CHAPTER 65

FULL-SCALE INVESTIGATION OF BERTHING IMPACTS AND EVALUATION OF A HYDRAULIC-PNEUMATIC FLOATING FENDER

by

Theodore T. Lee
Research Hydraulic Engineer
U. S. Naval Civil Engineering Laboratory
Naval Facilities Engineering Command
(formerly Bureau of Yards and Docks)
Port Hueneme, California, U. S. A.

ABSTRACT

Two experimental hydraulic-pneumatic floating fenders (camels) were in-service tested in protected and exposed harbors. Due to their high energy-absorption characteristics, the fenders were effective in reducing damage to piers, pier-fender systems, and berthing or moored ships. Their performance relative to a number of individual ship-impacts is discussed, conclusions drawn, and recommendations made.

Measurements as a function of time of ship velocity, berthing force, position of point of impact, and energy absorption by fenders are presented and discussed for 35 berthings involving 14 ships of from 1,400 to 17,600 tons displacement. Load-deflection and energy-absorption curves of the hydraulic and pneumatic fender bags are presented and discussed, and results compared with those predicted by theory. Berthing forces and energy-absorption characteristics are analyzed statistically; their relationships with point of impact are compared with those established with a model of a tanker by the Hydraulic Research Station, Wallingford, England. The resistance to ship motion including hydrodynamic effect is analyzed. It is concluded that hydrodynamic effect is an important parameter which requires further investigation.

It is recommended that full-scale tests of berthing impact at exposed harbors be continued and that model tests of berthing impact be initiated, particularly tests of the resistance to ship motion, so that hydrodynamic mass can be properly evaluated.

INTRODUCTION

Commercially, ocean transportation has been, and will likely continue to be, the most economical means for carrying the majority of the products that comprise world trade. Militarily, fleets play a significant role in scientific, economic, and social exploration as well as in national defense. The ship is anything but outmoded. However, the current trend toward increasing size and speed of seagoing vessels confronts engineers with a critical problem: that of designing more economical and effective berthing structures than ever before.

This problem assumes prime importance when berthing and mooring of ships take place in exposed coastal areas. Despite the obvious and pressing need for more effective and more economical berthing structures, little progress has been made toward new concepts. This is particularly true in such vital research areas as: (1) berthing impact investigations and (2) improvement of existing inefficient fender systems.

The most recent contribution to the subject field is the NATO Study Institute on Analytical Treatment of Problems of Berthing and Mooring Ships held in Lisbon 19 - 30 July 1965 (Dock and Harbor Authority, 1966). Both model and prototype investigations on berthing and mooring forces were comprehensively reviewed.

GENERAL DESCRIPTION

This paper describes in-service tests of a floating fender system (camel system) conceived by Bowman and Cave of the Naval Facilities Engineering Command (NAVFAC) as a remedy to the two deficiencies of berthing impact investigation and fender system improvement noted above.

Technical development and evaluation was made in the light of the following criteria (Lee, 1965a): (1) flexibility so that the floating fender will conform to the shape of the vessel; (2) strength to withstand compression between ships and piers; (3) sufficient length to distribute pressure along a ship's hull; (4) compatibility with typical piers having fender piles or hanging posts; (5) provision for an optimum distance between ship and pier; (6) minimum maintenance requirements; and (7) provision for shock absorbers such as inflatable units of rubber, fabric, or plastic which can also prevent ship-coating damage from rubbing action.

The objective of this new-type fender was to reduce damage to ship-hulls, pier-fender systems, and to piers themselves at a combined initial and maintenance cost lower than that of existing floating log-fenders. The system was intended to serve berthing and moored ships up to 20,000 long-tons displacement. However, it can be modified to accommodate ships of larger size.

Two experimental units of the hydraulic-pneumatic floating fender have been tested in both protected and exposed harbors; i.e., Port Hueneme Harbor and San Diego Bay in California respectively. Experimental as well as operational tests were conducted.

HYDRAULIC-PNEUMATIC FLOATING FENDER

The hydraulic-pneumatic floating fender (Figure 1) consists of a floating bulkhead, two air-filled and two water-filled bags floating in front of the bulkhead, chains with weights to maintain position, and a keel in the form of an 18-inch-OD (outside diameter) pipe filled with concrete ballast. The bulkhead is 50 feet long, 1 foot 8 inches wide, and 11 feet 6 inches high. It has a steel framework, a creosoted-timber covering, and a core of polyurethane foam for buoyancy. The four rubber bags are standard off-the-shelf items, each 40 inches OD by 60 inches long. They tend to absorb most of the impact energy of berthing and moored ships. The air-filled bag absorbs energy by air compression and the water-filled bag by water displacement. Water is forced out of the bag through a screen connected by a hose to axial openings in each end of the bag. After compression the bag is restored to its original shape by the spring action of water "hoses" inside the bag. Absorption depends on the magnitude and velocity of the mass of the incident ship.

The total energy-absorption capacity of the fenders is from 490 inch-tons minimum to 2,300 inch-tons maximum. Measurements are based on (1) initial pneumatic-bag pressure of 12 psi per bag; (2) maximum working pressure of 50 psi per bag; (3) total allowable load of 42.5 tons over 15 square feet of the ship's hull; (4) only one pneumatic bag in action at minimum capacity and all four bags in action at maximum capacity; (5) deflection of 70% and/or 28 inches. At 70% bag deflection, the minimum and maximum energy-absorption capacity would be 330 and 1,940 inch-tons respectively.

The fender weighs approximately 12 long tons in air.

Load-deflection and energy-absorption characteristics of individual pneumatic and hydraulic rubber bags are shown in Figure 2. A comparison of the energy-absorption capacities of pneumatic and hydraulic bags is shown in Figure 3.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

EXPERIMENTAL INSTRUMENTATION (Lee, 1963)

Ship-velocity Meter. The approach velocity of the berthing ships was measured by means of two mutually perpendicular probes each employing a tachometer as sensor. As shown in Figure 4, one probe, a steel channel, is pushed back laterally by the berthing ship; thereby the velocity component normal to the wharf was measured continuously. The other probe is a bicycle wheel fastened to the steel channel. It is free to rotate, and thereby the velocity component parallel to the wharf was measured.

Pressure Transducer. The energy absorbed and berthing force induced by each of the pneumatic or hydraulic rubber bags was determined from measurement of the pressure exerted on it. Eight pressure pick-ups (one pick-up per bag) were installed.

Ship-acceleration Sensors. Ship acceleration perpendicular to the wharf face was measured by one accelerometer fastened to the ship's side abreast the center of gravity of the ship. In addition, one accelerometer was fastened to the ship-velocity meter as back-up. Unfortunately, the measurements were insignificant.

Water-level Variation. This was measured by a pick-up of the harbor-bottom-pressure type.

Wind-velocity Pick-ups. Two anemometers, one a fixed type and the other portable, were situated near the test-site at Port Hueneme, measuring wind velocity at the time of berthing.

TEST PROCEDURE

Measurement as a function of time of ship velocity, berthing force, position of point of impact, and energy absorption by the fenders was the essential criteria applied (Lee, 1966).

