel, the pier or other mooring facility, and the environment on spreadsheet-like window screens. The mooring is then set up in an arrangement window or in a plan-view graphic window. Each time input data are changed in the arrangement window, a mooring analysis is immediately performed, and the resulting mooring line tensions, fender loads, and vessel movement are displayed.

Wind and current force and moment coefficients for many vessel types, including licensed OCIMF (1994) coefficients, are included in the OPTIMOOR program. Strength and stretch data for many types of mooring lines, fiber, wire rope, and chain are included in the program.

Wind-sweep and current-sweep polar graphs displaying line tensions and other output data can be displayed in special windows and can be printed or saved as graphics.

The OPTIMOOR standard version performs static analyses of vessel moorings alongside conventional quays, piers, and sea islands. The plus version performs static analysis of vessel moorings, employing catenary anchor legs, such as sea berths, and moorings with fenders on two faces of the vessel. In batch mode, many static analyses can be set up to run unattended by combining specified environment and ship conditions. The program then runs all cases automatically and identifies worst-case scenarios.

The OPTIMOOR dynamic version uses vessel hydrodynamic characteristics and ship maneuvering theory to perform dynamic analysis. The user can input force and moment time histories for wind, current, wave drift, ice flow, tug actions, and other time-varying phenomena.

The program can calculate force and moment time histories for several wind spectra and for passing ship scenarios, including effects of speed and vessel separation. Dynamic analysis results can be displayed and printed as time histories.

The OPTIMOOR optional Ship-2-Ship module analyzes a guest vessel moored alongside a primary or host vessel. Mooring lines can be run from host to guest, from guest to host, and from either or both ships to shore or seafloor. In addition to the regular data output, this option also calculates, displays, and prints intervessel mooring line tensions, fender forces, and motions of selected targets. It can be used with any of the three OPTIMOOR versions.

The optional OPTIMOOR Wave Response module (formerly known as Seakeeping) calculates first-order six degrees of freedom vessel motions. It calculates the resulting extreme vessel fairlead movements, and from these it calculates the resulting increased mooring line tensions. It does the same for fender forces and for tanker manifold or other vessel target location movements. It also calculates the quasistatic wave drift forces for static analysis and simulates the varying drift forces in dynamic mode. OPTIMOOR uses hydrodynamic coefficient files (HCFs) to calculate the wave-induced vessel motions. An HCF represents nondimensional hydrodynamic properties for a particular shape and can thus be used for similar vessels of any size. The RAO functions are calculated for the moored ship over a range of drafts and water depths, in open water and alongside a solid quay wall, accounting for the mooring characteristics, GM, and roll damping specified by the user. These OPTIMOOR HCFs are now available for many vessel forms, including typical gas carriers and tankers. This option can be used with any of the three OPTIMOOR versions.

More than 400 OPTIMOOR licenses have been granted since 1993. Users have successfully compared and verified the dynamic OPTIMOOR with other dynamic computer programs and with measured mooring line loads.

5.3.4 EMOOR and FIXMOOR

Although not a computer software program, the spreadsheet program EMOOR developed by Seelig (1998) is worthy of mention. EMOOR is a planning and preliminary design tool for evaluating ship moorings and optimal mooring line layouts at piers and wharves. The NAVFAC program FIXMOOR was developed into a web-based interactive program with access to U.S. Naval Ships' database and is capable of static pier-side mooring analysis for naval vessels subject to wind and current and tide level changes. The original program was intended for planning analysis and preliminary design purposes. This program is available in the public domain but requires a password from the U.S. Navy.

5.4 PHYSICAL MODELS

Physical modeling of mooring systems is somewhat rare given the sophisticated numerical models now available. Physical models tend to be more time consuming and expensive than numerical models and yield a smaller set of analysis cases. Nonetheless, physical models may be useful where the environmental forces on the moored ship are more complicated than may be represented by numerical models or where verification of numerical results is needed. Examples of mooring problems that may benefit from a physical model include

- Long-period harbor oscillations,
- Passing vessel effects,
- Ice flow conditions, and
- Eddy currents or multilayer currents.

Physical modeling should be conducted in a reputable laboratory with experience in modeling vessel moorings. Physical hydraulic models are subject to Froude's model law. Selection of the model scale is important and should be undistorted. Often this is a balance or trade off between minimizing scale effects and cost. If harbor features (breakwaters, quay walls, etc.) are included, the model scale is often determined by the physical constraints of the laboratory basin and the scale necessary to represent all harbor elements. Typical model scales for vessel moorings are 1:50 to 1:100. Larger scales may be possible if harbor geometry is less important (for example in a tow tank). The hydraulic model basin operator will be able to provide guidance on appropriate scale for the problem being investigated.

