



US Army Corps
of Engineers

Deep-Draft Coastal Navigation Entrance Channel Practice

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PURPOSE: The Coastal Engineering Technical Note herein summarizes U.S. Army Corps of Engineers (USACE) deep-draft coastal navigation entrance channel design practice and describes elements of a USACE research effort for improving this practice.

NEEDS AND BENEFITS: Entrance channels are the initial points of entry to ports and harbors. Almost all of United States overseas trade by weight, and approximately 50 percent by value (air transport accounts for a greater fraction of precious cargo), moves through our Nation's ports and harbors. The waterborne commerce through U.S. ports and harbors has increased continuously over the last four decades (U.S. Department of Transportation 1997; Webster 1992), and many ports are expanding to serve larger vessels. Economics of scale and increased containerization of cargo are producing containerships of increased size (U.S. Department of Transportation 1997), exceeding the dimensions of Panamax class ships (Panama Canal maximum ship dimensions are 965-ft length, 106-ft beam, and 39.5-ft draft). The economics of scale is applicable to all cargo classes and has fueled demand for port expansions, infrastructure capable of rapid on-and-off loading, larger stockyards, and efficient land-based facilities for truck and rail transport. With the ever-present political and economic pressures to serve larger vessels, ports are faced with planning for costly infrastructure upgrades, deeper/wider channels, larger turning basins and berthing areas, and open and modernized terminals. To attract waterborne commerce and decrease shipping costs, many U.S. ports and harbors are now planning for the next generation of vessels with increased draft even though these ports are not equipped to accommodate such vessels through channels leading to them.

DEEP-DRAFT ENTRANCE CHANNEL RESEARCH: Although USACE (USACE 1984, 1995, 1999) provides detailed guidance for the design of inland waterways, the guidance for coastal entrance channels is not as comprehensive. The design guidance for coastal entrance channels, particularly underkeel clearance allowances (principally squat and waves as defined in Figure 1), appears to be overly conservative. Consequently, differences exist between USACE, States (Harkins and Dorrell, in preparation), and other international design guidelines (Permanent International Association of Navigation Congresses (PIANC) 1997). Recent work to update EM 1110-2-1613 "Hydraulic Design of Deep-Draft Navigation Projects" revealed the need to develop verified guidance for the design of approach, entrance, and bar channels where vessels are subjected to waves and other coastal conditions. The absence of a verified design methodology often leads to conservative estimates on channel size, which gives rise to increased initial/maintenance dredging costs. Recent advances in measurement and modeling allow for improvements in the USACE channel design guidance.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE MAR 1999		2. REPORT TYPE		3. DATES COVERED 00-03-1999 to 00-03-1999	
4. TITLE AND SUBTITLE Deep-Draft Coastal Navigation Entrance Channel Practice				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Army Engineer Research and Development Center, Coastal and Hydraulic Engineering ,3909 Halls Ferry Road, Vicksburg, MS, 39180				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 11	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

