FERRY LANDING DESIGN
PHASE I

WA-RD 253.1

Final Report
October 1993

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Transit, Research, and Intermodal Planning (TRIP) Division
in cooperation with the U.S. Department of Transportation
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16. ABSTRACT

A procedure is developed for selecting design criteria for the berthing energy fender systems at ferry landings. In particular, end berthing arrangements are considered. A sample of 568 landing events are reviewed to find the distribution of approach velocity for kinetic energy calculations. An upper bound for the berthing coefficient is also identified. The design procedure is developed that involves 1) identification of the upper limits of the approach velocity by analyzing a sample of berthing events, 2) selection of a safety factor by making systematic judgements, 3) selection of a berthing coefficient based on experimental results, and 4) selection of design berthing energy using the kinetic energy formula. Further research is recommended to improve the placement of landing aids and to develop design criteria for other landing structures.

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Final Report

Research Project GC 8719, Task 16
Ferry Landing Structures Design

FERRY LANDING DESIGN
PHASE 1

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DISCLAIMER

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SUMMARY

Ferries are an integral part the transportation system in the Puget Sound region. In comparison to other vessels, ferries land more often and spend a greater proportion of time using terminal facilities. Therefore, the proper design of landing structures is crucial to the efficient operation of the Washington State Ferries (WSF).

In most cases, the existing terminal structures have performed satisfactorily. However, WSDOT would like to reduce the frequency of repairs, avoid the use of creosoted lumber (which has been declared a hazardous substance that requires special disposal), and develop innovative structures. Innovations are required to improve safety and efficiency and address difficult foundation conditions.

Existing designs are not based on rational design criteria. Rather, they have evolved gradually, with incremental improvements as necessary. Before innovative designs are developed, a set of rationally developed design criteria should be adopted. This project's objective was to recommend such design criteria for the wing walls of WSF's landing structures.

The wing walls act as a fender system at the ferry landing. They absorb energy by deflecting as they push against the vessel and bring it to a stop. They also guide the vessel to the transfer bridge and hold it in place during its call. Each ferry landing has two wing walls. They are located just beyond the transfer bridge and set at a 40-degree angle from the centerline of the slip to funnel the bow of the vessel to the end of the transfer bridge.

A literature review showed that past research has concentrated on design criteria for side-berthing vessels. The berthing energy may be selected in two ways: 1) by selecting a design approach velocity and estimating the berthing energy by calculating kinetic energy and the berthing coefficient, or 2) by reviewing a statistical analysis of a sample of berthing events and selecting a design berthing energy that will result in an acceptable probability of failure.

WSF vessels use end berthing maneuvers. Therefore, neither the approach velocities nor the berthing energies from the literature review are applicable to WSF's situation.

Using a closed circuit television (CCTV) system and a video recorder, the research team collected a sample of 568 berthing events at WSF's Edmonds Ferry Terminal. This sample was analyzed to find the distribution of approach velocities. The average approach velocity was 0.58 ft/sec (0.18 m/sec). The 95th percentile velocity was 0.91 ft/sec (0.28 m/sec) and the highest recorded approach velocity was 2.0 ft/sec (0.61 m/sec). The size of the vessel and seasonal weather conditions had little influence on the approach velocity, while wind speed was shown to have some influence.

The berthing coefficient was estimated by comparing the apparent kinetic energy of the vessel to the energy absorbed by the wing walls. Because the force vs. deflection relationship of the wing walls had been established by field testing, the researchers were able to estimate energy absorption by estimating the wing wall's deflections. The upper limit of the berthing coefficient for most events was found to be 0.60.

The following procedure is recommended for selecting design criteria for a ferry landing.

1. Obtain a sample of approach velocities and note the parameters that describe the upper limits of the distribution. Alternatively, use a sample from a landing that has similar characteristics.

2. Select a safety factor by considering the importance of the landing structure, vessel reliability, time and cost of repairs, and environmental factors that were not included in the sample.

3. Select the design berthing energy by considering the upper limits of the approach velocity distribution, the safety factor, the vessel's mass, and the berthing coefficient.

4. Consider two different design cases: Case *i*, where the vessel lands in the wing walls' throat, and Case *ii*, where the vessel lands against one wing wall and later moves to the throat.

Specific recommendations should be reviewed and included in a manual for ferry landing design. In addition to design criteria, the manual should contain information on existing landing geometry and vessel characteristics. Further research should be conducted to collect samples from other locations and to develop design criteria for other structures.

The effects of wind and current on the berthing maneuver were difficult to detect with the methodology developed for this project because only the last 5 to 15 feet (1.5 to 4.6 meters) of the berthing maneuver were recorded, while the effects of wind and current are probably more apparent during an earlier stage of the berthing maneuver. In a continuation of the project, researchers are tracking the berthing maneuver for its last 5,000 ft (1,500 m). The results are expected to help improve the placement of landing aids and further the development of design criteria with respect to berthing energy.

CONCLUSIONS AND RECOMMENDATIONS

The following recommendations resulted from the research.

- The design criteria for ferry landing structures should be developed according to three types of berthing events:

    1. **Type I — No Damage.** A fender system should perform adequately for most berthing events for its entire service life. Repairs should be limited to normal maintenance.

    2. **Type II — Repairable Damage.** A fender system may be damaged by unusually hard berthing events. Repairs should be limited to replacement of a portion of the system. The system may be analyzed to identify probable repair requirements, and contingency plans may be made to speed the repair process.

    3. **Type III — Catastrophic Damage.** A fender system and its supporting structure may fail during a catastrophic occurrence. If the structure yields sufficiently, deceleration forces should be limited as the vessel is brought to a stop; this should limit injuries and vessel damage. An example of a catastrophic occurrence is a propulsion failure as the vessel applies reverse thrust to stop.

- The design berthing energy should be based on the upper limits of a sample of berthing events, multiplied by a safety factor.

- The safety factor should be varied according to importance of the structure, ease of repair, vessel reliability, and environmental conditions not included in the sample.

- Further research should be conducted to collect approach velocity distributions for locations other than Edmonds, and for structures other than wing walls .

- The distribution for berthing energy should be developed by observing deflection on fender systems that allow better deflection vs. energy calibrations.

- Further research should be conducted to develop design criteria for Type II and Type III events. Historical records should be consulted to develop a model for predicting severe accidents.

- WSDOT should review these recommended design criteria and develop a design manual for ferry landings.

Designers may use the Edmonds Ferry Terminal case study as a point of comparison for their own samples. The following conclusions were drawn from the study.

- The average distribution approach velocity, $q(V)$, for wing walls at Edmonds is 0.58 ft/sec (0.18 m/sec), and the 95^{th} percentile is 0.91 ft/sec (0.28 m/sec). The maximum observed approach velocity was 2.0 ft/sec (0.61m/sec).

- The displacement of the vessel and seasonal conditions have little effect on the distribution of approach velocities at the wing walls.

- The wind speed has some effect on the approach velocities at the wing wall.

- Most of the berthing events occur at the piles near the throat.

- $C = 0.60$ appears to be an upper limit for the berthing coefficient for an impact with one wing wall.

BACKGROUND

The Washington State Ferry System (WSF) comprises eight routes, 19 terminals, and 22 vessels and conducts over 200,000 landings per year. Structures at a typical ferry landing terminal include a transfer bridge that connects the ferry and the land, a pair of wing walls that absorb berthing impacts and hold the ferry in place while it is at the dock, and dolphins that guide the ferry into the berth and keep it aligned despite cross currents and winds (Figure 1). Because of the 19-foot (6-meter) tidal variation in the Puget Sound, the transfer bridge must be adjustable. A system of wire rope, counterweights, and pulleys is mounted in a steel and concrete or timber tower at the seaward end of the transfer bridge. This system provides a mechanism for adjusting the transfer bridge. The wing walls are constructed from creosoted wooden piles and timbers that are connected with bolts and cable lashings (Figure 2). Dolphins are either timber pile clusters or floating structures. The floating dolphins are either steel or concrete pontoons that are moored by anchors.

The vessels range in displacement from 1,350 to 4,336 long tons (lt) (1,372 to 4,405 metric tons (mt)) (Table 1). They are double-ended, i.e., they have pilot houses, propellers, and rudders at both ends to eliminate the need to turn them at the terminals. Like many ferries, WSF vessels head directly into the berth instead of approaching from the side. During the berthing maneuver, the ferry slows by reversing the thrust of its propellers. Its contact with the wing walls and other structures brings the vessel to a complete stop.