The hydraulic model lab may have specialized equipment for investigating particular phenomena and may vary from facility to facility. The engineer is advised to verify capabilities when soliciting proposals for the work. Specific capabilities may include

- Random wave generation,
- Single or multiple wave directions,
- Uniform or varying currents,
- Wind effects, and
- Ice modeling.

Data collected in a physical model include time series measurements by instrumentation. For vessel moorings instrumentation should include mooring restraint loading, fender loading, vessel motion tracking in six degrees of freedom, local water surface elevation, and current velocity (if needed). Photos and video recordings of the model experiments provide valuable documentation of the response of the moored vessel and are useful for presentation of results.

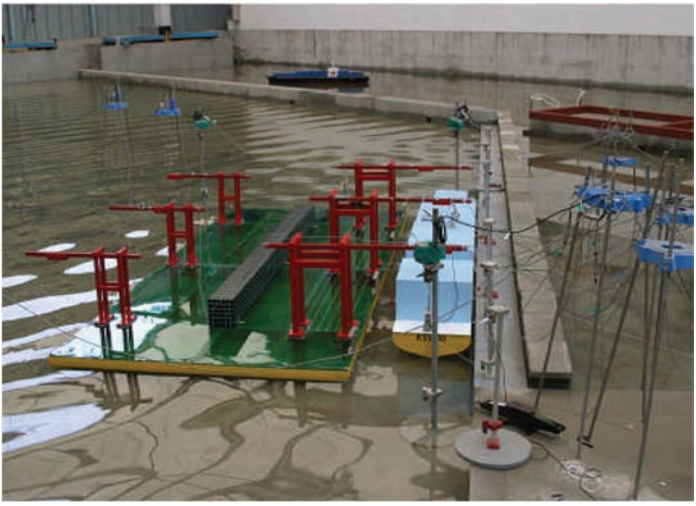


Fig. 5-15. Physical model setup for floating port and containership motions study
Source: Courtesy of Korea Institute of Ocean Science and Technology

An example of physical model studies in mooring investigation include the research of Kriebel (2005), which investigated the effects of mooring loads due to parallel passing ships at the U.S. Naval Academy. The paper describes the scaling methods, instrumentation, procedures, and results of 144 tests of a passing vessel on a moored ship. Figure 5-15 shows a 1–100 physical model test setup to evaluate the operational safety of a floating hybrid quaywall and containership moored alongside a fixed quaywall under wave action. Mooring line tensions, fender reactions, and vessel motions were measured over a range of environmental conditions.

CHAPTER 6

OPERATIONAL CONSIDERATIONS

6.1 GENERAL CONSIDERATIONS

Ultimately the successful berthing and mooring of ships within ports and at marine terminals depends on the combined efforts of many parties who seldom interact directly. Broadly, the major parties can be classified as representing the "ship side" or the "port side." On the ship side are the owners and operators, including the ship's crew and the ship's designers and builders. On the port side are owners and operators, often a public or semipublic port authority, and the designers, builders, and port engineers responsible for facility and infrastructure maintenance. Also on the port side are local regulatory authorities, such as the harbor master, Coast Guard, etc. Pilots, tugs, and line handlers fall somewhere in between these two broad categories. Generally, the ship side is responsible for supplying and tending the mooring lines and keeping watch, whereas the port side is responsible for providing ample and secure mooring points and fenders and for advising the ship's captain and crew of any particular hazards, such as strong currents and conditions, that would require the vessel to vacate the berth. Sometimes the division of responsibility may become blurred, for instance when the ship must remain alongside under adverse conditions and the port provides additional storm rigging and mooring points.

6.2 VESSEL MOVEMENTS

Vessel motions at berth, due primarily to wave action, may be a limiting factor in mooring analysis especially as it affects operations and the transfer of cargo. This section addresses allowable vessel motions and possible mitigation measures.

6.2.1 Introduction

A port or harbor is by definition a place where vessels can seek shelter from prevailing winds and waves. Nonetheless, harbors vary widely in the degree of shelter actually provided, as does the resulting exposure of vessels to movements caused by wind, waves, and currents. As natural harbors become congested and the cost of creating artificial harbors escalates, vessel berths are increasingly being built in more exposed locations where vessel movements can become a limiting factor in the viability of a port. Although some degree of vessel movement at berth is unavoidable, excessive vessel movements can lead to increased wear and tear on equipment, hamper the ability to efficiently load and unload cargo, and jeopardize operator safety. In extreme instances, the economic viability of a port can be undermined by the severity of the resulting vessel motions at the berth. For these reasons, considering the vessel motions during the planning process and establishing acceptable movement limits are critical parts of developing the design criteria for the berth in question.