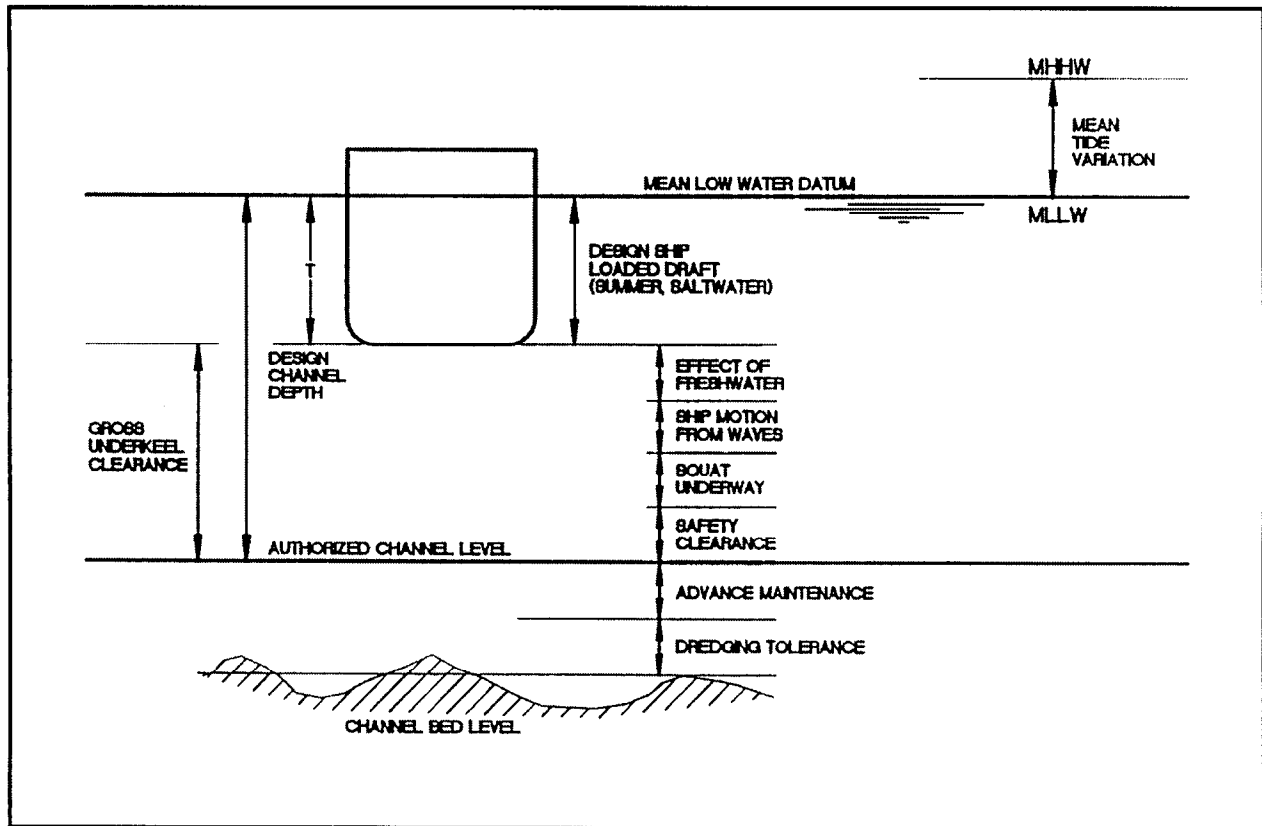


Figure 1. Underkeel clearance allowances

The USACE guidance (USACE 1984, 1995, 1999) defines authorized depths and widths for navigable channels. Figure 1 shows various factors that influence the authorized channel depths or, conversely, the maximum allowable draft under various environmental and/or transit conditions. Water levels and currents (tidal) are reasonably well known through such efforts as long-term measurements and predictive models by the National Oceanic and Atmospheric Administration (NOAA) (<http://www.opsd.nos.noaa.gov/>) and recent development of numerical models such as ADCIRC (Luettich, Westerlink, and Scheffner 1992). Less well understood are the effects of waves and ship speed and resulting vessel motions in the navigable channels and shallow waterways. The current effort will identify channel depth/width allowances caused by waves and vessel speed through (a) prototype data studies, (b) parametric model studies, (c) transferring knowledge and databases to the USACE ship simulator, and (d) retrofitting an existing probabilistic vessel response model.

USACE DEEP-DRAFT CHANNEL PRACTICE: Many different parameters enter into the planning, design, and operation of deep-draft navigation channels. For example, in the planning of a navigation channel, a design ship, typically the maximum size ship from the projected user fleet, is selected on the basis of economic analyses. The two main design dimensions of navigation channels are width and depth, and these must be determined to accommodate the design vessel (USACE 1984, 1995, 1999). Likewise, for safe operations within a channel, it is necessary to consider the effects of winds, waves, tides, currents, visibility, and navigational aids

(navaids). The density and type of traffic (one- or two-way traffic), ship speed, turning basins, and tug assistance are other factors that need to be considered in the operation of channels. USACE defines navigation projects into two classes as follows:

“Deep-draft navigation refers to channel depths greater than 4.5 m (15 ft) and applies to commercial seagoing vessels and Great Lake freighters, requiring cost sharing for depths in excess of 6 m (20 ft). Shallow-draft implies channel depth being less than 4.5 m (15 ft) for navigation, and 6 m (20 ft) for project cost sharing” (USACE 1994, 1995, 1999).