The Puget Sound region has experienced rapid population growth over the last 12 years (a 23 percent increase from 1980 to 1990, including Thurston, Mason, Pierce, Kitsap, King, Snohomish, Clallam, Jefferson, Island, Snohomish, Skagit, San Juan, and Whatcom counties). Ferry ridership has also increased for the same period: 20 percent in passengers and 38 percent in vehicles. (Note: 1980 figures were adjusted to eliminate the effect of temporary service provided because of the Hood Canal Bridge sinking.)

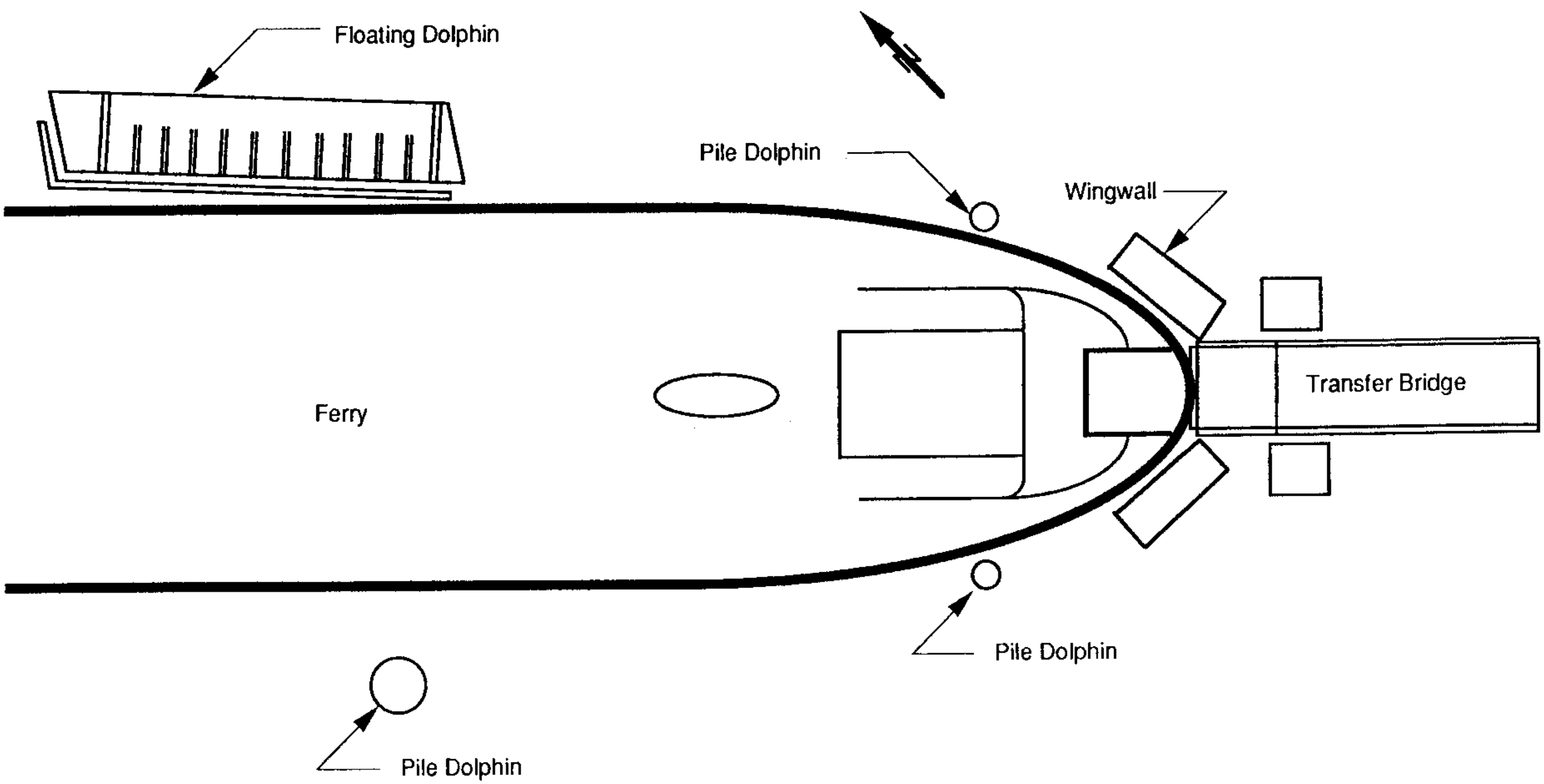

Figure 1. Layout of Edmonds Terminal

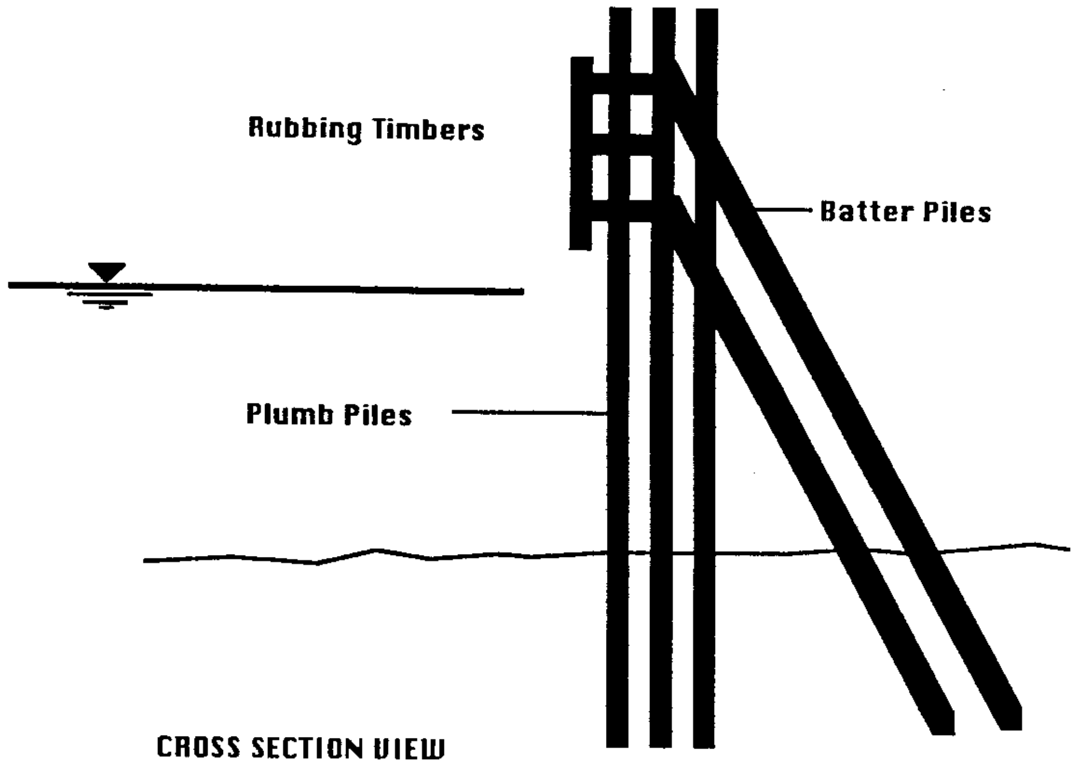

Figure 2. Wing Wall

Table 1. Vessel Characteristics

Class	**Length** ft (m)	**Beam** ft (m)	**Draft** ft (m)	**Displ.** lt[1] (mt)
Jumbo	440 (134)	87 (26)	18 (5.5)	4336 (4405)
Super	382 (116)	73 (22)	16 (4.9)	3283 (3335)
Issaquah	328 (100)	78 (24)	16 (4.9)	2943 (2990)
Evergreen State	310 (94)	73 (22)	15 (4.6)	2062 (2095)
Steel Electric	256 (98)	74 (23)	12 (3.7)	1806 (1834)
Rhododendron (typical small ferry)	226 (69)	63 (19)	12 (3.7)	1350 (1372)

[1]lt = long ton = 2240 lb.

In 1990, WSF moved 12,172,305 passengers and 9,113,347 vehicles (WSDOT Marine Division Traffic statistics). In this environment, the reliability of the ferry system is critical; proper performance of the terminal facilities is necessary for reliable service.

In most cases, existing terminal facilities have performed satisfactorily. However, WSDOT would like to develop new designs for the following reasons.

1. The existing structures must be repaired and replaced frequently. A wing wall at a busy terminal may require yearly maintenance that involves development of plans and specifications, competitive bidding by construction contractors, mobilization of floating construction equipment, and interference with vessel operations during the repairs. The cost, administrative effort, and delays are considerable.