As discussed in Chapters 2 and 4, vessel motions may be caused by many driving forces, including wind, waves, swell, harbor seiche, currents, and the transient effects of passing vessels. How a vessel responds to a given wave climate is discussed in Section 4.5 and depends largely on the vessel characteristics and the height, frequency, and direction of the waves relative to the vessel heading. For most large vessel mooring problems, waves of less than 1.0 m in height and 6 s in period will have little effect and can usually be neglected. Wave periods in the range of 6–20 s can coincide with the vessel's natural frequencies in roll, heave, or pitch. Such waves can generate periodic vessel motions at about the same frequency with a range in direct proportion to the wave height. Low-frequency energy from harbor seiching or second-order wave drift effects can produce excitation forces with periods of 20 s to several minutes. Energy at these frequencies can coincide with the natural frequency of the vessel mooring system, generating a response in the horizontal modes (i.e., surge, sway, and yaw). As discussed in Section 5.2 the horizontal motion at these frequencies can be very large, often an order of magnitude or more in excess of the wave height.

6.2.2 Acceptable Limits for Vessel Motions

Although numerous authors, some of whom are described in the following discussion, have proposed limits for what constitutes "acceptable" limits for vessel motions, as yet no widely accepted set of movement thresholds exists that will apply in all cases. The amount of movement considered acceptable for a vessel berth varies widely depending on a complex set of factors, including

- The size of vessel;
- Whether the ship is loaded or light;
- Type of cargo and cargo-handling equipment;
- Operator/stevedore skill;
- The wave frequency (i.e., the speed of movement);
- The particular degree of freedom being considered (roll, heave, surge, etc.);
- The nature of the landside mooring system (e.g., fixed bollards versus quick release hooks);
- The type of mooring winches used on board the vessel (e.g., constant tension or fixed);
- Whether "safety" or "cargo-handling efficiency" is the primary concern; and
- Local opinion and traditions of tolerance.

With the exception of certain specialty types of vessels such as LNG tankers (where movements may be limited by the amount of articulation possible in the loading arms), the proposed limits generally do not represent absolute upper bounds beyond which further operation becomes impossible. Rather, the effect of increasing ship movements is to progressively degrade operational efficiency in a more or less continuous spectrum. As in all areas of engineering, a certain amount of professional judgment must be used to determine what is reasonable under the particular circumstances.

One of the most widely quoted sources for vessel movement limitations is Bruun (1981), as shown in Table 6-1.

Thoresen (2003) also provides an excellent discussion of suggested limits for vessel motions and wave height thresholds. Much of the material is based on the recommendations of various PIANC working groups. These publications establish recommended motion limits not only for operational working conditions but also for maximum allowable motions from a safety point of view (see Table 6-2).

Thoresen notes that these PIANC recommendations do not enjoy universal agreement among design practitioners. D'Hondt (1999) maintains that container vessels require much smaller motion thresholds than those presented here due to the small tolerances in the cell guide locations on container ships. D'Hondt recommends the following limits for 100% efficiency in container-handling operations:

- Pitch: 0.4 deg;
- Roll: 0.24 deg;
- Combined pitch/roll: 0.45 deg; and
- Heave: maximum amplitude of 0.20 m, maximum speed of 7.5 cm/s.

Table 6-1. Recommended Motion Criteria for Safe Working Conditions[1]

Ship Type	Cargo-Handling Equipment	Surge (m)	Sway (m)	Heave (m)	Yaw (°)	Roll (°)
Tankers[2]	Loading arms/ hoses	2.3	1	0.5	3	4
Ore carriers	Crane/clam shell	1.5	0.5	0.5	2	4
Grain	Elevator or suction	0.5	0.5	0.5	1	1
Container	Lift on/lift off	0.5	0.3	0.3	2	3
Container	RO-RO (side)	0.2	0.2	0.1	0-1	0-1
Container	RO-RO (bow or stern)	0.1	0	0.1	0	0
General cargo[3]		1	0.5	0.5	2	3
LNG/LPG	Loading arms	Values for tankers sometimes accepted. Others reduce movements to 1/3 for safety reasons				

Notes:

1. All movements are +/− from equilibrium position (i.e., roughly half the peak-to-peak motions).
2. Larger for SBM and SPM systems
3. Depending on hoisting equipment and cargo

Source: Adapted from Bruun (1981)

In 2012 PIANC published new guidelines for container operations, noting that substantial evolution in the sizes of container vessels had occurred over the last two decades and that some 90% of the world's general cargo is now carried on container vessels. The new PIANC (2012a) guidelines predict a continual degradation in handling efficiency as the amplitude of motion increases, with high-frequency motions being generally more disruptive than lower frequency motions at the same amplitude (i.e., the crane operators can compensate more easily for low-frequency motion; see Table 6-3).