Kinetic energy, E, of a berthing ship in inch-tons (2,000 pounds), upon contact with fenders is predicted by:

$$E = \frac{C}{2} MV^2 = \frac{CWV^2}{2g}$$

$$E = 0.209CWV^2$$

where W = ship displacement at the time of berthing, long tons

V = beam-on ship speed at the gravity center of the ship feet per second

C = an impact correction factor = $c_e\ c_g\ c_d\ c_c\ c_m$ (Risselada and van Lookeren Campagne, 1964)

where $c_e = \frac{k^2}{a^2 + k^2}$ = eccentricity coefficient (Saurin, 1963) depending upon the point of impact relative to the ship's center of gravity, a, and radius of gyration, k, of the ship about its vertical axis

c_g = ship geometric coefficient depending upon the curvature of the ship at the point of impact

c_d = ship deformation coefficient depending upon the relative stiffness between ship hull and fender

c_c = berth configuration coefficient depending upon type of berth

c_m = virtual mass coefficient

Methods for theoretical determination of ship's kinetic energy distributed to the floating fenders, berthing velocities at the center of gravity of the ship, and for selecting the impact correction factor are given in Appendix A. Figure 5 shows a typical recording of such measurements as bag pressures, ship velocity, etc.

TEST CONDITIONS AND EXPERIMENTAL TESTS

TEST CONDITIONS

Tests covering 35 berthings were conducted for 14 months in the Harbor of Port Hueneme (Figure 6). Ships varied in size from 1,400 to 17,600 tons displacement. All ships berthed broadside with the assistance of two 1030-horsepower tugs. Water depth at the time of berthing varied from 28 to 34 feet. Clearance between ship keel and mudline was 3 feet minimum and 19 feet maximum. Ship and dock clearance prior to a broadside berthing was estimated as 50 to 100 feet. Wind velocities ranged from 2 to 40 knots, mostly from NW, that is 45° off port beam of the wharf face. Waves and currents were insignificant.

POSITION OF BERTHING IMPACT

The point of ship/fender contact, calculated from measurements of initial and final ship positions, varied from 0.14 to 0.92 of the ship length, L, as measured from the stern. There were many impacts at 0.50 (the center of the berthing ship).

For multiple impacts the point of ship/fender contact as well as longitudinal motion of the ship was calculated from measurements of the tangential berthing speeds.

In the calculations the radius of gyration, k, was assumed to be 0.24 L (Figure A-1). This seems reasonable since k, for naval and merchant ships, varies from 0.20 L to 0.29 L (Lee, 1965a). Saurin (1963) and Vasco Costa (1964) suggest 0.2 L.

The eccentric coefficient, c_e, was computed from Equation 1a, using the values of a and k as given earlier. This was used in Equation 1, along with the other coefficient, to predict the kinetic energy of the berthing ship upon contact with the fender.

BERTHING FORCE CHARACTERISTICS

The maximum impact force varied from about 3 tons for a 1,000-ton ship to 40 tons for a 15,000-ton ship. These are loads of 0.06 and 0.8 tons per linear foot of berth, which is low compared to the design load of 1.2 tons per linear foot. An exception was an 87-ton impact force in the accidental berthing of the 17,000-ton USNS GENERAL BRECKINRIDGE (Figure 7).

It is estimated from Figure 7 that for ships of 20,000 tons displacement the maximum force should not exceed 60 tons for a normal berthing or 100 tons for an accidental berthing; that is, 1.2 or 2.0 tons per linear foot of berth.

The frequency of berthing force transmitted to dock and to ship hull was analyzed, using measurements of 35 berthing impacts (Figures 8, 9, and 10). Normally, the berthing force transmitted to the dock did not exceed 1,500 pounds per linear foot of berth where 2,500 is conventional for design. The exception noted above resulted in a load of 1.7 tons per linear foot. No damage was observed.

The existing U. S. Navy design criteria (NAVFAC, 1961, 1962) requires a minimum value of 2,000 pounds per linear foot of berth for a moored ship, notwithstanding the force due to impact from berthing vessels. In addition, it calls for pier superstructures to be designed for the effects of dynamic loadings with a load factor of 1.33. Applying this load factor to the minimum lateral load requirement, then the berthing structure should be able to sustain lateral loads of at least 2,700 pounds per linear foot in the majority of berths. With comparison to the maximum value of 3,400 pounds per linear foot without damage to the dock, it seems that the safe limit of lateral loading of 3,000 to 3,500 may be accepted. Furthermore, Navy installations are usually concerned with lighter dock construction than found in commercial ports. The reason for the heavier commercial dock is obviously the greater frequency of berthing of extremely large ships (Thorn, and et al, 1966).

LOADING TO SHIP HULL

The berthing force transmitted to ship hull was 0.2 to 4.0 tons per square foot, or 3 to 55 pounds per square inch, averaging approximately 15 pounds per square inch. No damage to hulls was noted.

No consensus of agreement was noted in literature as to the loads required to cause plastic deformations of a ship's hull. Basing his conclusion on existing literature, Thorn et al (1966) determines that for vessels from 15,000 to 20,000 tons, hull pressures of 35 pounds per square inch are generally acceptable, with overloads of up to 50 psi as an upper limit.

BERTHING VELOCITY CHARACTERISTICS

Berthing speeds both normal and parallel to the dock face were measured either at the point of impact or at the center of the ship. Those normal to the dock varied from 0.1 to 0.4 foot per second under normal conditions; the maximum was 1.0 foot per second. It is apparent that the magnitude and direction of the motion of a berthing ship varies significantly with time. In many model studies in the laboratory the magnitude and direction of motion are kept significantly constant (Wallingford, Great Britain, 1961, 1962, and Saurin, 1963); consequently, these measurements cannot readily be compared with those obtained in actual berthings in harbors.

A general relationship between berthing force and beam-on berthing speed for USNS General William Mitchell was formulated (Figure 11). It indicates that during the initial stage of impact, i.e., when the ship accelerated, the berthing force was low compared to that at a later stage when the ship decelerated at a similar rate. This is probably due to the fact that the pneumatic rubber bag is softer at the initial stage, whereas at the later stage, the bag is compressed more fully and offers more resistance. Both acceleration and deceleration are involved in the process of berthing.

The tangential speed of the berthing ship was low, and its effect was trivial.

Again, there is no consensus of opinion as to the berthing velocity of vessels in the 2,000 - 20,000 tons displacement class. Thorn et al (1966) developed a curve showing general relationship between berthing velocity and ship displacement. Normal velocities measured during the tests at Port Hueneme are low as compared to the curve in Figure 12. It is believed that this can be attributed to the human factor. Knowing that the vessels were not only under observation but were instrumented would tend to inhibit the individual pilots and ship captains, resulting in a more than usually cautious berthing.

EFFECTS OF HYDRODYNAMIC MASS AND WATER FRICTION

Beam-on speed has a significant effect on the resistance to motion in this direction (Figure 13). At lower beam-on speeds (0.1 foot per second or less), resistance effects increase considerably. No attempt was made to separate hydrodynamic mass from these effects; the value recommended by Vasco Costa is shown on the figure for comparison only.