2. The presently used building material, creosoted lumber, has been declared a hazardous substance. WSDOT retains responsibility for the proper disposal of hazardous substances even after they have been placed in landfills. Therefore, WSDOT may want to reduce the use of creosoted lumber.

3. Propeller wash from vessels is scouring the harbor bottom near the terminal structures. Thus, longer pilings are required to provide a foundation for the structures. Such long timber pilings are difficult to purchase. Alternatively, steel or concrete pilings could be used.

4. Innovative structures could be developed that would improve safety during Type II and Type III occurrences. Also, innovations could increase the efficiency of pedestrian loading and reduce visual impacts.

The existing design is not based on a set of rational design criteria. Instead, it has evolved gradually, with incremental improvements as necessary. However, if completely new designs will be developed to use different construction materials, a set of rationally-developed design criteria would be desirable. The objective of this research project was to start the development of such rationally-designed criteria.

REVIEW OF PREVIOUS WORK

Fender systems must absorb the kinetic energy associated with the vessel's approach velocity. The kinetic energy (KE) of a vessel was calculated by Bruun (1), NAVFAC (2), and PIANC (3) in the following equation :

$$KE = 1/2\,(w/g)CV^2 \tag{1}$$

where w = weight of vessel,

V = approach velocity (usually the component normal to the face of the fender system),

g = acceleration of gravity, and

C = a coefficient that accounts for the vessel's approach angle, the eccentricity of impact, and various hydrodynamic effects.

Because kinetic energy varies with the square of the velocity, proper selection of the design velocity is imperative. Most references provide tables or graphs in which design velocity is a function of the vessel's displacement and the degree of environmental exposure at the berth. For large ships, PIANC recommended the following design approach velocities:

1. very favorable conditions: 0.33 ft/sec (0.10 m/sec),
2. in most cases: 0.49 ft/sec (0.15 m/sec), and
3. very unfavorable conditions with cross currents or much wind: 0.82 ft/sec (0.25 m/sec).

PIANC cautioned that the probability of exceeding these design approach velocities "appears to be rather high." With regard to ferries, it suggested increasing the design velocity by 15 to 20 percent. PIANC also recommended that 0.50 m/sec (1.64 ft/sec) is an adequately conservative design velocity for *end fenders*. Apparently, end fenders serve the same function as wing walls. PIANC reported the use of higher design velocities (up to 3.0 m/sec or 9.84 ft/sec) for guiding or side fenders; however, the angle of approach is limited to 15 to 20 degrees.

The coefficient C is calculated as follows:

$$C = C_e C_m C_b \qquad (2)$$

where C_e = *Eccentricity Factor.* Eccentric impacts cause the vessel to spin, thus reducing the amount of energy that the fenders must absorb.

C_m = *Mass Factor.* Water that is entrained with the vessel tends to increase the amount of energy that the fenders must absorb. For end berthing vessels, such as WSF's, PIANC states $C_m = 1.0$.

C_b = *Configuration Factor.* Water that is trapped between the side of a vessel and a solid bulkhead tends to cushion the impact and reduce the amount of energy that the fenders must absorb if the vessel makes a side approach. Such situations do not apply to WSF; therefore, $C_b = 1.0$.

PIANC described a statistical approach for designing fender systems. By reviewing the results of several studies, it developed a database of 4,926 berthing events. The vessels were bulk carriers with displacements ranging from 15,000 to 400,000 mt (14,765 to 393,700 lt). In reviewing these data, it concluded that current conditions and the vessel's displacement were the parameters that most influenced the berthing energy.

The impulse response function (IRF) is a numerical method that accounts for interactions among the vessel, the surrounding water, and the fender system in a precise and systematic manner. (4, 5) It has been confirmed by model tests and some full-scale tests. (5) This method is more mathematically complex than the kinetic energy method and has not gained wide-spread acceptance as a design method. However, it is potentially useful for side berthing, shallow-draft situations in which entrained water (C_m) is significant.

Pankchik and Ladegaad described the ferry landing design criteria for Danish State Railways and the procedure that was used to design a new landing facility at Helsingør, Denmark. Computer simulation of vessel approaches was an important part of the design procedure. (6)

Ishii surveyed WSF's on-board staff to better understand how environmental factors, types of vessels, and locations of landings influence the approach velocity. (7) He stated that wind, current, and fog were the environmental factors that most influenced the approach velocity. It was most difficult to land ferries in terminals with strong, unpredictable currents .

On a scale from 1 to 7, the most difficult terminal received an average rating of 5.7, while the easiest terminal received a rating of 2.1. Most vessels were described as relatively easy to land. Respondents indicated a desire for a landing structure that could safely absorb emergency impacts associated with propulsion failures.

PROCEDURES

A method was developed for selecting the design approach velocity (V) and the berthing coefficient (C) for Type I berthing events (no damage). The approach velocity density function, $q(V)$, was analyzed to select the design approach velocity. For a limited subset of data, the energy distribution, $q(E)$, was also analyzed.

Images from video recordings were analyzed to obtain the approach velocity distribution. Two closed circuit television cameras were mounted on the walkway connecting the counterweight towers at WSF's Edmonds Terminal (Figure 3). Each camera was aimed at one of the wing walls. A split image was recorded to simultaneously show the events that occurred at each wing wall. The date and time were imprinted on the video image. A motion detector was installed to initiate recording when the ferry arrived.

More than 1,500 berthing events were recorded over 10 months. For some video tapes, every event that was recorded was analyzed. This procedure produced a data set of 568 events. Otherwise, the recordings were scanned to select events in which the deflection of the south wall was greater than 4 in. (102 mm) and that of the north wall was greater than 6 in. (152 mm). This process provided a special data set of 102 events that resulted in relatively high berthing energies. A larger deflection limit was selected for the north wall because the north wall had greater deflections than the south wall for events of the same energy.

The approach velocity (V) was estimated by scaling the video images with marks of known size on the deck of the ferry. The position of the vessel was plotted for the last 10 to 20 seconds of the vessel's approach. Thus, the V for the vessel's last 5 to 15 ft (1.5 to 4.5 m) of approach could be estimated. For each event, the following factors were noted: V perpendicular and parallel to the face of the wing wall (V_{perp} and V_{para}, respectively), position of the impact, the name of the vessel, and the deflection at each end of the wing wall (s_{near} and s_{far}). If several impacts were recorded for one landing, the approach velocity

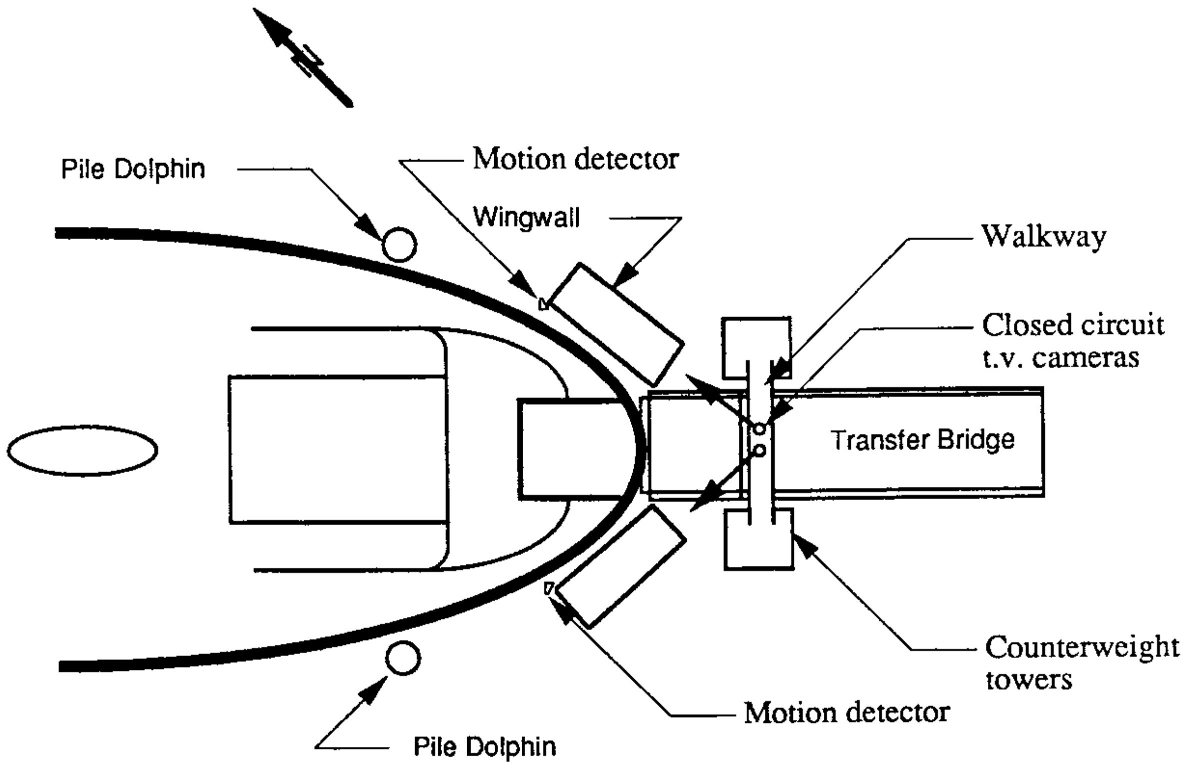

Figure 3. Test Layout

of the first impact was considered. The location of the impact was also noted by observing which plumb pile was closest to the point of impact. Plumb piles were equally spaced along the 26-foot length of wing wall and numbered 1 through 11, starting at the throat. An anemometer was installed for the last four months of data collection. During this time, wind speed and wind direction were also recorded.