The above distinction is a practical criterion based on typical dimensions of ocean-going cargo vessels. It is generally assumed that deep-draft ports connect with the oceans, seas, and Great Lakes and serve seagoing vessels for trade/commerce and support various military functions. In contrast, shallow-draft ports generally serve pleasure craft and/or private and commercial fishing vessels, although these vessels can always utilize deep-draft channels. The USACE has responsibility for maintaining more than 200 deep-draft and 600 shallow-draft ports and harbors.

WAVE PREDICTION FOR CHANNELS: Wave information is required for the design and operation of entrance channels. The design vessel hydrodynamics and maneuvering characteristics, size and orientation of the channel/waterway, and establishment of appropriate navigational aids (navaids) are all dependent on the wave climate at the site. There are three sources for wave information: field data, laboratory experiments (physical models), and numerical modeling. In most cases, little (if any) wave data are available for engineering planning and design studies. Wave transformation and ship response models have not to date been fully incorporated into ship simulators. Because field observations are usually unavailable and physical modeling of waves over large regions may exceed budget and time constraints, the necessary wave information for entrance channels is often obtained from numerical wave transformation models using wave hindcast data. Several numerical wave models, including RCPWAVE, REFDIF/REFDIFS, STWAVE, and CGWAVE, are presently in use by USACE. STWAVE and CGWAVE are integrated into the Surface-Water Modeling System (SMS) for rapid grid generation and visualization of model results (Demirbilek and Panchang 1998).

The other aspect of wave information required for navigation channels, ports, and harbors deals with the prediction of vessel motions and maneuvering characteristics. Wave and ship data must be integrated into numerical (or physical) models that determine vessel hydrodynamic responses and maneuvering behavior. The ability to do this requires the use of a well-tested and reliable (numerical) ship response model.

A ship can undergo wave-induced motion in six degrees of freedom (DOF) as shown in Figure 2 (in general, six DOF motions apply to any rigid body). Three of the DOFs are in the vertical plane (heave, roll, and pitch), while the remaining DOFs are in the horizontal plane (surge, sway, and yaw). In naval architecture (Society of Naval Architects and Marine Engineers (SNAME) 1989), the motion (or response) amplitude for each DOF is usually normalized (divided) by the incident wave amplitude and called a Response Amplitude Operator (RAO). The corresponding RAO phase angle for each DOF is with respect to an incident wave crest at the center of gravity of the ship. RAOs in the vertical plane contribute to the vessel underkeel clearance, defining the channel depth requirements because of waves. The horizontal RAOs relate to the maneuvering