EXPERIMENTAL RESULTS

The maximum total kinetic energy absorbed by the floating fender seems to be about 16 inch-tons per 1,000 tons of displacement; i.e., it varied from 6 to 320 inch-tons for ships of about 1,200 to 20,000 tons displacement (with the exception previously noted, which measured 843 inch-tons, or 50 inch-tons per 1,000 tons). See Figure 14. This linearization is an arbitrary method to enclose a scattering of measured points. Its validity is questionable since such nonlinearly related factors as the pilot's ability to maneuver, the navigation conditions, and marine environment have a significant effect on berthing speed and hence on kinetic energy. Nevertheless, for broadside berthing, the estimate of a maximum-required fender energy absorption as 16 inch-tons per 1,000 tons of displacement for normal berthing, and 50 inch-tons per 1,000 tons of displacement at accidental levels is of the same order determined by others (Lee, 1965a, 1965b and Risselada and van Lookeren Campagne, 1964). The probability of occurrence is, respectively, 14 and 1 chances in 100 (from Figure 15 which defines the energy-absorption capacity required in Hueneme Harbor, a well-protected harbor with moderate winds and trivial waves and currents). This writer's recomendation (Lee, 1965b) coincides with 5% probability (Figure 15b). Economics may dictate changes in these values for particular designs. The curves are fitted by eye through points based on measurements; they did not warrant use of such elegant approaches as extreme value theory (Saurin, 1963) since the data collected are rather limited.

Maximum berthing force occurred during a high wharf-on wind with gusts to 40 knots, but there were some fairly high forces during moderate wharf-off winds. Generally, berthing impacts were relatively light during calm weather.

The measured berthing forces and related energy absorption were compared with those measured on models by Wallingford Research Station (1961 and 1962). See Figure 16. Agreement is fair, but perhaps comparison is not pertinent because of the many differences. The Hueneme test fender is much less stiff than those used at Wallingford; thus, the energy-absorption capacity of the Hueneme fender is also less. Ship size and test conditions (such as berth configurations, relative stiffness of ship hull and fender, and natural environment) were not identical. The model tests at Wallingford are concerned with forces caused by rotation of the ship about the stern rather than those caused by beam-on translation as in the Hueneme tests. Theoretically, in the latter, for an equal velocity at the same point of contact, the amount of energy to be absorbed by a fender is larger when the impact is caused by a ship translation than when it results from a ship rotation (Vasco Costa, 1964). The amount of absorbed energy varies with the position in which the berthing ship contacts the fender; resistance to motion at various berthing speeds is significant.

Many investigators assume that the center of gravity of a ship coincides with the center of a ship's length (Wallingford, 1961, 1962; Saurin, 1963; Vasco Costa, 1964; Lee, 1965a). Errors proportional to the difference will result if the center of mass is remote from the center of the ship, as in naval destroyers. Generally the center of mass tends to vary with draft quite independently of any architectural aspects.

Resistance to motion at a ship beam-on speed of 0.10 foot per second varies as much as 600 to 800% from that suggested by Vasco Costa (1964) as due to the hydrodynamic mass effect alone (Figure 13); at 0.26 foot per second the difference is negligible. Full-scale measurements conducted at Finnart, Scotland and Bombay, India indicate a similar effect (Grant, 1965).

Furthermore, the computed or predicted values of the kinetic energies absorbed by the floating fenders compare fairly only with those actually measured (Figures 17, 18). The error was $\pm 25\%$ generally. As shown in Figures 19 and 20, the measured energy is considerably higher than predicted when a ship's beam-on speed is lower than 0.1 foot per second, but measured energy is lower at ship speeds greater than 0.2 foot per second. Fortunately, the energy-absorption characteristics at extreme low speeds have no significant value in the determination of a fender capacity; therefore, for design purposes, the predicted energy normally induced by a ship at a relatively high speed is adequate.

OPERATIONAL TESTS

The hydraulic-pneumatic floating fender performed in an outstanding manner and demonstrated its capacity to reduce damage significantly during an accident in the berthing of a ship of 17,300 tons displacement. The superiority of the hydraulic bag was demonstrated as shown in Figure 21. The load transmitted by the hydraulic bag was considerably lower than by the pneumatic bag.

Results from three years' continuous in-service test of the subject floating fender at both protected and exposed harbors indicate that the fender protected piers, dock fender systems, and ships in a very effective manner. Demurrage cost was reduced. First cost is considered to be high for berths with light traffic and quiet environment. However, cost-effectiveness would be favorable at locations where mechanical damage to dock fenders or marine borer infestation of conventional timber piles is severe. The addition of a floating fender would defer major replacement of existing inefficient fender systems at many installations.

Cargo handling was slightly complicated because the floating fenders tended to hold ships farther off than desired. The standoff distance necessitated by the fender is considered a major drawback by some users, as is the rebound of the ship induced by the pneumatic rubber bags. Generally, the tests showed that the hydraulic bags absorb energy better from sudden impacts and the pneumatic bags absorb better from gradual impacts. These major deficiences may be improved by modification of the separate hydraulic and pneumatic aspects of the existing fender by means of an original concept involving an air-filled bag within a water-filled bag (Figure 22).

COST-EFFECTIVENESS EVALUATION

In formulating criteria to evaluate cost-effectiveness of a fender system in a particular environment, cost and effectiveness must be considered on a long-term basis. Therefore, the initial values are not necessarily the controlling factor. The most economical fender system must offer the lowest annual cost (combined initial and maintenance costs over an extended period). The most effective system must meet not only service requirements initially but also maintain its effectiveness during a substantial service life.

A fender system's effectiveness is measured by (a) system serviceability, (b) system reliability, and (c) system availability. Annual cost is determined by taking into consideration initial cost, maintenance, replacement, intangibles, obsolescence, interest and other related costs as well as the service life or longevity of a fender system (Lee, 1965a). In this study, cost-effectiveness is measured by the annual cost per linear foot of berth, per inch-ton of energy-absorption capacity occurring in a particular fender system.

Test and evaluation of the experimental floating fenders and analyses of cost-effectiveness of existing Navy pier fender systems (Lee, 1966a) showed that the floating fenders are not economical and technically feasible for berths with light traffic and quiet marine environment. However, the experimental fenders would be economical and technically feasible for a number of Navy berths at Pearl Harbor and Norfolk Naval Bases where mechanical damage by berthing ships and biological deterioration of fender piles are high. A comparison of cost-effectiveness between the hydraulic-pneumatic fenders and existing timber-fender systems or other improved systems is given in Table 1. It should be noted in connection with Table 1 that some of the existing fender piles are severely deteriorated biologically, to the point that only 30 to 40% of their original effectiveness remains. The portable floating fenders should be very effective and economical for increasing system effectiveness while replacement work is in progress. They should also be useful in upgrading the existing fender system, in case of an increase in the use of the berth or in the size of ships, without a complete alteration of the existing system.

Efforts have been made to evolve new concepts for the purpose of improving cost-effectiveness of floating fenders generally (Thorn et al, 1966). Evaluation of a promising concept is planned.