A knowledgeable viewer was required for estimating from the video images. Experienced observers would provide different estimates after watching the same recordings. For five berthing events, four researchers provided comparative estimates for the same data. This comparison was analyzed to provide the following confidence interval for a single reading: ± 2 pilings for the location of impact, ± 0.2 ft/sec for the approach velocity, and ± 1.5 in for wing wall deflection.

The data were sorted into subsets so that comparisons could be made to discover how different factors changed $q(V)$. The factors considered were as follows:

1. Summer vs. winter — In the Puget Sound area, calm winds and high visibility are common in the summer, while the opposite is true in the winter. It is accepted practice to increase the design V for winter-like weather conditions. To find the influence of the season on $q(V)$, the research team compared $q(V)$ for the summer months (April through September) and the winter (February) for the MV *Yakima*. The MV *Yakima* was chosen because it was the only vessel on the Edmonds to Kingston run that operated in both summer and winter.

2. Size of vessel — It is accepted practice to assume that V increases as w, the vessel's displacement, decreases. To find the influence of w on $q(V)$, the researchers compared the $q(V)$ of the MV *Yakima* (Super Class, w = 3,283 lt) and the MV *Tillikum* (Evergreen State Class, w = 2,062 lt) during February. These vessels were normally assigned to the Edmonds to Kingston run during the winter months.

3. Different vessels of the same size — Although it is accepted practice to assume that $q(V)$ is the same for similar vessels, differences in $q(V)$ may occur because of differences in the crews' operating practices and minor differences in the vessels. During the summer months (April through September), two Super Class vessels (the MV *Yakima* and the MV *Hyak*) were assigned to the Edmonds to Kingston run. The $q(V)$ for these two vessels were compared.

4. North wing wall vs. south wing wall — Prevailing winds and a landing's geometry may create differences in V for the two wing walls. The $q(V)$ of the north and south wing walls were compared.

For each subset, comparative histograms were developed, and the mean, median, standard deviation, and range were calculated. The researchers compared the overall $q(V)$ to the normal distribution by using the chi squared test for goodness of fit.

The researchers estimated the berthing coefficient, C, by comparing two calculations for the berthing energy that were based on separate field measurements. One calculation produced the kinetic energy on the basis of the approach velocity:

$$E_v \quad = \quad 1/2\,(w/g)V_{perp}^2 \tag{5}$$

Equation (5) is similar to Equation (1), except that C is missing in Equation (5). The other calculation based berthing energy on deflection measurements:

$$E_s \quad = h(s) \; = \; \int_0^{s_{max}} g(s)ds \tag{6}$$

where E_s = berthing energy calculated from fender deflection,

$h(s)$ = the energy vs. deflection relationship for the wing wall, and

$g(s)$ = the force vs. deflection relationship for the wing wall.

For this project, $g(s)$ was developed for selected locations on the south wing wall at Edmonds Terminal from field test data recorded by R. Jones and C. T. Jahren. (8) The test was accomplished by pulling on the wing wall with a barge-mounted winch. One hundred kips (45.6 mt) of force and 4 in (10.2 cm) of deflection were measured during the test. The force was limited by the holding power of the barge's anchors. After slack is removed from the wing wall, $g(s)$ is a linear relationship. To use $g(s)$ for this study, the linear portion of the field test result had to be extrapolated. For piles 3, 6, and 9, $h(s)$ was calculated directly from $g(s)$. For piles 4, 5, 7, and 9, $h(s)$ was interpolated from the values of $h(s)$ for piles 3, 6, and 9. The function for $h(s)$ for pile 2 was assumed to be the same as that for pile 3. Eighteen berthing events were analyzed, providing a data set for analyzing $q(E_s)$, the probability density function for berthing energy based on deflection, and $q(C_{est})$, the probability density function for the estimated berthing coefficient.

C was estimated by:

$$C_{est} \quad = \quad E_s / E_v \tag{7}$$

where C_{est} is an estimate of the berthing coefficient.

In addition to the factors specified for C in the definitions for Equation (2), C_{est} is also influenced by the thrust of the propulsion system, difficulties in obtaining accurate deflection measurements, and uncertainties in developing $h(s)$.

DISCUSSION

The frequency histogram for the approach velocity of 568 events is depicted in Figure 4. Although *q(V)* appeared to be normally distributed, the *chi squared* test rejected that hypothesis at $\alpha = 0.10$. Deviations in the upper tail caused this rejection. The approach velocity ranged from 0.0 ft/sec to 1.28 ft/sec (0.39 m/sec), with an average of 0.58 ft/sec (0.18 m/sec). In the special data set of 102 high deflection landings, the highest reported approach velocity was 2.0 ft/sec (0.61 m/sec). The average and maximum for $q(V_{perp})$ were 0.44 and 1.00 ft/sec (0.13 and 0.30 m/sec), respectively. V_n is the approach velocity that exceeds *n* percent of the other occurrences. The 95th percentile velocity (V_{95}) was 0.91 and 0.75 ft/sec (0.28 and 0.23 m/sec) for $q(V)$ and $q(V_{perp})$, respectively. Other statistics are summarized in Table 2. Analysis showed that the approach velocity distribution was similar for the following subsets of data (Table 2):

1. north and south wing wall (Figure 5),
2. winter and summer seasons (MV *Yakima*) (Figure 6),
3. Super Class and Evergreen State Class vessels (MV *Yakima* in winter, MV *Tillicum* in winter) (Figure 7), and
4. MV *Yakima* and MV *Hyak* (summer) (Figure 8).

On the basis of an analysis of 139 events in which wind speed was available, wind speed was found to have only a small influence on the berthing velocity. Most of the landings occurred at the wing walls' throat (Figure 8).

Berthing energy (E_s) was estimated from deflection measurements for 18 events. Measurements ranged from 0.3 to 31 ft-kips (0.4 to 42 kNm). E_{s50} was 2.1 ft-kips (2.8 kNm); values of berthing energy from velocity measurements ranged from 7 to 103 ft-kips (9.5 to 140 kNm), while E_{v50} was 28.6 (38.79 kNm). C_{est} ranged from 0.02 to 1.09, while C_{est50} was 0.11. Other statistics are shown in Table 3. A scatter plot was developed to show E_s vs. E_v for each event (Figure 9). The line marked $C = 0.60$ served as the upper bound for all but one event.