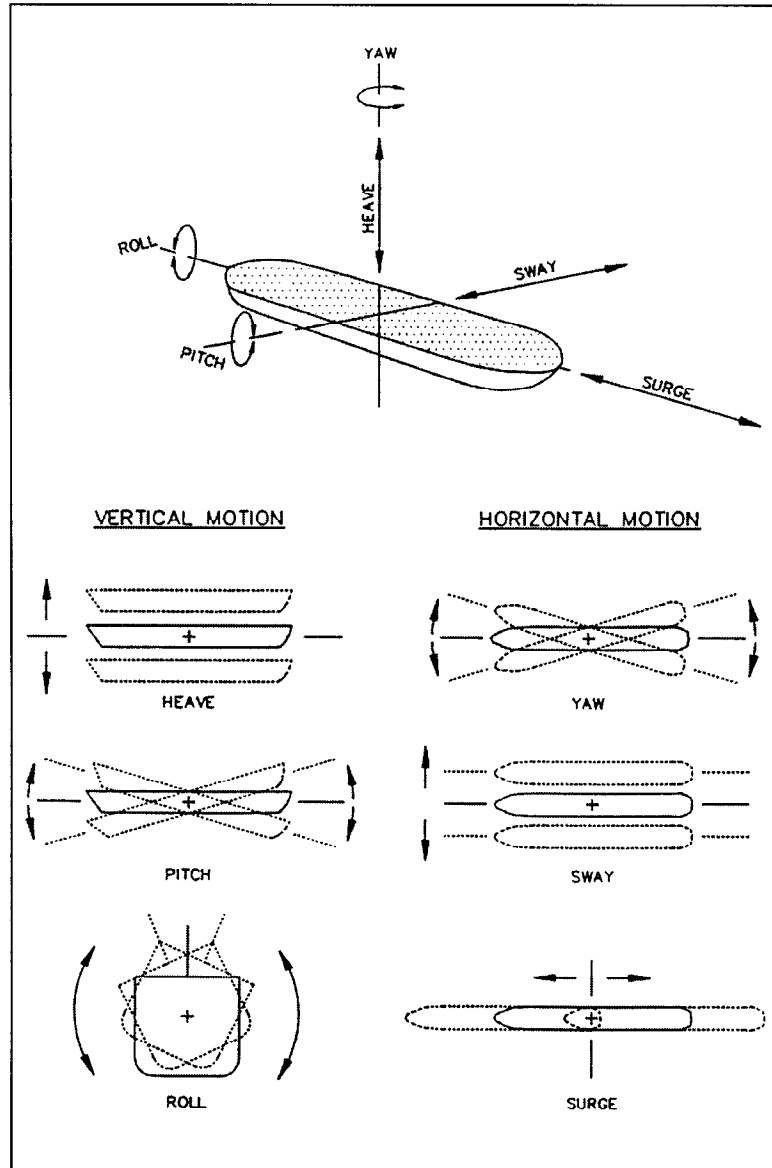


Figure 2. Six degrees of freedom of rigid body motion for ships

and station keeping ability of the ship, hence determining the required channel width. Vessel responses are uniquely defined for a given ship geometry and weight distribution and vary with the ship's forward speed, bathymetry, and environmental conditions along the ship track.

DESIGN VESSEL REQUIREMENTS FOR CHANNELS: A design vessel (a set of design vessels) is (are) chosen for channel design projects. The pertinent USACE guidance states the following:

“For deep-draft projects, the design ship or ships is/are selected on the basis of economic studies of the types and sizes of the ship fleet expected to use the proposed channel over the project life. The design ship is chosen as the maximum or near maximum size ship in the forecasted fleet” (USACE 1984, 1995, 1999).

Deep-draft channels are typically designed to provide safe and efficient passage for a selected vessel under specified transit conditions. Both the design ship and transit conditions must represent the most adverse combination of conditions under which the project would be expected to maintain normal operations. It then would be reasonable to assume that the project would perform adequately for smaller vessels under the same transit conditions. In practice, harbor pilots often transit vessels larger than the design ship(s) under conditions of (a) high tide, (b) milder wave conditions, (c) reduced speed, and (d) tug assistance. The first three of these factors increase the effective depth of the channel, and the last factor increases horizontal control of the vessel.

Channel width is tied to horizontal vessel motions, and it is reasonable to assume that a larger dimension vessel with the largest motions will impose the most severe limitations. By similar reasoning, the maximum draft vessel would produce the minimum underkeel clearance throughout the channel. The combinations of hydrodynamic response, speed, heading, and wave direction for various design vessels using the channel may very well dictate otherwise. Because ships have different wave-response characteristics, the required channel depths may vary at different locations along the channel. However, it is not necessary to design a deep-draft channel for extreme or rare events, as vessel operators and port authorities usually suspend operations during these conditions. For cost-efficient transits, it is prudent to include wave statistics into the design process from the onset by eliminating the highest waves to reduce the transit downtime.

FACTORS INFLUENCING VESSEL TRANSIT: The major operational factors considered by USACE to affect the vessel transits in channels includes the following:

“Wind, wave, and current conditions; visibility (day, night, fog, and haze), water level (including possible use of tidal advantage for additional water depth), traffic conditions (one- or two-way, push-tows, cross traffic), speed restrictions, tug assistance and pilots, underkeel clearance, and ice” (USACE 1984, 1995, 1999).

Tides and/or water-level fluctuations may enter into entrance channel design, reducing the depth requirements for vessels that would otherwise be restricted at low water. However, if channel usage were limited to high tide, port access would be adversely affected, resulting in large economic loss and higher vessel-operating costs. Care should be exercised when incorporating water-level variability in the channel-depth specification. If water levels were included in the design, a water-level probability analysis would be necessary to determine the safest channel depth for optimum operability.