CONCLUSIONS

1. The energy-absorption capacity of the hydraulic-pneumatic floating fenders is adequate for both protected and moderately exposed harbors. The experimental fenders have served their intended purpose of protecting piers, ships and pier-fender systems. Protection against wear to the bulkhead of the floating fender and to fixed fender piles is necessary, particularly at locations exposed to water waves.

2. The test fenders are suitable for moored ships as well as for berthing ships. This is of vital importance at locations where berthing and behavior of the moored ship are of equal importance in the choice of type of fender. In this case, Vasco Costa (1964a) suggested that the best solution is to adopt fenders that can act as a stiff fender during berthing and as a soft one when the ship is moored. The test fenders meet such requirements.

3. Despite the high combined initial and maintenance cost of the test fenders, it is believed that they would be economical and technically feasible at berth locations where mechanical damage by ships and biological deterioration by marine borer infestation to fixed fender systems constitute a serious problem. The portable floating fenders should be very useful in increasing or in upgrading effectiveness of an existing system. No significant modification of the existing system would be required.

4. A fender system for a well-protected harbor should be designed with a minimum absorption capacity of 16-inch-tons per 1,000 tons of ship displacement for normal berthing, and with a maximum capacity of 50 inch-tons per 1,000 tons displacement. This also seems a sensible maximum for coping with accidental berthings.

5. Resistance to motion in berthing is a very important parameter which needs to be investigated further. It includes the effect of hydrodynamic mass which is important in the analytical treatment of berthing problems.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Full-scale investigation of berthing impact in exposed harbors should be considered in order to determine the energy requirements for new fender designs for such harbors.

2. Model tests of berthing impact should be conducted, particularly tests of resistance to motion, so that hydrodynamic mass can be properly evaluated. A recent study by Giraudet (1966) of Port of Le Havre contains pertinent information.

ACKNOWLEDGMENTS

Permission by the U. S. Naval Civil Engineering Laboratory of Naval Facilities Engineering Command to publish this paper is acknowledged.

Appendix A

THEORETICAL DETERMINATION OF SHIP'S KINETIC ENERGY DISTRIBUTED TO THE FLOATING FENDER IN OPERATION

General Formula

The kinetic energy of the ship when in contact with the camel is expressed as (Risselada and van Lookeren Campagne, 1964):

$$E = C \frac{WV^2}{2g} = C \frac{MV^2}{2}$$

or

$$E = 0.209CWV^2$$

$$C = c_e \, c_g \, c_d \, c_c \, c_m$$

where E = kinetic energy to be absorbed by the camel in inch-tons

W = ship displacement at time of berthing in long tons

= Mg where M is mass of ship in slugs/long ton

V = ship velocity component normal to wharf face, at the gravity center of the ship, in feet per second

g = acceleration due to gravity (32.2 fps^2)

C = impact correction factor (details under Operational Tests)

c_e = eccentricity coefficient

c_g = ship geometric coefficient

c_d = ship deformation coefficient

c_c = berth configuration coefficient

c_m = virtual mass coefficient = $E/c_e \, c_d \, c_g \, c_c \, (MV^2/2) = M'/M$, where M' is the virtual mass of the ship ($M' = M + M''$, where M'' is the added mass of the ship due to acceleration) and $c_m - 1 = M''/M = c_h$ = hydrodynamic mass coefficient

Eccentricity coefficient, c_e, is expressed as

$$c_e = \frac{k^2}{a^2 + k^2}$$

where a = distance between the point of impact and the center of gravity of the ship

k = radius of gyration of the ship, which varies from 0.20 to 0.29 of ship's length, l

The value of c_e varies from 0.14 to 1.0 as shown in Figure A-1.

Geometric coefficient, c_g, depends upon the geometric configuration of the ship at the point of impact. It varies from 0.85 for an increasing convex curvature to 1.25 for concave curvature. Risselada and van Lookeren Campagne (1964) recommended 0.95 for the impact point at or beyond the quarter points of the ship, and 1.0 for broadside berthing in which contact is made along the straight side.

Deformation coefficient factor, c_d, corrects the energy reduction effects due to local deformation of the ship's hull and deflection of the whole ship along its longitudinal axis. The energy absorbed by the ship depends on the relative stiffness of the ship and the obstruction. The deformation coefficient varies from 0.5 for a nonresilient camel such as a log to nearly 1.0 for a very flexible camel. It is assumed as 0.77 in this report.

Construction coefficient, c_c, covers the effects of berth types. For a solid bulkhead wharf, kinetic energy is absorbed partially by water-cushion effect, especially when the ship is berthed broadside at high speed during a low tide; this effect is negligible with open wharves. Risselada and van Lookeren Campagne (1964) recommend a value of 0.80 for a closed berth, 0.90 for a semiclosed, and 1.0 for an open berth. In this study, the wharf has a solid bulkhead (see Figure 4) but the camel was located outside the wharf fender system, which projected approximately 6 feet beyond the wharf face. It is considered to be a semiclosed berth, and 0.90 was used for c_c.

Virtual mass coefficient, c_m, considers that the virtual mass of an accelerating ship is greater than its dead-weight mass, because the surrounding water moves with the ship. It should be applied in determining the kinetic energy induced by the berthing ship. Such mass effects have been investigated theoretically, experimentally, or both by Grim (1955), Russel (1959), Wilson (1960), Leendertse (1962), Lee (1963), and Vasco Costa (1964).

The virtual mass coefficient, c_m, varies from 1.20 to 3.5, depending on types of ships, water depth, berths, and berthing conditions, including speed and direction of ship motion.

In this study, a c_m value of 1.33 was first assumed for energy prediction. This was later adjusted to measured energy as a result of comparing absorbed energy with computed energy and of checking with the prediction obtained using the following formula suggested by Vasco Costa (1964).

$$c_m = 1 + 2\frac{D}{B}$$

where D = draft of ship

B = beam of ship

The effect of water depth and ship speed on the virtual (effective) mass was not considered.

Ship Velocity Normal to Wharf Face

The normal speed of the ship at the gravity center was determined from measurements as a function of time of bag deflection and ship speed using bag-pressure pickups and a ship velocity meter. Since berthings were always made on the straight side of the ship, a linear relationship between berthing speed and bag deflection was assumed. By knowing the relative positions of the center of the ship's length, the ship velocity meter, and the camel bags, the ship speed at the gravity center is determined proportionally. Note that the gravity center is assumed to coincide with the center of the ship's length.

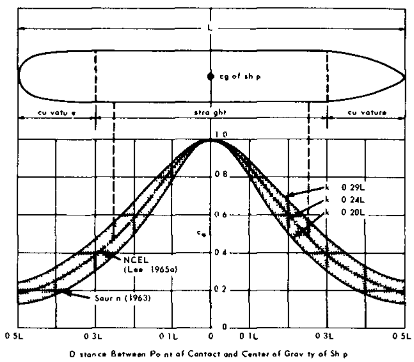


Figure A-1 Eccentricity coefficients

REFERENCES

1. Baker, A. L. L. (1953). Paper S-II, Q-2 18th International Navigation Congress, pp. 111-142, Rome 1953.

2. Belyea, P. S. (1963). The berthing forces of ships. M.S. Thesis, Civil Engineering Department, University of New Brunswick, September 1963.