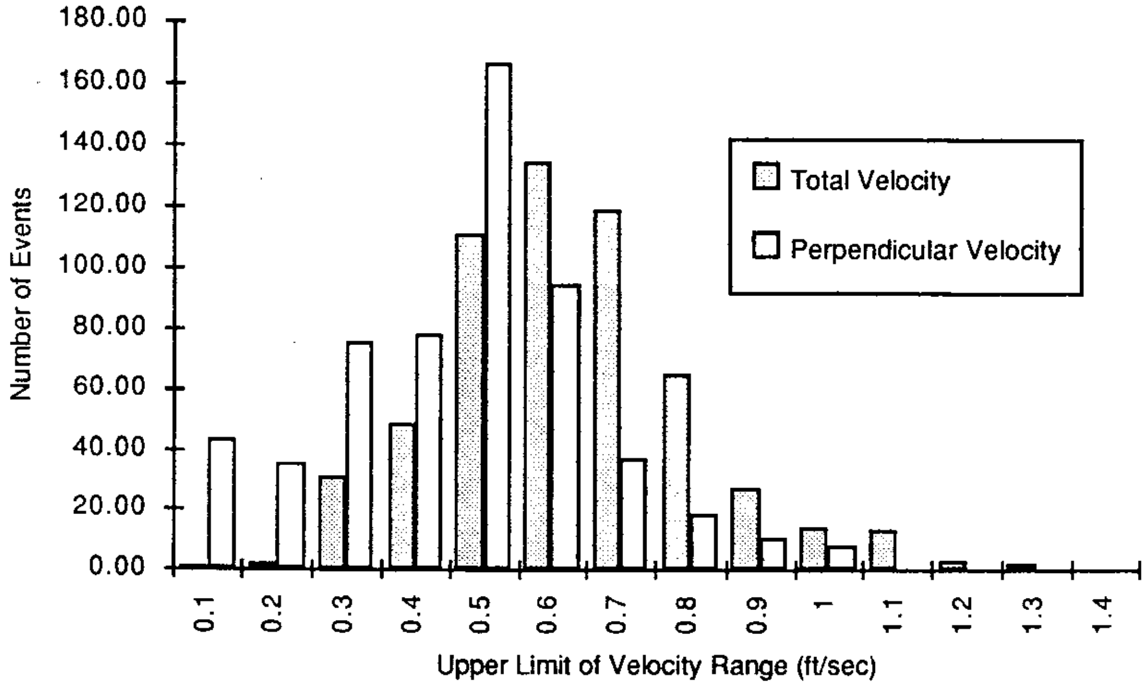

Figure 4. Frequency Histogram for 568 Berthing Events

Table 2. Descriptors of Approach Velocity Distributions

	Approach Velocity ft/sec (m/sec)															
	Combined Distribution 568 Events		MV *Yakima* Summer Runs		MV *Yakima* Winter Runs		MV *Ilyak* Summer Runs		MV *Tillicum* Winter Runs		South Wing Wall		North Wing Wall		High Deflection Events	
	Total	Perpen-dicular	Total	Perpen-dicular	Total	Perpen-dicular	Total	Perpen-dicular	Total	Perpen-dicular	Total	Perpen-dicular	Total	Perpen-dicular	Total	Perpen-dicular
Mean	0.58 (0.18)	0.44 (0.13)	0.59 (0.18)	0.43 (0.13)	0.58 (0.18)	0.45 (0.14)	0.59 (0.80)	0.43 (0.13)	0.57 (0.17)	0.43 (0.13)	0.59 (0.18)	0.47 (0.14)	0.58 (0.18)	0.39 (0.12)	0.85 (0.26)	0.76 (0.23)
Std. Dev.	0.18 (0.05)	0.19 (0.06)	0.19 (0.06)	0.20 (0.06)	0.18 (0.05)	0.18 (0.05)	0.17 (0.05)	0.22 (0.07)	0.17 (0.05)	0.16 (0.05)	0.18 (0.05)	0.19 (0.06)	0.18 (0.05)	0.20 (0.06)	0.24 (0.07)	0.24 (0.07)
V_{50}	0.57 (0.17)	0.45 (0.14)	0.58 (0.18)	0.47 (0.14)	0.56 (0.17)	0.50 (0.15)	0.57 (0.17)	0.45 (0.14)	0.56 (0.17)	0.45 (0.14)	0.56 (0.17)	0.50 (0.15)	0.57 (0.17)	0.42 (0.13)	0.83 (0.25)	0.73 (0.22)
V_{90}	0.80 (0.24)	0.65 (0.20)	0.85 (0.26)	0.63 (0.19)	0.80 (0.24)	0.65 (0.20)	0.83 (0.25)	0.69 (0.21)	0.78 (0.24)	0.60 (0.18)	0.83 (0.25)	0.73 (0.22)	0.78 (0.24)	0.60 (0.18)	1.12 (0.34)	1.00 (0.30)
V_{95}	0.91 (0.28)	0.75 (0.23)	0.96 (0.29)	0.75 (0.23)	0.90 (0.27)	0.75 (0.23)	0.85 (0.26)	0.70 (0.21)	0.84 (0.26)	0.70 (0.21)	0.90 (0.27)	0.80 (0.24)	0.90 (0.27)	0.70 (0.21)	1.24 (0.38)	1.20 (0.37)
Number of Events	568		200		108		152		50		287		279		102	

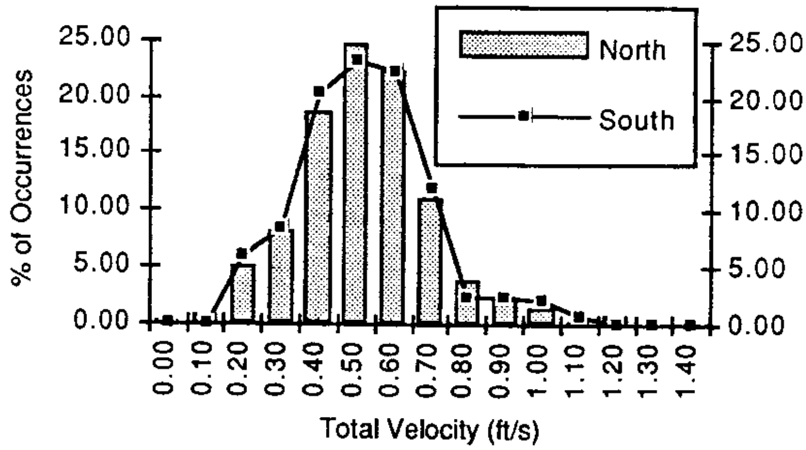

Figure 5. Comparison of North and South Wing Wall Approach Velocities

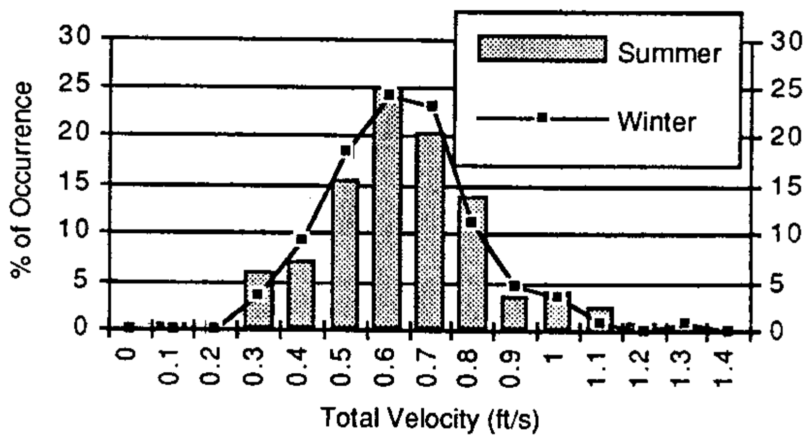

Figure 6. Comparison of Summer (April through September) and Winter (February) Approach Velocities (M.V. *Yakima*)

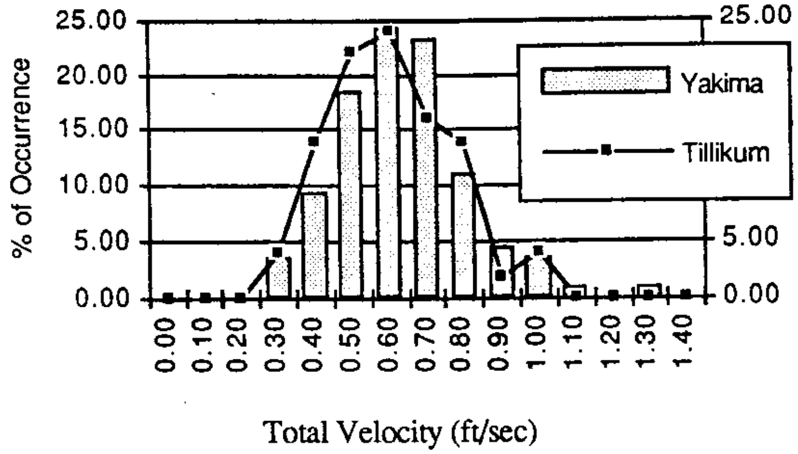

Figure 7. Comparison of Large Ferry (M.V. *Yakima*, 3283 lt or 3335 mt.) vs. Small Ferry (M.V. *Tillikum*, 2,062 or 2,095 mt.)