Ueda (1988) also recommends movement limitations, which in some cases are larger than Bruun's recommendations (1981) and in other cases smaller. Ueda's recommendations are not reproduced here, but the reader can refer to the original publication for these data if desired.

Given the somewhat wide range in acceptable movement criteria, the designer should adopt the following process:

- Select limits that are appropriate for the local circumstances.
- Formally document these movement limits as part of the design criteria for the berth.

Table 6-2. Recommended Motion Criteria for Safe Working Conditions[1]

Ship Type	Cargo-Handling Equipment	Surge (m)	Sway (m)	Heave (m)	Yaw (°)	Pitch (°)	Roll (°)
Fishing vessels	Elevator crane	0.15	0.15	-	-	-	-
	Lift-on lift-off	1.0	1.0	0.4	3	3	3
	Suction pump	2.0	1.0	-	-	-	-
Freighters, coasters	Ships gear	1.0	1.2	0.6	1	1	2
	Shore cranes	1.0	1.2	0.8	2	1	3
Ferries, RO-RO	Side ramp[2]	0.6	0.6	0.6	1	1	2
	Dew/Storm ramp	0.8	0.6	0.8	1	1	4
	Linkspan	0.4	0.6	0.8	3	2	4
	Rail car ramp	0.1	0.1	0.4	-	1	1
General Cargo		2.0	1.5	1.0	3	2	5
Container vessels[3]	100% efficiency	1.0	0.6	0.8	1	1	3
	50% efficiency	2.0	1.2	1.2	1.5	2	6
Bulk carriers	Cranes	2.0	1.0	1.0	2	2	6
	Elevator/ bucket	1.0	0.5	1.0	2	2	2
	Conveyor belt	5.0	2.5	-	3	-	-
Oil tankers	Loading arms	3.0[4]	3.0	-	-	-	-
Gas tankers	Loading arms	2.0	2.0	-	2	2	2

Notes:

1. Motions refer to peak-to-peak values (except for sway, which is zero peak).
2. Ramps equipped with rollers
3. PIANC has subsequently published new guidelines for container vessels, see Table 6-3.
4. For exposed locations 5.0 m from where loading arms are specifically designed to allow large movements

Source: Adapted from Thoresen (2003), based on PIANC (1995)

- Validate the proposed limits both with the facility owner and with the operations staff.
- Verify through calculations or other means that the design will achieve the stated criteria.

Table 6-3. Recommended Motion Criteria Container Vessels for 95% Efficiency in Crane Operations

Ship Type	Cargo-Handling Equipment	Surge (m)	Sway (m)	Heave (m)	Yaw (°)	Pitch (°)	Roll (°)
Container vessels	95% efficiency	0.2 to 0.4	0.4	0.3	0.3	0.3	1.0

Note: Motions refer to maximum allowable significant motion amplitude (not peak to peak).

Source: Based on PIANC (2012a)

Unless more stringent project-specific criteria are stipulated by the facility owner or operator, the limits provided in Table 6-2 should be followed for most vessel types and Table 6-3 for container vessels in particular. General adherence to these limits should provide reasonable working conditions for most types of cargo-handling operations.

Whatever motion thresholds are adopted, the thresholds may occasionally be exceeded under severe or unusual wind and wave conditions. The berth downtime associated with such excessive conditions should be limited to a reasonable level, up to perhaps 1 week per year (2% of the time) for container or passenger vessel facilities where the economic or political impact of a disruption is high. For other types of berths (e.g., bulk or general cargo), a higher level of operational downtime may be an acceptable economic tradeoff for the owner if it results in substantial cost savings in the berth construction.

6.2.3 Recommended Wave Height Limitations

Setting design criteria limits on allowable vessel motions is practical only if the designer has a reliable means of establishing what the actual vessel motions are for the particular case being evaluated. Unfortunately, accurately predicting a vessel's dynamic response is rather difficult. In fact, a comprehensive analytical treatment of a moored floating body under the influence of unsteady winds and random spectral seas is perhaps one of the most challenging tasks in all of civil engineering. The two primary tools available for the practitioner are the numerical models discussed in Sections 5.2 and 5.3 and physical models discussed in 5.4. A growing body of technical literature exists in both naval architecture and engineering journals with case studies and design examples that can be used to gain some insight into the range of motion to be expected under certain conditions.