3. Dock and Harbor Authority (1966). Berthing and Mooring Problems Analysed - Report on the 1965 NATO Conference. Vol XLVI, No. 546, April 1966, pp. 391 - 392.

4. Giraudet, P. (1966). Recherches Experimentals Sur L'energie D'Accostage des Navires (Experimental Research on the Berthing Energy of Ships), Port of Le Havre, France, 1966.

5. Grant, E. J. (1965). Technical Paper no. 301: Ship berthing and mooring. Florida Engineering and Industrial Experiment Station, University of Florida, Gainesville, Apr. 1965.

6. Great Britain (1961). Hydraulic Research Station. Report no. Ex-143: A model investigation to determine impact forces on fenders caused by the berthing of tankers. Wallingford, England, Jan. 1961.

7. ________ (1962). Report no. Ex-181: Further model tests to determine impact forces on fenders during the berthing of tankers. Wallingford, England, Aug. 1962.

8. Green, D. F., U. S. Naval Civil Engineering Laboratory (NCEL). Technical Note N-424: Summary and discussion of the replies to the questionnaire sent to the Naval Shore Establishment on the use of camels. Port Hueneme, Calif., Feb. 1962.

9. Grim, O. (1955). Das Schiff und der Dalben. (The Ship and the Dolphins), Schiff und der Dolben Hafen No. 9, September 1955.

10. Lee, T. T. (1963). Technical Note N-515: Evaluation of a hydro-pneumatic floating fender or camel. NCEL, Port Hueneme, Calif., June 1963.

11. ______(1965a). Technical Report R-334: A hydraulic-pneumatic floating fender. NCEL, Port Hueneme, Calif., Feb. 1965.

12. ______(1965a). Technical Report R-312: A study of effective fender systems for Navy piers and wharves. NCEL, Port Hueneme, Calif., Mar. 1965.

13. ______(1965b). Technical Report R-376: Review of "Report on the effective fender systems in European countries", by Risselada and van Lookeren Campagne, NCEL, Port Hueneme, California, October 1965.

14. ______(1966). Technical Report R-430: Hydraulic-pneumatic floating fender--additional in-service tests, first series, NCEL, Port Hueneme, California, March 1966.

15. _____(1966a). Technical Report R-: Technical and economic analysis of fixed fender systems at 10 U. S. Naval stations, NCEL, Port Hueneme, California, July 1966 (in preparation).

16. _____(1966b). Technical Report R-430: Addendum Hydraulic-pneumatic floating fender-Additional In-Service Tests, first Series, U. S. NCEL, Port Hueneme, Calif., July 1966.

17. Leendertse, J. J., NCEL. Technical Report R-174: Design criteria for camels or floating fenders. Port Hueneme, Calif., Jan. 1962.

18. Leimdorfer, P. (1957). Paper S-II, Q-2, 19th International Navigation Congress, pp. 179 - 195, London, 1957.

19. Naval Facilities Engineering Command (1961). Design Manual: Waterfront Operational Facilities, DM-25, 1 November 1961.

20. Naval Facilities Engineering Command (1962). Design Manual: Harbor and Coastal Facilities, DM-26, 19 Feb. 1966.

21. Risselada, T. J. and J. P. A. van Lookeren Campagne (1964). Report on Contract N-62558-4054 for the U. S. Naval Civil Engineering Laboratory: Report on the effective fender systems in European countries. Rotterdam, The Netherlands, May 1964. (Unpublished manuscript on file at NCEL).

22. Russell, R. C. H. A study of the movement of moored ships subjected to wave action. Institution of Civil Engineers, Proceedings, vol. 12, paper no. 6341, April 1959, pp. 379 - 398.

23. Saurin, B. F. (1963). "Berthing forces of large tankers," in 6th World Petroleum Conference, Proceedings, Frankfurt am Main, Germany, June 1963, Section VII, Paper 10.

24. Thorn, B. J., A Torum, and B. W. Wilson (1966). Report on Contract NBy-62205 for U. S. Naval Civil Engineering Laboratory: An engineering and economic evaluation of floating fender concepts, San Marino, California, U.S.A., June 1966 (in preparation).

25. Vasco Costa, F. (1961). Loads due to ship impact during docking operations. Thesis (in Portuguese) submitted in a competitive test for position of Professor of River and Maritime Affairs, Superior Institute of Technology, Lisbon, Portugal, March 1961.

26. Vasco Costa, F. (1964). "The berthing ship," Dock And Harbour Authority, vol. 45, no. 523, pp. 22-26; no. 524, pp. 49-52; no. 525, pp. 90-94, May, June, July 1964.

27. Vasco Costa, F. (1964a). Stiff fenders versus soft fenders, Proceedings of Fourth International Harbor Conference, Antwerp, Belgium, 22-27 June 1964, pp. 193-194.

28. Wilson, B. W. Discussion on the paper, "A study of the movement of moored ships subjected to wave action," by R. C. H. Russell. Institution of Civil Engineers, Proceedings, vol. 15, April 1960, pp. 444-450.

Table 1. Comparison of cost-effectiveness between test fenders and existing fender systems or other improved systems.

	Initial Cost ($/lin ft berth)	Average Annual Maintenance Cost ($/lin ft berth)	Life (yr)	Annual Cost ($/lin ft berth)		Capitalized Cost ($/lin ft berth)		Energy-Absorption Capacity (in -tn)				Annual Cost-Effectiveness (10-yr period ($/lin ft berth/yr/in -tn)			
								Full Effectiveness		Average Dependable Effectiveness		Full Effectiveness		Average Dependable Effectiveness	
				Life Period	10-yr Period	Life Period	10-yr Period	Normal (Working Stress)	Ultimate (Breaking Stress)	Normal (Working Stress)	Ultimate (Breaking Stress)	Normal (Working Stress)	Ultimate (Breaking Stress)	Normal (Working Stress)	Ultimate (Breaking Stress)
Part I Comparison of Various Fender Systems for Bravo Docks, Berths B-22 through B-25, Pearl Harbor, Hawaii															
Hydraulic-pneumatic floating fenders with existing fender-pile system	150	1 0	10	22 0	22 0	420	420	1,180	2,720	1,120	2,500	0 019	0 008	0 020	0 009
Retractable fender system (Lee, 1965)	150	2 0	15	16 7	22 0	417	413	475	1,350	450	1,280	0 046	0 016	0 049	0 017
Reinforcing existing fender system by reducing pile spacing from 8 to 4 feet	82	8 0	10	12 0	12 0	230	230	360	1,440	250	1,000*	0 033	0 008	0 048	0.012
Existing fender-pile system	41	12 5	3	29 2	17 7	557	338	180	720	165	660*	0 098	0.025	0 107	0 027
NOTE The effectiveness of the fender system has been reduced to 75 percent of energy-absorption capacity owing to biological deterioration The capacity has been further reduced to 92 percent due to mechanical damage Thus overall dependable effectiveness is 69 percent of original capacity															
Part II Comparison of Various Fender Systems for High Impact Areas at Piers 2, 3, 4, 5, and 7, U S Naval Station, Norfolk, Virginia															
Hydraulic-pneumatic floating fenders with existing fender-pile system (treated oak piles)	143	1 0	10 0	19 8	19 8	380	380	1,140	2,560	1,100	2,400	0 02	0 01	0 02	0 01
Retractable fender system (Lee, 1965)	150	2 0	15 0	16 7	22 0	318	420	475	1,350	450	1,280	0 05	0 02	0 05	0 02
Reinforcing existing fender system by reducing pile spacing from 4 5 to 2 3 feet (untreated oak piles)	42	12.0	3 0	28 0	17 5	533	334	280	1,160	200	800	0 06	0 02	0 08	0 02
Reinforcing existing fender system by reducing pile spacing from 4 5 to 2 3 feet (treated oak piles)	66	12 0	4 0	33 0	23 0	630	438	280	1,160	250	1,000	0 08	0 02	0.09	0 02
Existing fender system (untreated oak piles)	25	13 0	1 5	21 0	16 4	400	313	140	560	100	400	0 11	0 03	0 16	0 04