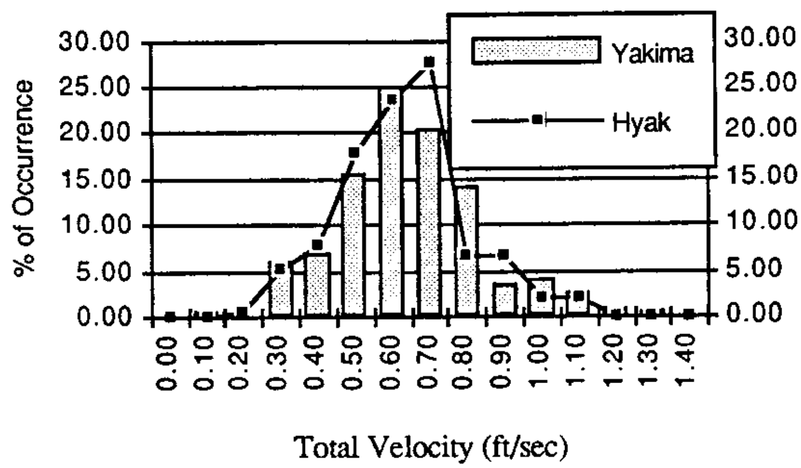

Figure 8. Comparison of Vessels of the Same Class (M.V. *Yakima* and M.V. *Hyak*)

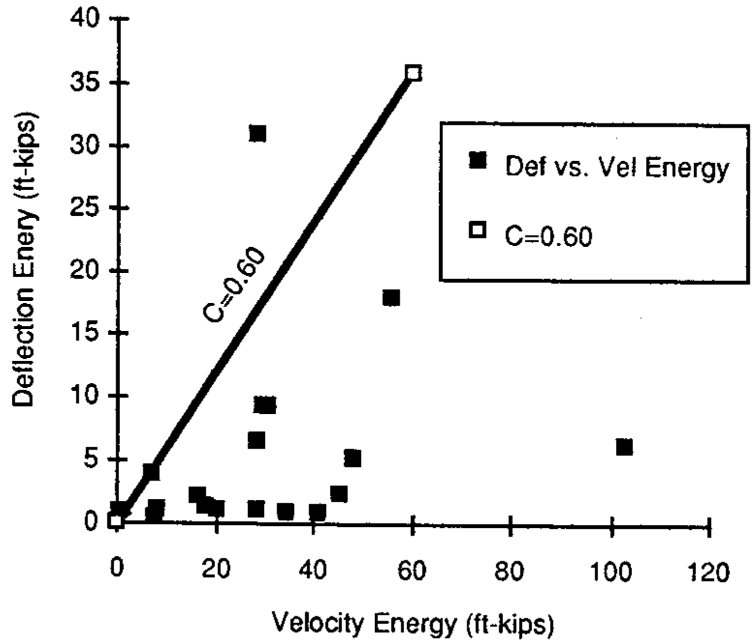

Figure 9. Deflection Energy vs. Velocity Energy

Table 3. Berthing Energy Observations

	$q(E_S)$ (kNm) ft-kips	$q(E_V)$ (kNm) ft-kips	$q(C_{est})$
Average	(5.9) 4.3	(44.5) 32.8	0.15
50th percentile (median)	(2.8) 2.1	(38.8) 28.6	0.11
75th percentile	(12.5) 9.2	(61.6) 45.4	0.30
Maximum	(42.2) 31.1	(139.8) 103.1	1.09

APPLICATION AND IMPLEMENTATION

DEVELOPING DESIGN CRITERIA

None of the recorded events caused visible damage to the structure. It seems reasonable that any ferry landing structures built in the future should be able to accommodate these events without damage. Therefore, the $q(V)$ developed by this study is assumed to reflect the randomness of the approach velocities of ordinary berthing maneuvers. Unusual or catastrophic events can be caused by mechanical failure or human error. An example is the failure of the propulsion system as the vessel lands. Because reverse propulsion is required to stop the vessel, an accident is almost certain under this circumstance. It is doubtful that the frequency or severity of such events can be predicted by analyzing $q(V)$ because the causes of events such as propulsion failures are different from the causes of random variation in $q(V)$.

In most cases, it is uneconomical to provide sufficient energy absorption to prevent permanent damage on either the vessel or the fender system during a catastrophic landing. However, Ishii developed concepts for innovative landing aids that may reduce the negative consequences of catastrophic landings under some circumstances. (7) Ishii suggested that it may still be possible to stop the vessel with minimum damage to the vessel if the landing aid is destroyed during the collision — in such a case, the destruction of the landing aid allows kinetic energy to be absorbed.

By considering three types of berthing events, it is possible to develop a set of appropriate design criteria:

1. **Type I — No Damage.** A fender system should perform adequately for most berthing events for its entire service life. Repairs should be limited to normal maintenance.

2. **Type II — Repairable Damage.** A fender system may be damaged by unusually hard berthing events. Repairs should be limited to replacement of a portion of the system. The system may be analyzed to identify probable repair requirements, and contingency plans may be made to speed the repair process.

3. **Type III — Catastrophic Damage.** A fender system and its supporting structure may fail during a catastrophic occurrence. If the structure yields sufficiently, deceleration forces should be limited as the vessel is brought to a stop; this should limit injuries and vessel damage. An example of a catastrophic occurrence is a propulsion failure as the vessel applies reverse thrust to stop.

Engineers could develop wing wall design criteria for Type I berthing events for terminals that are similar to the Edmonds Terminal on the basis of information from this study. Additional research will be required to develop design criteria for Type II berthing events and for all types of events for dolphins. Ishii provided information that may be used to develop design criteria for Type III events for terminals similar to Edmonds'. (7)

When design criteria are developed, consideration is given to both the load and the resistance of the structure. The actual values of both the load and resistance are uncertain. Possible probability density functions for load, $q(S)$, and resistance, $q(L)$, are depicted in Figure 10. A prudent planner will design a structure so that its expected resistance will exceed most of the loads that it will experience. For a failure to occur, an unusually high load must be imposed on an unusually weak structure.

Manipulation of probability density functions is too difficult for day-to-day use with design criteria. Instead, point values (i.e., single numbers) are substituted for the probability distributions. In developing such design criteria, two questions must be asked: (1) What point values will be used to characterize the design load and design resistance? (2) By how much should the design resistance be separated? A common method is to select an unusually large load, S_l, and an unusually small resistance, R_s (Figure 10). The design is considered adequate if

$$R_s \quad \geq \quad FS_l \qquad (3)$$

where F = the factor of safety.

Table 4 lists some factors of safety that are currently used. Larger factors of safety are used for cases in which $q(S)$ and $q(R)$ have large dispersions or in which the consequences of failure are highly undesirable. For example, the recommended factor of safety for wire rope is 3.0 to 5.0 (ref. 5 on Table 4). The strength of wire rope is uncertain because it is subject to

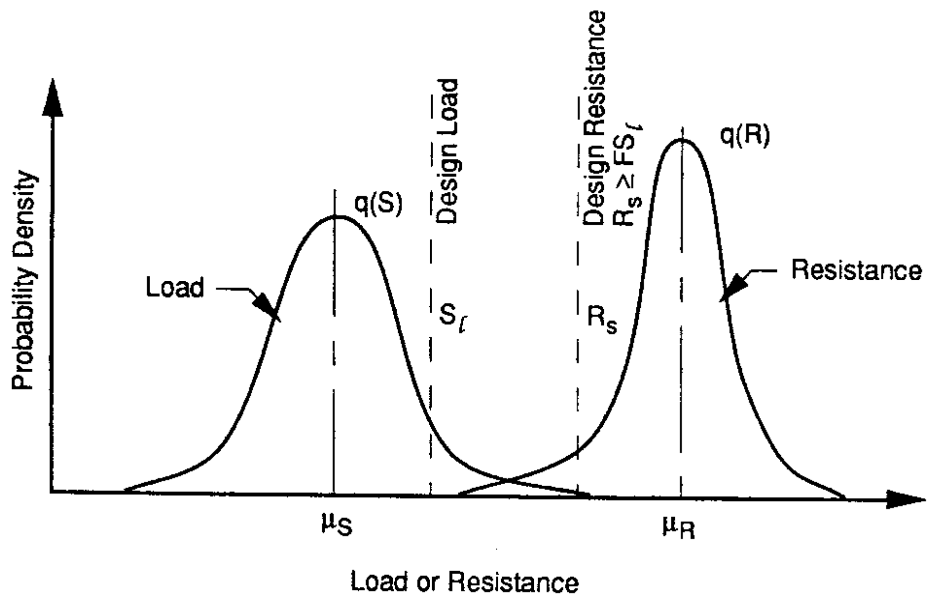

Figure 10. Development of Design Criteria from Probability Density Functions of Load and Resistance

Table 4. Safety Factors

Steel[1]		
Tension	1.67 - 2.22 ($0.45f_y$ to $0.60f_y$)	Allowable stress design
Shear	2.5 ($0.40f_y$)	
Bending	1.33 - 1.67 ($0.60f_y$ to $0.75f_y$)	
Steel[2]		
Dead load	1.2	Load and resistance factor design
Live load	1.5	
	Note: Stress reduction factor from ultimate stress is 0.90 in most cases.	
Concrete[3]		
Dead load	1.4	Load and resistance factor design
Live load	1.7	
	Note: Stress reduction factor from ultimate stress is 0.85 for shear and 0.90 for bending	
Cellular cofferdam[4]		
Permanent loads	1.5 to 3.0	Depending on failure mode
Temporary loads	1.25 to 3.0	
Seismic load	1.1 to 1.5	
Wire rope		
Rigging and Hoisting[5]	3.0 to 5.0	

[1] *Manual of Steel Construction, Allowable Stress Design*, 9th edition, American Institute of Steel Construction, Chicago, IL, 1989.