Although case-specific physical and numerical models currently offer the best available means of evaluating vessel motions and their effects on the mooring system, the tools tend to be somewhat time consuming and

Table 6-4. Maximum Significant Wave Heights for Various Types of Vessels

	Limiting Wave Height H_s(m)	
Type of Vessel	0° (head/stern seas)	45°–90°
Small craft marinas	0.3	0.3
Fishing boats	0.4	0.4
General cargo	1.0	0.8
Container or RO-RO ship	0.5	
Dry bulk (30,000–100,000 DWT) loading	1.5	1.0
Dry bulk (30,000–100,000 DWT) unloading	1.0	0.8–1.0
Tankers (<30,000 DWT)	1.5	
Tankers (30,000–200,000 DWT)	1.5–2.5	1.0–1.2
Tankers (>200,000 DWT)	2.5–3.0	1.0–1.5
Passenger ship	1.0	0.7

Source: Adapted from Thoresen (2003)

expensive to carry out. In some cases the project schedule and owner's available resources may preclude the use of such tools, and the designer is faced with the need to apply "rules of thumb" and other approximate measures.

One such approximate measure is to describe the limiting sea state at a berth rather than proscribing the vessel motions directly, because establishing the prevailing wind and wave climate for a site is usually easier than carrying out a site-specific dynamic analysis.

It is intuitively known that larger vessels can tolerate higher wave conditions than smaller vessels and that seas approaching the head or stern of the ship create less severe motion than similar waves approaching the vessel's beam or quarter. These intuitive relationships are reflected in the sea state limits proposed by Thoresen, shown in Table 6-4.

The limits shown in Table 6-4 apply to waves of periods up to about 10 s and should be used with caution. As with most rules of thumb, there are many exceptions and special circumstances where these limits would not apply. For example, the author is aware of a dry bulk export berth for 60,000 DWT ships on the coast of Chile, where the design wave height (and associated vessel motion) was up to 2.0 m. In this case the berth was fully exposed to the open Pacific Ocean, and a larger operating wave limit was established to ensure enough berth availability on a year-round basis. At the other extreme, the harbor seiche problem described at Pier J in

Section 5.2.4 had a wave height of only 4.6 cm, yet this resulted in unacceptable surge motions of up to 1.3 m.

6.2.4 Mitigation Measures

Existing berth facilities are frequently redeveloped for new uses, often with more stringent motion limitations than may have been previously acceptable. For example, many general cargo wharves built decades ago are now being converted for container operations. Conversely, a new facility may prove to have a higher degree of motion-induced downtime or wear and tear than was anticipated in the design stage. In either case, a designer may be faced with having to modify an existing berth to reduce vessel motions.

For an existing facility, changing the orientation of the berth to better suit the prevailing wind and wave directions is obviously very difficult, if not impossible. Improving the degree of shelter at the berth by constructing a breakwater or similar infrastructure may be possible in some cases (e.g., the new breakwater built at Pier J in the Port of Long Beach, discussed in Section 5.2.4). However, such radical solutions may be prohibitively expensive or face major obstacles from a permitting point of view.

Another approach that may prove beneficial is to modify the characteristics of the vessel mooring system, in effect "tuning" the natural frequency of the moorings to avoid conditions of resonance. Several authors have presented case studies describing this sort of adjustment to mooring systems (Shirashi et al. 1996, Sakakibara and Kubo 1992). The basic premise is that the combination of somewhat stiff buckling-type rubber fenders with nylon or polypropylene mooring lines may lead to a mooring system with an inherently unbalanced stiffness matrix between "on-berth" and "off-berth" directions. The authors believe these large unbalances in stiffness can sometimes lead to harmonic low-frequency behavior in the moorings, creating large displacements in sway and surge. By replacing the stiff fenders with softer, pneumatic-type fenders and by using stiffer mooring lines (such as Kevlar or wire rope), the stiffness in the off-berth direction can be made to more closely match the stiffness in the on-berth direction. In some cases, such modifications were shown to greatly reduce vessel motions. The effect may be improved even further by providing greater hysteresis (energy damping) in the fender system, rather than having highly elastic fenders that recoil and "push the energy back" to the vessel.

Shirashi et al. (1996) used a numerical model to evaluate the effect of modifying the fenders and mooring lines for a 60,000 DWT bulk carrier. Prior to modification, the vessel responded to low-frequency wave energy that created movements of 6–8 m in surge and 1–2 m in sway, with a period of about 120 s. After the fenders were replaced with softer versions and the mooring lines were made stiffer, the motions under these conditions were dramatically reduced. Based on the results of the numerical model, the full-scale berth in question was modified in a similar manner. The full-scale results showed a similar improvement in vessel motions, which appears to substantiate the premise of the numerical model.