Harbor pilots provide the local knowledge and expertise necessary for safe ship transits. The pilot assumes control of the vessel during channel transit, issuing rudder and engine commands to steer the vessel and uses the nav aids to maintain ship alignment safely within the channel. One or more tugs also may accompany the ship to assist in tug-aided phases of transit and docking.

Transits involve going through a series of channel segments, straight or curved. Channel turn angles in excess of 30 deg pose maneuvering challenges even to experienced mariners because

the direction of prevailing winds, surface currents, vessel speed, and position relative to channel banks all change quickly. Crosscurrents, winds, waves, and channel shoaling can be particularly troublesome at the start of entrance channels. A vessel in a confined channel does not respond as quickly to rudder and engine commands because of channel bank effects, reduced speed, and confined propeller/rudder dynamics. Vessel captains know that they have to slow down well before approaching the berth or terminal areas, relinquishing the control and maneuvering of their crafts to tugs at speeds less than 4 knots. Tugs may be in full control for positioning vessels against the dock and mooring them. When vessels arrive at the port entrance with drafts exceeding the channel depth, they might fully or partially offload their cargo to lighters to reach an acceptable draft before proceeding to port.

The density of ship traffic further complicates the channel transit, and inclement weather, charter schedules, and ship rerouting may also affect port access. The degree of complication resulting from these various factors to the vessel transit should dictate whether the channel design is one-way or two-way. A two-way channel may significantly reduce or eliminate the amount of time ships must queue while waiting. The obvious advantages of two-way channels must be balanced against their higher dredging costs and increased safety risk.

The maximum speed of a vessel in confined, shallow-water channels is significantly less than that in deep and open seas (SNAME 1988). The maximum speed in restricted channels is known as the Schijf limiting speed (USACE 1995) and is a function of the blocking factor (the ratio of channel to ship cross-sectional areas). As an example, speed reductions of 50 percent or more can occur in highly confined waterways. Both the proximity of channel banks and channel overbank depths also influence vessel hydrodynamics and maneuvering. These effects are difficult to quantify and are not directly accounted for in the present USACE practice.

CHANNEL DEPTH ALLOWANCES BECAUSE OF WAVES AND SHIP SPEED:

Channel depth typically is chosen on the basis of economic optimization to meet the present need and, if possible, anticipated traffic requirements. This is a key factor in the cost and usage of a navigation channel. In a cost-effective project, the depth of a channel, for either deep-draft and shallow-draft navigation projects, does not have to be constant throughout. Channel depth can, and often does, vary in segments of the channels to allow the design vessel to make safe and efficient transit. There may be different factors affecting the vessel underkeel clearance in different channel segments, and these influences must be determined as a depth increment and added to the design vessel draft to determine the required channel segment depths. USACE refers to this as the *authorized channel depth* (USACE 1984, 1995, 1999), which is less than the dredged (or contract) depth considering potential sedimentation. The permitted depth is the extreme dredging depth allowed by regulators.

PIANC (1997) provides a step-by-step procedure for estimating the contributions of numerous factors that determine the entrance channel depth. Procedures describing the USACE guidance are specified in USACE (1984, 1995, 1999). USACE guidance states:

“Maximum heave of a vessel due to waves with wavelength twice the vessel length is approximately a fifth of wave height; maximum pitch and roll magnitudes are half of wave

height. Net depth allowance for waves is 1.2H for deep-draft and 0.5H for shallow-draft channels where H is the wave height."

The above estimates provide ample safety margins, but may be overly conservative based on fundamentals of naval architecture and rigid-body ship motions. Recent advances in data-acquisition technology and ship-motion modeling can provide accurate estimation of vessel motion from waves. Vessel RAOs are strongly dependent on the height, period, and direction of waves as well as the encounter frequency, the relative frequency of waves with respect to the forward speed of a moving vessel. Vessel responses vary substantially from restricted, shallow-water to unrestricted, deep-water conditions. Ship-response prediction models are now available that provide accurate estimates of the vessel motions in open seas resulting from the combined action of winds, waves, and currents. Extending these predictive tools to shallow water is an area of ongoing research.