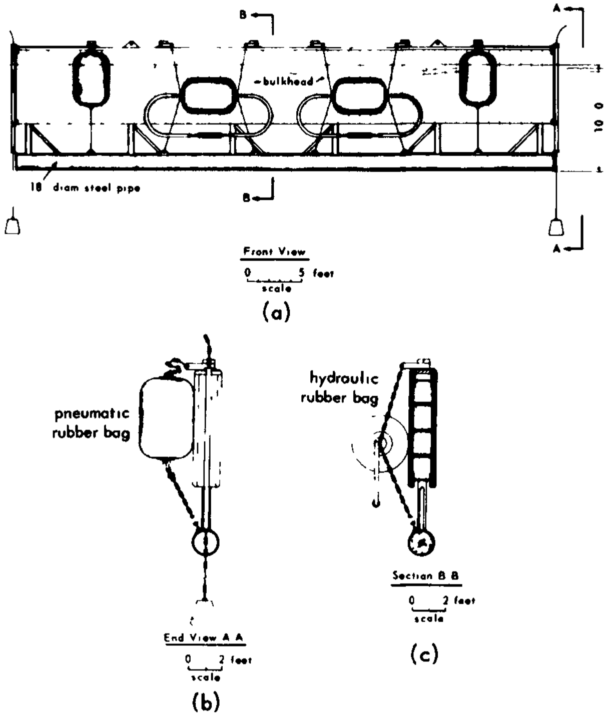


Fig. 1. Hydraulic-pneumatic floating fender (camel).

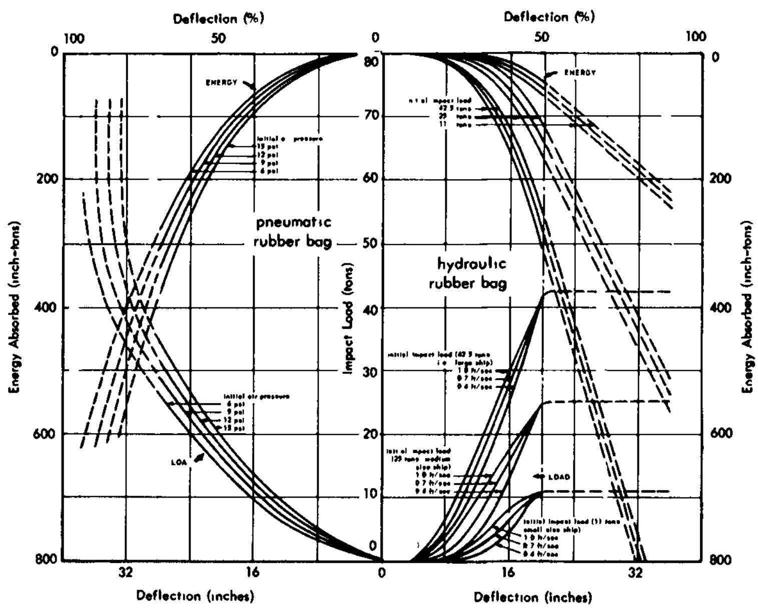
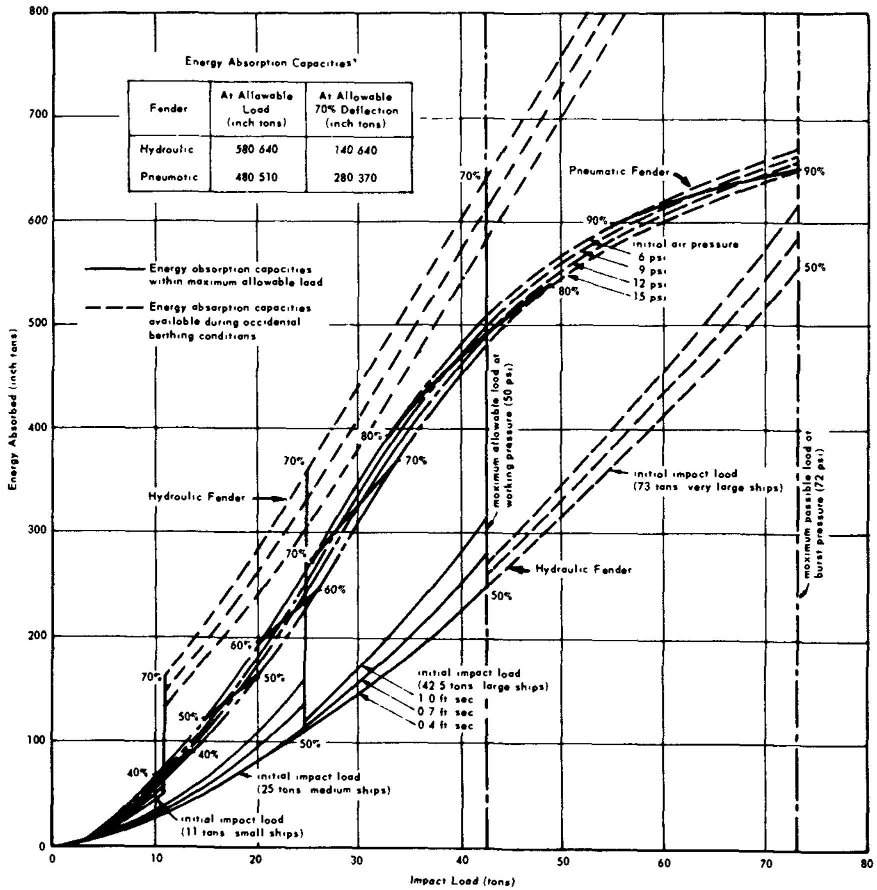


Fig. 2. Load-deflection and energy-absorption characteristics of hydraulic bag and pneumatic bag.



Fender	At Allowable Load (inch tons)	At Allowable 70% Deflection (inch tons)
Hydraulic	580 640	140 640
Pneumatic	480 510	280 370

Resistant loads and energy absorption capacities for the hydraulic fender are dependent upon the impact speed and size of the berthing ships

Resistant loads and energy absorption capacities for the pneumatic fender are dependent upon the initial air pressure and deflection of the fender

Fig. 3. Comparison of load and energy-absorption capacities of hydraulic fender and pneumatic fender.