This sort of approach has some limitations and drawbacks however. In general, it is only possible to address low-frequency motions in this manner. If the vessel motions are due to wave energy with periods of less than about 16–20 s, then modifying the characteristics of the mooring system is unlikely to have much effect on the dynamic response of the vessel. Furthermore, the use of "softer" fenders (i.e., those with lower initial stiffness) generally requires the use of larger fenders with a greater standoff dimension and greater deflection range to provide the same reaction energy as a buckling-type fender. For berths where standoff height is critical (e.g., container berths with crane outreach limitations) increasing the standoff height may not be feasible. In addition, the facility operator may not have much control over the type of mooring lines that are carried aboard the ship, especially in cases where the berth is a public facility or is visited by several different vessel lines. The latter difficulty can potentially be resolved by having the owner or operator keeping a supply of stiffer mooring lines on hand for use during, hopefully rare, periods when low-frequency oscillations are an issue.

In general, thoroughly evaluating vessel motions at the design stage using appropriate dynamic analysis tools is far better and more cost effective than attempting to fix a problem after the facility is built.

6.3 INCIDENTS/BREAKAWAYS

The purpose of this section is to highlight incidents and accidents resulting from poor mooring practices or the lack of an engineering assessment. Mooring incidents can result in any of the following scenarios:

- High winds with vessel at ballast condition;
- High current (magnitude and direction) with vessel at deep draft;
- Passing vessel loads;
- Excessive ice around or impacting moored vessel;
- Tsunami run-up;
- Larger vessels (larger sail area and/or arrival mass) than in the original design; and
- Mooring hardware or equipment failure.

Some examples of these types of failures/scenarios follow.

6.3.1 High Winds with Vessel at Ballast Condition

The vessel involved in this incident was a U.S.-flagged oil tankship, the Keystone Canyon (124,000 DWT; LOA 855 ft; and beam 173 ft). The incident occurred at 1:00 p.m. on October 26, 1994, at Pier One, Port of Astoria, Oregon. The vessel was in the process of being inspected by the U.S. Coast Guard and was at ballast conditions (13 ft fore, 20 ft aft). Both Coast Guard and inspection personnel were on board the vessel at the time of the incident. The propeller was about 8 ft out of the water, and the vessel was loaded with bunker fuel, diesel oil, and slops. The vessel height above the wharf was about 50 ft. The vessel had "mixed" mooring lines: 11 were steel wire and seven were synthetic. The vessel/wharf had no procedure for monitoring environmental conditions, and thus the facility was unaware that the weather service had put out a bulletin that winds up to 70 mph were expected in the afternoon. The mooring lines parted, the vessel drifted off the berth and hit soft mud on the opposite side of the channel. With part of the propeller out of the water, the vessel lacked propulsion as it left the wharf. Before grounding, the vessel impacted two bridge abutments and did minor damage. In addition, the vessel had a 4-ft long gash along its side (WSOMS 2000).

6.3.2 High Current with Vessel at Deep Draft

The Provence (57,000 DWT, LOA 700 ft) was unloading 11 million gallons of fuel oil in the Piscataqua River, with a 3-knots current, on July 1, 1996. The 21 mooring lines were "mixed" (steel wire and synthetic). A 3-knots maximum flood current was in line with the vessel. All mooring lines parted, and the vessel drifted off the wharf at approximately 10:45 p.m. and crossed the river and grounded in the mud. Two 10-in. loading hoses were broken. As the vessel was being freed, the anchor was caught on a rock and penetrated a tank. The spill was somewhat small, reportedly less than 1,000 gallons, and 400 lobsters died (NOAA/NOS 1996).

6.3.3 Passing Vessel Loads

A tragic example of a passing vessel incident occurred at an oil terminal on the Saginaw River (Taylor and Kokarakis (2007). The tank vessel M/V Jupiter (LOA 390 ft) was unloading gasoline on the morning of September 16, 1990, at 1:45 a.m. on the Saginaw River. The mooring was "mixed" with four steel wire lines and two synthetic. The vessel was unloading 2 million gallons of gasoline through a hose, when a larger vessel, the bulk carrier Buffalo (LOA 620 ft) passed nearby at high speed. The Jupiter surged 15 ft, came back 10 ft, and then surged again. The steel mooring lines were attached to timber king piles that were seriously deteriorated. When the king piles failed, the synthetic mooring lines parted, the loading hose ruptured, gasoline spilled, and a fire started followed by three explosions. The dry rot in the king piles was determined to be the root cause, with less than 10% remaining capacity. The vessel was destroyed, and two people died in this incident.

Another more recent passing vessel incident occurred at an LNG terminal on Elba Island along the Savannah River. The tankship Golar Freeze (LOA 940 ft) was ripped off its moorings in the early morning of March 14, 2006 as a result of a passing vessel (Savannah Morning News 2006). The Golar Freeze was discharging LNG at the Elba Island terminal, when the chemical tanker Charleston sailed past in the same channel. The moored vessel surged, all mooring lines parted, and the vessel started to drift away. Two tractor tugs immediately went into operation and pushed the vessel back into the berth. The quick disconnect of the LNG loading arm worked well, and there was no reported spill. The facility was taken out of operational status for 36 h while the mooring system and loading arms were inspected, tested, and evaluated. No casualties occurred, and the vessel did not drift away and cause any additional damage.