Because vessel motions enter the design and operations of navigation channels, ports, and harbors, a RAO curve representing a bulk carrier (Harkins and Dorrell, in preparation), is shown in Figure 3 as an example of ship motions. This RAO curve represents only one of many possible combinations of vessel displacement for a wave heading of 45 deg and 3-ft underkeel clearance. The RAOs of the vertical DOFs, heave, roll, and pitch, are shown together with their respective phases. The RAO for each DOF represents the maximum excursion of the ship bottom for unit wave amplitude, indicating the degree to which each principal DOF contributes to the total excursion. The total RAO (combining the individual RAO and phase relationships) shown in Figure 3 suggests a maximum amplification of 1.5 for wave periods of 16 to 24 sec versus the present guidance of 2.4 for all wave periods or, conversely, a limiting wave height of 4 ft versus 2.5 ft. The present USACE estimate would require 50 percent more allowance for wave motion contribution to the channel depth.

When a deep-draft cargo vessel is underway, water passes around its hull, creating a depression into which the vessel sits (USACE 1995; SNAME 1985). This phenomenon is called squat, defined as the combined effects of sinkage (heave), trim (pitch), and heel (roll) caused by the forward speed of the vessel. Vessel squat depends on many factors including ship geometry (length, beam, draft, shape, etc.), channel geometry (depth, width, area, etc.), ship position (proximity to channel bank), and forward speed. Several empirical formulas have been proposed for estimating vessel squat. The estimation of vessel squat in shallow water and restricted channels is more complicated than its prediction in deep water. Some progress in shallow-water squat prediction has been made since 1990 (SNAME 1996).