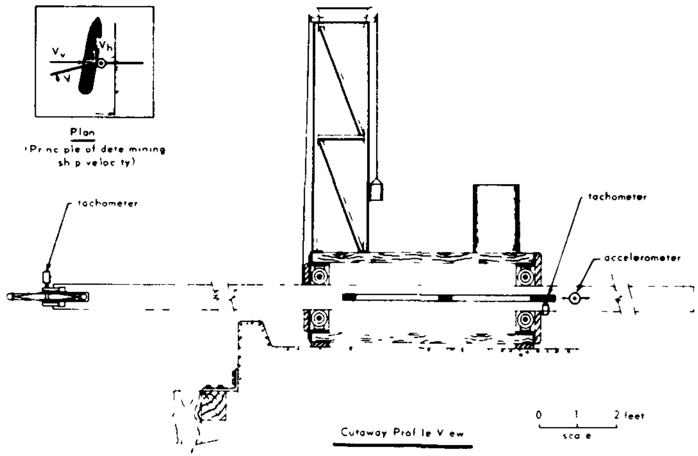


Fig. 4. Ship-velocity measuring apparatus.

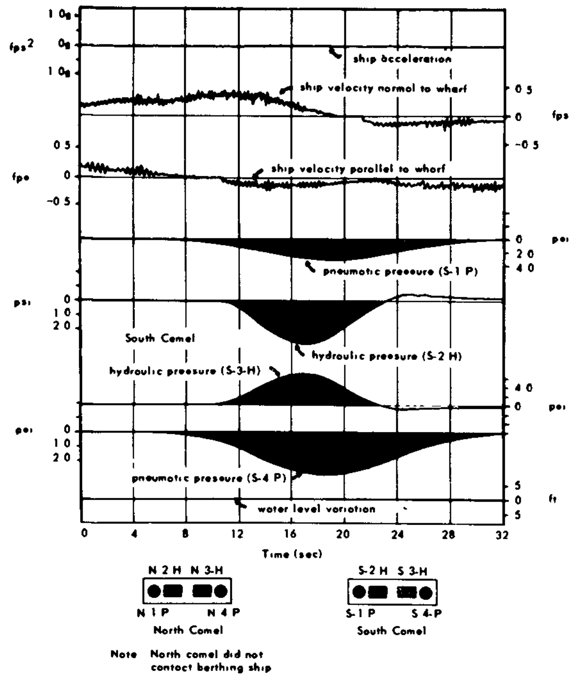


Fig. 5. A typical recording of field measurements.

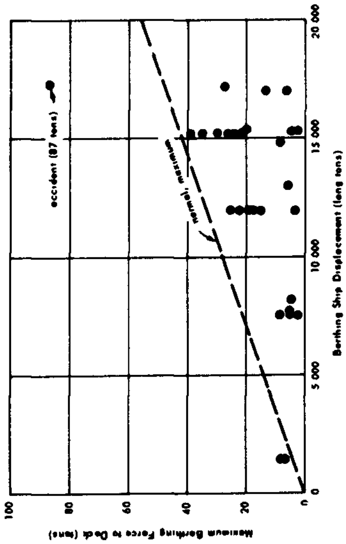


Fig. 7. Maximum berthing force to dock.

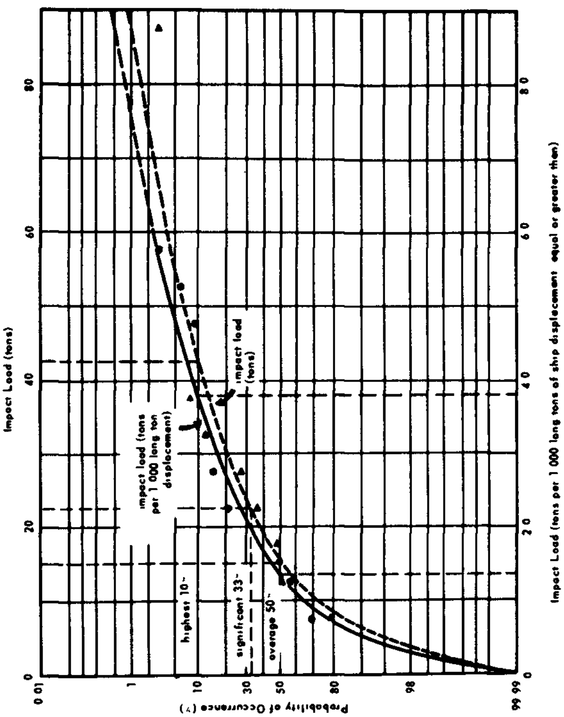


Fig. 8. Frequency analysis of berthing force.

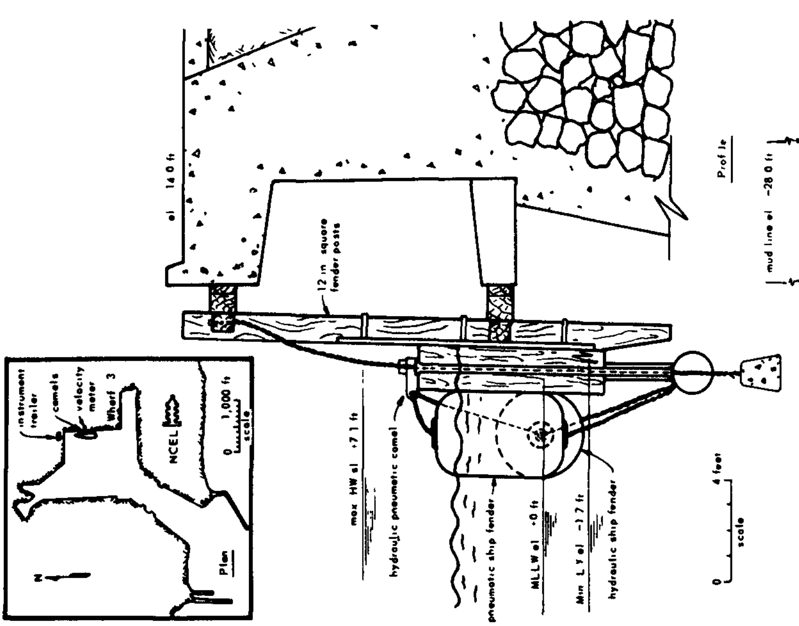


Fig. 6. General plan and profile of the test site, Wharf No. 3, Harbor of Port Hueneme, Calif.

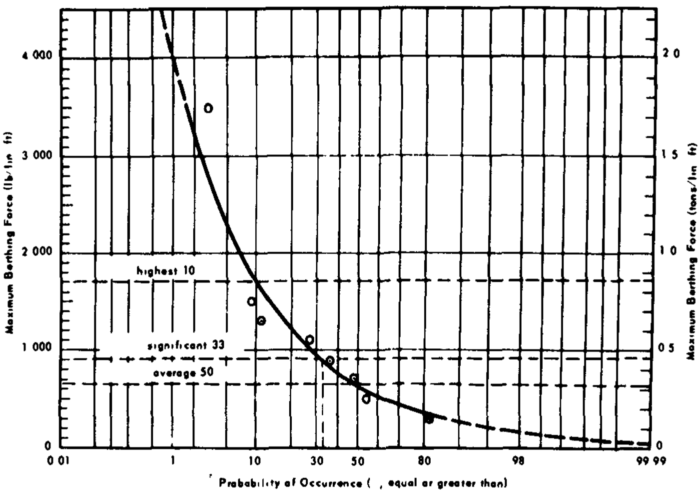


Fig. 9. Frequency analysis of berthing force to dock with hydraulic-pneumatic camels.