6.3.4 Excessive Ice around the Vessel

At 5:25 a.m., February 2, 2006, the Seabulk Pride (46,800 DWT, LOA 600 ft), a double-hull oil tanker, broke free of its moorings at Cook Inlet at the port of Nikiski. An ice floe that impacted the vessel, along with a strong current, was the root cause. All mooring lines parted, and the vessel drifted north approximately 0.5 mi before grounding. No major oil spill occurred, thus avoiding a major catastrophe, despite the area being full of rocks and reefs. A complete description of the incident and steps to avoid a recurrence are presented in Clark (2009).

6.3.5 Tsunami Run-up

The earthquake and tsunami of December 26, 2004, in Southeast Asia provided examples of tsunami loads on moored vessels. In the Port of Chennai, India, buoyancy forces from the rapid increase in water level were sufficient to break mooring lines and allow vessels to move freely within the port area. The port had no prior warning of a tsunami, nor was an earthquake felt by port personnel. Three vessels broke free of their moorings and moved in a circular manner around the port area. Facilities that were impacted by the vessels suffered damage, and crew members exited the vessels as they impacted the wharves.

One other observation and calculation indicated that the tsunami-induced current loads were not sufficient for a well moored vessel to break away. The current did not govern, but the rapid rise in water level and buoyancy forces were sufficient to break mooring lines (Eskijian 2008). PIANC (2010) covers tsunami-related events in much greater detail.

Fig. 6-1. Failed double bitt that occurred with thunderstorm wind gust
Note: Poor grout bedding likely contributed to overstressing of the bollard base, which also likely had a defect

6.3.6 Mooring Hardware Failure

Occasionally mooring hardware fails, typically suddenly and sometimes catastrophically, due to defective materials (castings), corroded or defective anchorage, and/or overload that includes cumulative damage from repeated overloading especially with improper line lead angles. Fig. 6-1 shows a cast iron double bitt that failed due to possibly defective, but certainly under capacity casting, plus overloading due to thunderstorm wind gust. Reportedly a mooring diagram was provided that indicated the ship should not tie up to it. The failed barrel of the double bitt went airborne and damaged a fire station, and the remaining bow lines parted sequentially. However, the stern lines held, and fortunately a tug was able to hold the ship until additional tugs arrived, and the ship was resecured to larger bollards.

Other accident scenarios related to mooring hardware are possible when vessels larger than those considered in the original design are moored. As vessels increase in size over the life of a structure, little thought is given to the increased current and wind loads on the larger sail/current areas. Existing operational limits of wind direction/magnitude and/or current values may exceed the mooring hardware or structural capacity of an existing terminal. A new mooring/berthing assessment may then be required per (MOTEMS 2011).

6.4 MAINTENANCE

Deterioration, wear, or damage commonly occurs to mooring and fendering systems. Setting up periodic maintenance programs for individual mooring components is necessary. The procedures for maintenance programs will vary according to mooring type, location, and usage.

6.4.1 Fender System

Fender systems are subjected to many repetitive berthing loads and accidental impacts during their service life. Deterioration of rubber fenders and corrosion of hardware after several years of service is inevitable. Rubber components in a fender system are viscoelastic materials that gradually lose their load-carrying capacities after years of service. Deteriorating rubber fenders develop surface cracks that may grow and eventually cause failure. Softened or cracked rubber fenders need to be replaced. Corrosion occurs at steel hardware locations such as fender panels, connection chains, anchor bolts, etc. Deterioration can be controlled by a good maintenance program, including periodic coating repair and replacement. Severe anchor bolt corrosion may cause adjacent concrete cracking or spalling, which can be prevented by using a stainless steel anchor system or hot-dip galvanized anchor bolts with embedded captive nuts with plastic housing. Thorough periodic visual inspections and routine maintenance programs can successfully control long-term deterioration and corrosion.

Sudden mechanical damage to rubber fenders and any connection hardware can occur at any time due to accidental berthing impacts. Careful damage inspection must be carried out right after an accidental berthing. An inspection report, including remedial actions, needs to be provided. Possible fender system damages include

- Fender piles: Cracking or spalling of concrete pile, dents on steel pile, and excessive deformation of plastic pile;
- Rubber fender damage;
- Anchor bolt failure (with concrete cracking or spalling); and
- Fender panel damage.

Based on the inspection report, damaged components need to be repaired or replaced properly. Damaged rubber fender must be replaced.

6.4.2 Mooring Hardware

To ensure safe mooring, wear on or damage to any mooring hardware needs to be properly controlled with a good maintenance program, preventing excessive deterioration or severe damage that may induce ultimate failure.