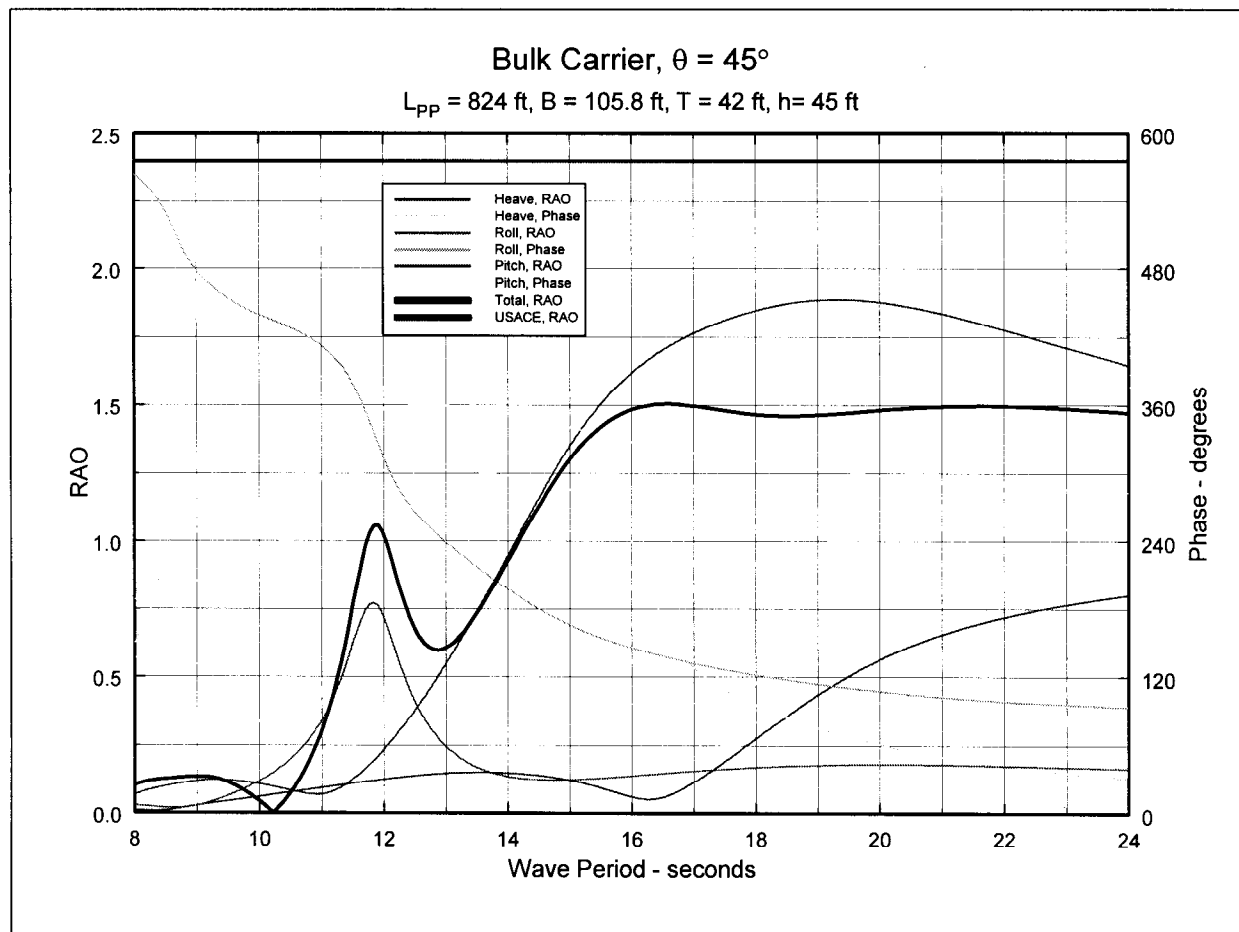


Figure 3. Excursion RAO curves and USACE guidance for bulk carrier

As an example of the difficulties present in estimating shallow-water squat, Figure 4 shows squat curves for a bulk carrier (Harkins and Dorrell, in preparation). Squat values from 10 empirical equations are extracted from PIANC (1997), USACE (1995), and Ankudinov et al. (1996) for a shallow fairway $h/T = 1.2$, where h = water depth, and T = vessel draft. Similar empirical relationships exist for trenched fairways and canals; these types of geometry restrictions usually result in greater values of squat when compared with an unrestricted channel having the same depth. In general, shallow-water squat is usually greater than deep-water squat and is approximately proportional to the square of the vessel speed. From Figure 4, for a speed of 10 knots, the squat estimates vary from 1.7 to 3.7 ft, a difference of 2 ft; for a speed of 15 knots, squat varies from 3.7 to 9.8 ft, a difference of 6.1 ft. This ambiguity in squat would limit vessel speeds by 4-5 knots based on the extreme estimators. Overly conservative squat estimators would result in either unnecessary dredging costs or reduced throughput capacity. It is necessary to revisit these predictors and arrive at a consensus for a unified squat estimator for both design and operational purposes.