[2] *Manual of Steel Construction, Load and Resistance Factor Design*, 1st edition, American Institute of Steel Construction, Chicago, IL, 1986.

[3] ACI Manual of Concrete Practice, American Concrete Institute, Detroit, MI, 1979.

[4] U. S. Army, Design of Sheet Pile Cellular Structures, Cofferdams, and Retaining Walls, Draft, U. S. Army Corps of Engineers, Washington, D.C., not dated.

[5] *Wire Rope Users Manual*, (2nd edition) Wire Rope Technical Board, Stevensville, MD, 1981.

fatigue as it bends over pulleys and to deterioration as it is exposed to the environment. The load is uncertain because of the dynamic component of a suspended load. Failure is undesirable because death or injury will result for nearby workers. By contrast, the factor of safety for steel or concrete design is lower because concrete strengths and building loads are more predictable and because the design profession has had considerable experience with these types of designs. If a failure occurs, it is likely that other members in a building will be able to support the load and prevent total collapse.

Using the factor of safety method, the design approach velocity, V_d, for Type I berthing events may be selected with the following equation:

$$V_d = FV_n \tag{3}$$

where V_n = the approach velocity that exceeds n percent of the events

F = factor of safety.

The design is considered adequate if the kinetic energy that results from the design approach velocity does not exceed the design limits for the fender system.

As n becomes smaller, V_d is less influenced by the unusually high speed events that are observed during the data collection period, but if n is too small, the dispersion of $q(V)$ is not indicated in the results. As F increases, the structure becomes more robust and is able to withstand a greater proportion of unusual events that are not included in $q(V)$. Little is known about the approach velocity distribution of such unusual events. Therefore, the selection of the factor of safety is a matter of judgment rather than calculation. However, this process does result in more rational design criteria because the design approach velocity is based on an upper percentile of the observed distribution of the approach velocity, $q(V)$.

In many cases, structures that are developed according to such criteria will be able to survive events that exceed the design load. Recall that the failure strength for most materials exceeds their design strength. Also, in some cases, a limited failure may not compromise the usefulness of a structure. For example, the design load of a fender system may be defined to prevent yielding in the steel supporting piles. In this example, an unusually hard landing may *technically* cause failure in the pilings by bending them back an inch, but may *not impair the function* of the fender system.

Using the factor of safety method, engineers can select the design berthing energy for Type I berthing events with the following equation:

$$E_d \geq 1/2(w/g)\,C\,(F_V V_n)^2 \qquad (5(a))$$

where V_n = the approach velocity that exceeds n percent in $q(V)$, the probability distribution for the approach velocity for normal landing events, and

F_V = the factor of safety based on the approach velocity.

V_n is an indicator of the dispersion of $q(V)$. Although a formulation involving the standard deviation could be used, V_n is preferred because it is more appropriate if $q(V)$ is a non-normal distribution. Alternatively, the design berthing energy can be selected with this equation:

$$E_d \geq [1/2\,(w/g)\,C\,V_n^2]\,F_E \qquad (5(b))$$

where F_E is the factor of safety based on the berthing energy. Note that for equivalent designs, $F_E = F_V^2$. This is because the energy varies by the square of the velocity, thus doubling the velocity and quadrupling the energy. A factor of safety that is based on energy will result in smaller energy absorbing requirements for the same factor of safety. However, approach velocity as a concept can be understood and grasped more easily than can berthing energy. For example, it would be easier to explain to a ship's master that the fender system was designed to accommodate twice the highest observed berthing velocity than twice the highest observed berthing energy. Furthermore, except under unusual circumstances, the ship's master can control the berthing velocity. Therefore, it is advisable to base the safety factor on approach velocity rather than berthing energy. Thus, F_V is the factor of safety that is discussed in this paper.

The following procedure is proposed for Type I events.

1. Obtain a sample of approach velocities and note the parameters that describe the upper limits of the sample's distribution.

2. Select n. n must be large enough so that V_n responds to $q(V)$'s dispersion, but small enough so V_n is not unduly affected by a few large measurements.

3. Select F by considering the following factors.

   a. Consider the importance of the landing structure. Are alternative berths available at the same landing? If there is only one berth, are alternative modes of transportation available (such as driving around a body of water), or will a community, such as an island, be isolated without ferry service? Higher factors of safety should be provided for structures for which few alternatives are available.

   b. Consider environmental factors, especially wind and current, that may not have been present while the sample was taken. Time and budget limitations may prevent designers from obtaining a sample that represents extreme environmental conditions that are relevant to terminal design. Also, it may be necessary to use a sample from a different location with modifiers. Adverse environmental factors may justify an increase in the safety factor because they increase the difficulty of the landing.

   c. Consider the time and cost required to repair the system. If repairs are easy and inexpensive, then the limit for Type I events may be lowered. If repairs are difficult and expensive, then the limit for Type I landings may be raised.

   d. Consider the vessel's maneuverability and reliability. Higher safety factors should be considered when vessel problems occur frequently.

   Tables should be developed to guide designers in the selection of F as they consider these factors. Furthermore, the design should receive input from a multi-disciplinary committee that can help to evaluate trade-offs between economy, safety, and service reliability.

4. Select C or by referring to Equation 2, field test results or the literature.

5. Calculate E_d with Equation 5(a).

EXAMPLE APPLICATION OF PROPOSED DESIGN METHOD

This section provides a set of example calculations for design criteria for the Edmonds Ferry Terminal. The factors of safety that are used in this example are for illustration. Although they serve as a starting point for further discussion and research, these example safety factors should be reviewed by designers and vessel operators before the are adopted as design criteria.

None of the events recorded in the Edmonds sample caused visible damage to the structure. It seems reasonable that any future ferry landing structures should be able to accommodate such landings without damage. Therefore, the case study's sample provides an appropriate basis upon which design criteria for Type I events can be developed.

The next step is to select a value for n. Recall that n must be large enough so that V_n responds to $q(V)$'s dispersion, but small enough so that V_n is not unduly affected by a few large measurements. Several subsets of $q(V)$ are shown in Table 3. V_{95} varies little from one subset to another, yet it serves as an indication of $q(V)$'s dispersion. Therefore,

$$n = 95$$

Discretion must be exercised in selecting the factor of safety (F) so that it provides a sufficiently robust design. Consideration of the following points is helpful in selecting a safety factor: 1) Little is known about the approach velocity distribution for unusual events; this is an argument for a larger safety factor. 2) Ferry landings withstand an unusually large number of berthing events in comparison to other port facilities; this is an argument for a larger safety factor. 3) The facility may be able to function after a landing in which the design velocity was exceeded because the ultimate strength of the material may exceed the design strength or because a small failure may not impair the function of the facility; this is an argument for a smaller safety factor. 4) Life safety issues are unlikely to be involved in Type I events (although they are a consideration for Type II and Type III events); this is an argument for a smaller factor of safety.

Because the arguments for larger and smaller factors of safety are evenly split, a basic factor of safety of $F_b = 2.0$ is a possible starting point. This is similar to many engineering factors of safety (Table 4). This factor of safety should be modified according to the previously mentioned considerations. Further judgment will be required to select the modification factors. Table 5 offers possible guidelines that could be used to select the modification factors. Recall that the values in Table 5 are provided only to illustrate the method.

The factor of safety (F) for the Edmonds Ferry Terminal can be selected in the following manner.