6.4.2.1 Hardware, Fittings, and Anchorages to Concrete Surrounding concrete below bollards or cleats may get damaged by corrosion of embedded anchor bolts and/or excessive mooring load applied. Crack initiation occurs due to either corrosion of embedded steel anchors or high mooring load. Chloride ions can easily penetrate cracks and cause severe corrosion and further cracking. The reduced mooring load-carrying capacity may cause crack propagation and create additional new cracks, allowing cumulative harmful chloride ion penetration to concrete. The damage cycle must be stopped with a good repair or rehabilitation maintenance program. Typical anchor bolt corrosion problems can be controlled with high-performance fiber-reinforced concrete materials, modern sealants or grouts, hot-dip galvanized anchor bolts with embedded captive nuts with plastic housing, or stainless steel anchor bolts.

Severe abrasion may occur due to excessive friction with mooring lines. This may damage coating, cause corrosion, and weaken hardware casting through loss of cross-sectional area. Severe corrosion may roughen the hardware surface, increasing the chafing and wearing of mooring lines.

UFC 4-150-08 (DoD 2001a) provides guidance for the planning, testing, and reporting of current mooring hardware load capacities as a tool to assist personnel tasked with maintaining berthing facilities for use by the fleet and in support of military marine operations.

6.4.2.2 Mooring Lines and Chains Mooring lines should be inspected and maintained to ensure mooring safety. Wire lines need to be lubricated periodically. Proper lubrication reduces the abrasive effect of individual wires sliding against one another and helps to prevent corrosion. Ideally, the line should be lubricated every two or three months. An abnormal increase in length indicates overloaded wires. It is necessary to pay additional attention to terminations exposed to high stress. The ends of wire should be periodically reversed to evenly distribute wear. The damaged wire sections (worn, kinked, or cut) should be cut off and removed. Monitoring of wire corrosion should be performed as part of a periodic inspection program. The wire lines should be replaced if corrosion develops below the surface of the wires.

Chains should also be inspected at regular intervals, depending on mooring type and usage, for corrosion, abrasion, deformation, and mechanical damage. More frequent inspection is required for moorings at exposed sites or critical facilities. All connections including links, swivels, shackles, and connecting links need to be secured and maintained in good condition throughout the service life.

Long-term deterioration and strength loss of synthetic mooring lines especially due to wear is not unusual. However, deterioration processes can be accelerated by exposures to heat, ultraviolet (UV) rays from sunlight, abrasion, wet/dry cycles, marine growth, and/or insects. Typical serious deteriorations are caused by sunlight exposure and heat generated by cyclic loading and friction. Fiber ropes may lose 50% of their strength after two years of sunlight exposure in hot climate conditions. Heat is normally generated by internal friction due to rope stretching and may cause internal melting of the rope strands. This may ultimately result in rapid failure of a fiber rope. Unnecessary exposure to sunlight or heat should be avoided. Any unusual practices with geometries (sharp bend, knot, wrong couple, etc.) that may cause line damage should not be allowed. Setting up a conservative periodic visual inspection program for synthetic mooring lines, considering local climate and service conditions, is important to avoid sudden failure. Sudden failure of the line can result in a potentially dangerous snapping back of line, because high energy can be stored in a highly stretched synthetic line. Deteriorated or damaged line needs to be replaced with new, except in the case of localized damage.

UFC 4-159-03 provides inspection guidelines for various mooring components and maximum recommended inspection intervals. *UFC 4-150 07* (DoD 2001b), *UFC 4-150 08,* and Vervloesem (2009) provide additional useful information and guidance on mooring line and hardware inspection and maintenance.

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APPENDIX
UNIT CONVERSIONS

NAUTICAL UNITS

1 nautical mile = 1.151 statute miles = 6,076.1 ft = 1,852 m (by definition)
1 knot = 1 nautical mile per hour = 1.151 mph = 1.688 fps = 0.515 mps
1 fathom = 6.0 ft (water depth)
1 long ton = 2,240 lb = 1.12 short tons = 1.016 metric tons

SI (METRIC)

1 ft = 0.3048 m
1 ft^3 = 0.0283 m^3
1 lbF = 4.448 N
1 lb/ft^3 = 16.0185 kg/m^3 (kg/cm) (1 kg = 9.80665 N)
1 ft-kip (moment or energy) = 1.356 kN-m
1 kip/ft = 14.59 kN/m
1 kip/ft^2 = 47.88 kN/m^2
1 kip/in.^{2} (stress or pressure) = 6.897 MPa
1 ton-meter = 9.807 kN-m

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INDEX

Page numbers followed by *e*, *f*, and *t* indicate equations, figures, and tables, respectively