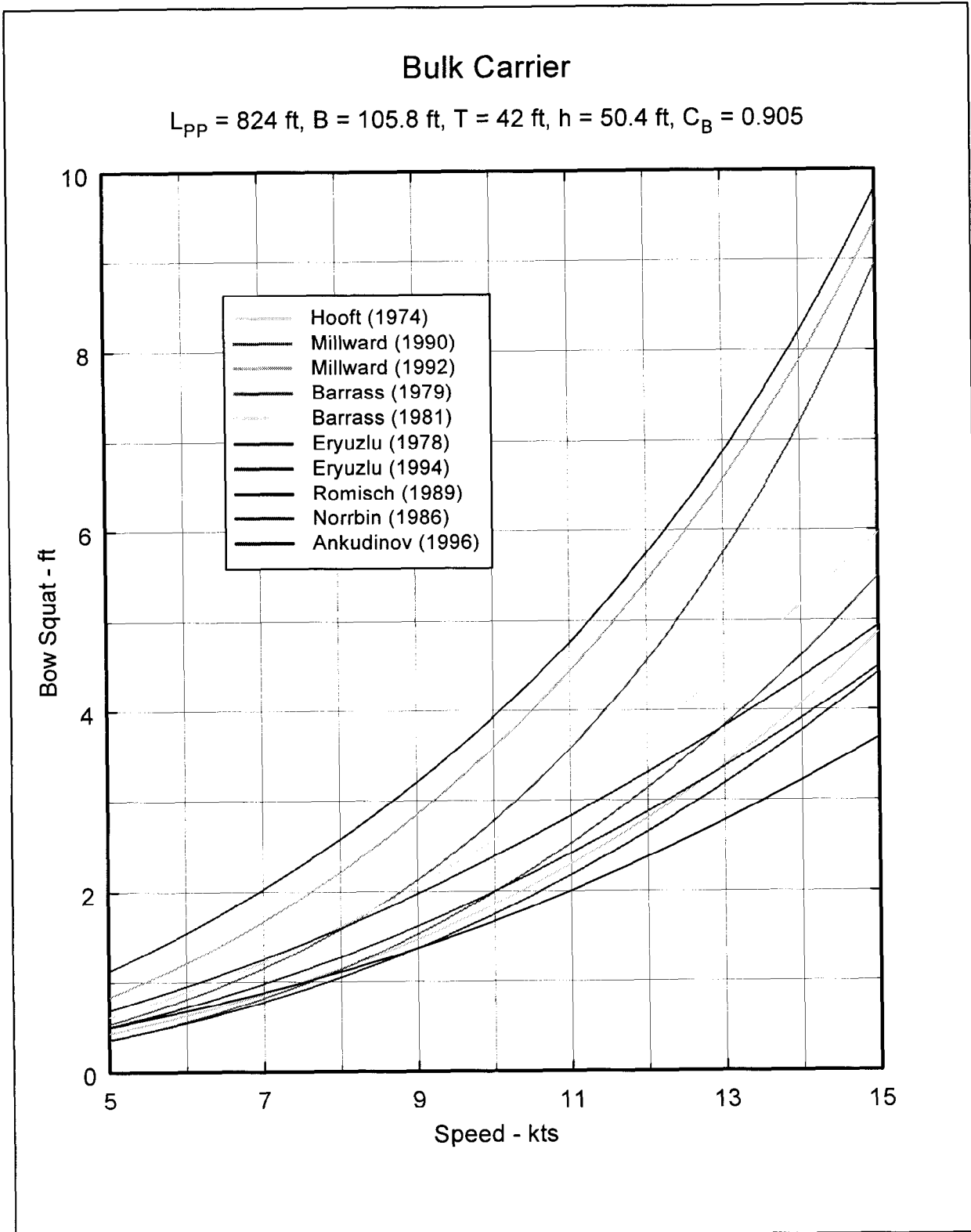


Figure 4. Squat predictions for bulk carrier in an open fairway

DETERMINATION OF CHANNEL WIDTH: *The optimum channel width varies with many factors, including channel alignment, transit routes, construction and maintenance costs, vessel transit time, vessel speed and maneuverability, horizontal vessel movements caused by winds, waves, and currents, proximity of channel banks, traffic pattern (one-way versus two-way traffic), and availability and frequency of nav aids. The channel width, measured from the bottom of the side slopes at the design depth, must accommodate the design vessel(s). The authorized channel width must allow normal vessel operations in a safe and efficient manner. Crosscurrents and winds adversely affect the station keeping and maneuvering of vessels, and quartering seas may cause the vessel to deviate from its route. USACE guidance for channel width states:*

“For one-way ship traffic, values for channel width vary from 2 to 7 times the design ship beam. Typically a range of 2.5 to 5 is used as design criteria. For straight one-way channels with low currents, widths of 2 or 2.5 times the design ship beam should generally be conservative. Recommending a similar criteria for two-way ship traffic is difficult due to lack of data” (USACE 1984, 1995, 1999).

Historically, width requirements have been based on piloting experiences and the accuracy with which pilots are able to transit entrance channels for various environmental and vessel-handling characteristics. Currently, the final design-width requirements are usually considered through the use of virtual ship simulators, which recreate the scene dynamics and horizontal vessel responses because of ship maneuvers taken by actual pilots in the simulator. Further research is needed to quantitatively establish horizontal vessel responses because of waves (and currents) and to incorporate those results into a preliminary design tool and enhanced ship simulator.

ADDITIONAL INFORMATION:

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Demirbilek, Z., and Sargent, F. (1999). “Deep-draft coastal navigation entrance channel practice,” Coastal Engineering Technical Note CETN I-63, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
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