Table 5. Example of Safety Factor Modifiers

$$F = F_1 \times F_2 \times F_3 \times F_4 \times F_b$$

Modifier	Unfavorable	Neutral	Favorable
F_1 = Importance	F_1 = 1.25 if the ferry slip is the only surface transportation access for an island. F_1 = 1.25 if the ferry slip is the only one at a terminal where inconvenient detours would be required in case of a shutdown.	F_1 = 1.0 for the main slip at a multi-slip terminal.	F_1 = 0.875 for an auxiliary slip at a multi-slip terminal.
F_2 = Environmental	F_2 = 1.125-1.50 if the sample of berthing events does not include severe environmental conditions that are known to increase the approach velocity.	F_2 = 1.00 if the sample is representative of significant environmental conditions.	F_2 = 0.75-0.875 if severe environment present in the sample is not present at the landing (e.g. the sample was collected at a location with more severe conditions, or improvements are made to eliminate wind and current).
F_3 = Repair factor	F_3 = 1.125-1.250 if repairs are expensive and difficult, requiring mobilization of heavy construction equipment and long shutdowns for the slip.	F_3 = 1.0 if repair involves slip closures for less than a day and construction equipment is mobilized with little difficulty.	F_3 = 0.875 if repair does not close the slip and construction equipment is easily mobilized.
F_4 = Vessel factor	F_4 = 1.125-1.250 if vessels are unreliable or difficult to maneuver.	F_4 = 1.0 if vessels have average maneuverability and reliability.	F_4 = 0.875 if vessels are highly reliable and easily maneuvered.
F_b = Basic factor of safety	For this example, F_b = 2.000		

1. This terminal has only one slip, so if the landing structure is closed, then the Edmonds to Kingston Route cannot operate. Vehicles can detour by driving around the Sound or by taking one of four other ferry crossings. Thus, the importance modifier is

$$F_1 = 1.125$$

2. The wind and current conditions are neither easy nor difficult. (7) The sample from Edmonds accounted for a wide range of environmental conditions. Therefore,

$$F_2 = 1.000$$

   Ishii conducted a survey in which WSF's on-board employees rated the relative difficulty of the terminals. The results provide guidance for applying the Edmonds sample elsewhere.

3. Suppose that the fender system is designed to fail in a way that it can be repaired easily. The repair crew consists of a small barge-mount and six people. Such crews are readily available, and the barge may be positioned so that the slip is not closed. Therefore,

$$F_3 = 0.875$$

4. The vessels that call on Edmonds received ratings that indicated that they were slightly more difficult to control than were other vessels in WSF's fleet. (7) Therefore,

$$F_4 = 1.125$$

The resulting safety factor is computed as follows:

$$1.125 \times 1.000 \times 0.875 \times 1.125 \times 2.000 = 2.215\text{, say } 2.2$$

Two different approach geometries should be considered. The approach velocity and berthing coefficient will differ, depending on the geometry selected.

In Case *i*, the vessel lands in the throat and is stopped by both walls simultaneously (Figure 11(a)). The fenders near the throat should be designed to withstand a Case *i* event. The wing walls must stop the vessel's total kinetic energy because little rotation may occur after the landing; therefore, $C_e = 1.0$. Because the fender system's combined reaction is directly opposite the line of travel, the vessel's total velocity [$q(V)$] should be considered as a design velocity. Therefore, the Case *i* design approach velocity is

$$0.91 \times 2.2 = 2.002\text{, say } 2.0 \text{ ft/sec}$$

$$(0.28 \times 2.2 = 0.616\text{, say } 0.62 \text{ m/sec})$$

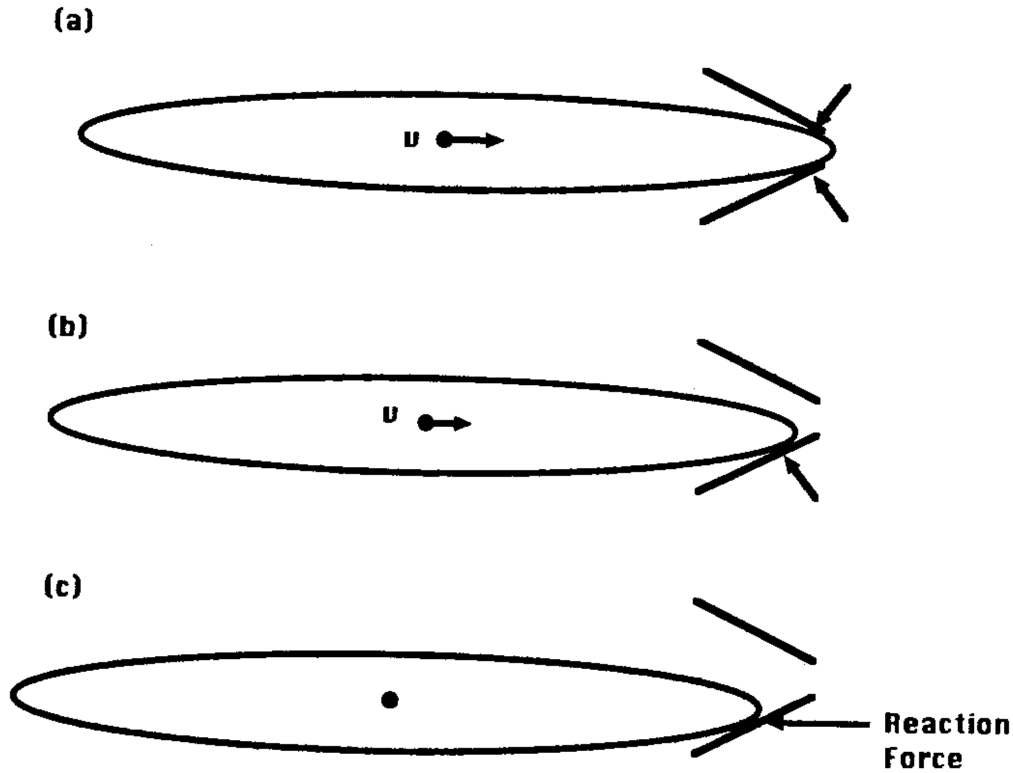

Figure 11. Three Cases for Wing Wall Design

The other factors in the berthing coefficient are selected as follows:

- For end-berthing vessels, such as those used by WSF, PIANC states that $C_m = 1.0$. (3)
- Because the terminal structures at Edmonds do not trap water so that a cushioning effect will occur, $C_b = 1.0$.
- Because WSF's vessels have a rigid belt rail that engages the fenders, little energy will be absorbed by the vessel; therefore, $C_s = 1.0$.

The resulting berthing coefficient is

$$C = 1.0$$

The Case *i* berthing energy for a Super Class Vessel (displacement = 3283 lt or 3335 mt) is

$$1/2 \times (3283 \times 2240/32.2) \times 2.0^2 = 456{,}765 \text{ ft-lb, say } 460 \text{ ft-kips}$$

$$(1/2 \times 3335 \times 0.62^2 = 642, \text{ say } 640 \text{ kNm})$$

(Note: 640 kNm ≈ 460 ft-kips due to differences in rounding numbers.)

In Case *ii*, the vessel hits one wing wall and bounces off, setting the vessel in rotation (Figure 11(b)). The fenders in the middle and outer ends of the wing wall should be able to withstand a Case *ii* event.

Unless the fenders' reaction force is in line with the vessel's center of gravity (Figure 11(c)), the vessel will rotate. Also, the vessel will usually slide along the wing wall. It is possible, but unlikely, that the vessel will stop without rotating. Therefore, $C_e = 1$. However, designing for $C_e = 1.0$ would result in an extremely conservative design because the simultaneous occurrence of the design speed and the reaction force acting on a line through the center of gravity is an extremely unlikely event. Experimental evidence from this study shows that 0.60 is an upper limit for the berthing coefficient.

The component of the velocity that is normal to the face of the wing wall is considered in fender calculations. Therefore, the vessel's perpendicular velocity $[q(V_{perp})]$ should be considered when a design velocity is selected. The resulting Case *ii* design approach velocity is

$$0.75 \times 2.2 = 1.65, \text{ say } 1.6 \text{ ft/sec}$$

$$(0.23 \times 2.2 = 0.506, \text{ say } 0.51 \text{ m/sec})$$

The Case *ii* berthing energy for a Super Class Vessel (displacement = 3283 lt or 3335 mt) is

$$1/2 \times (3283 \times 2240/32.2) \times 0.6 \times 1.6^2 = 175{,}348 \text{ ft-lb, say } 175 \text{ ft-kips}$$

$$(1/2 \times 3335 \times 0.51^2 \times 0.6 = 258, \text{ say } 260 \text{ kNm})$$

(Note: 260 kNm $\cong$ 175 ft-kips due to differences in rounding.)

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