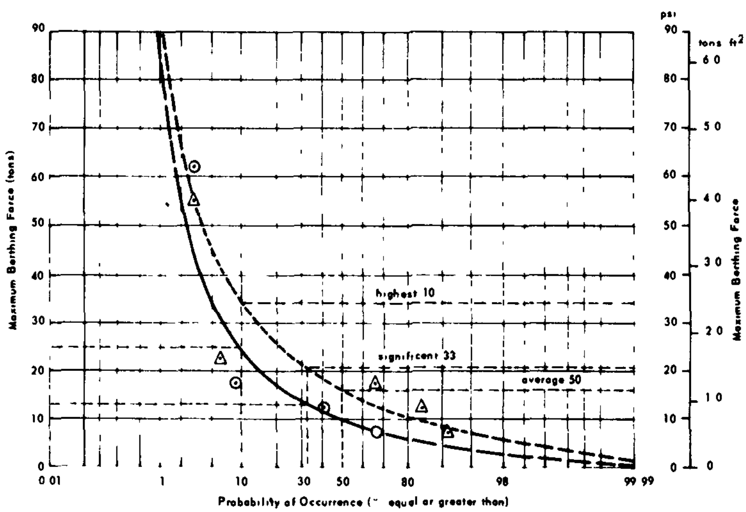


Fig. 10. Frequency analysis of berthing force to ship hull.

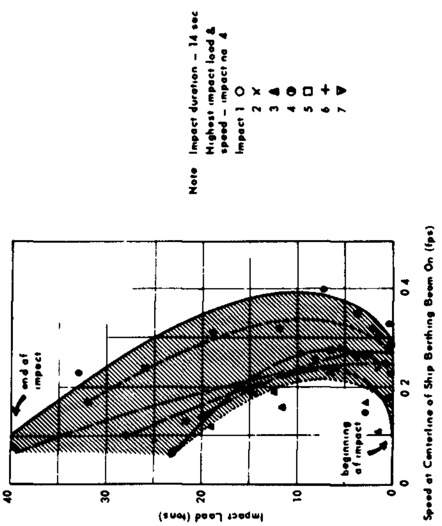


Fig. 11. The relationship of berthing force to ship speed from berthing measurements of the 15,200-ton USNS General William Mitchell.

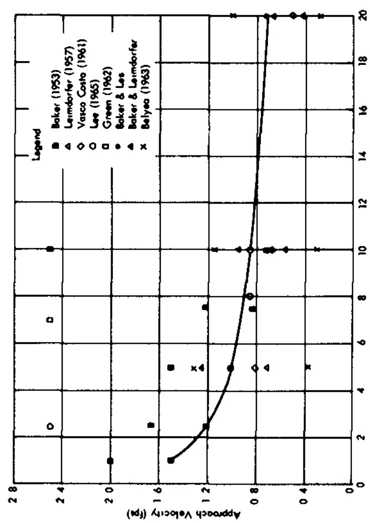


Fig. 12. Velocity vs displacement (Thron et al, 1966).

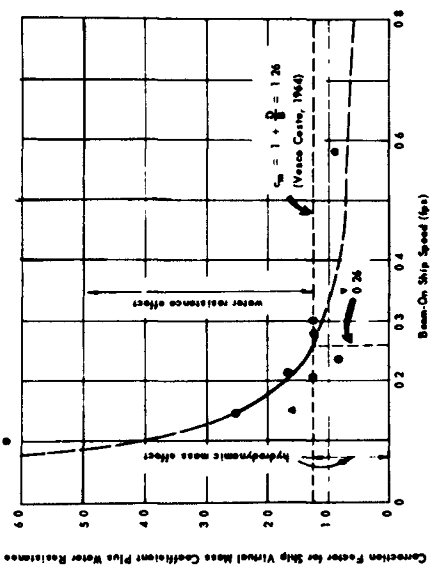


Fig. 13. The hydrodynamic effect of virtual mass plus water resistance versus beam-on ship speed, using berthing measurements of the 15,200-long-ton USNS General William Mitchell on 22 December 1963.

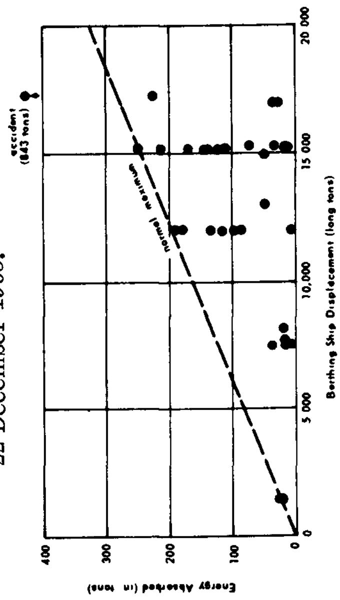


Fig. 14. Maximum energy absorbed by hydraulic-pneumatic fender.

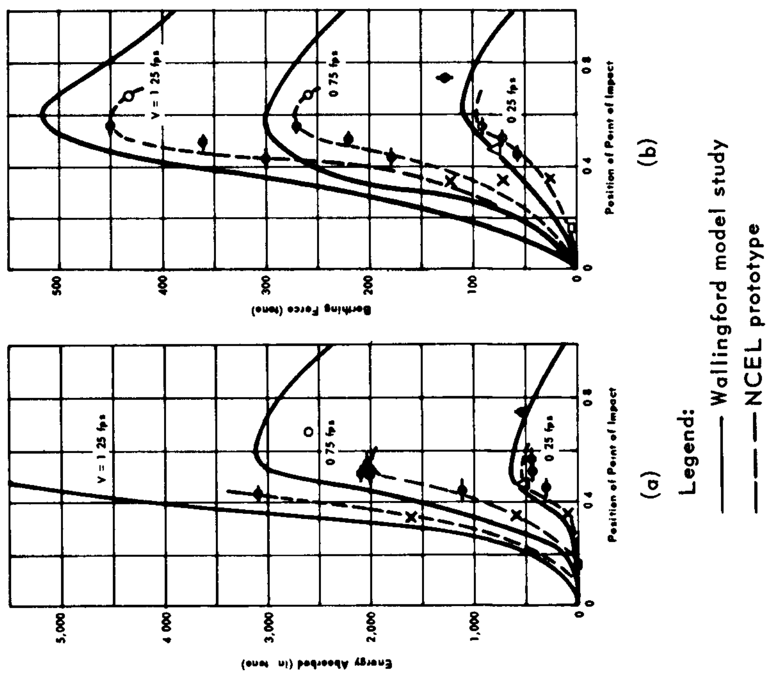


Fig. 16. Prototype vs model fender measurements.

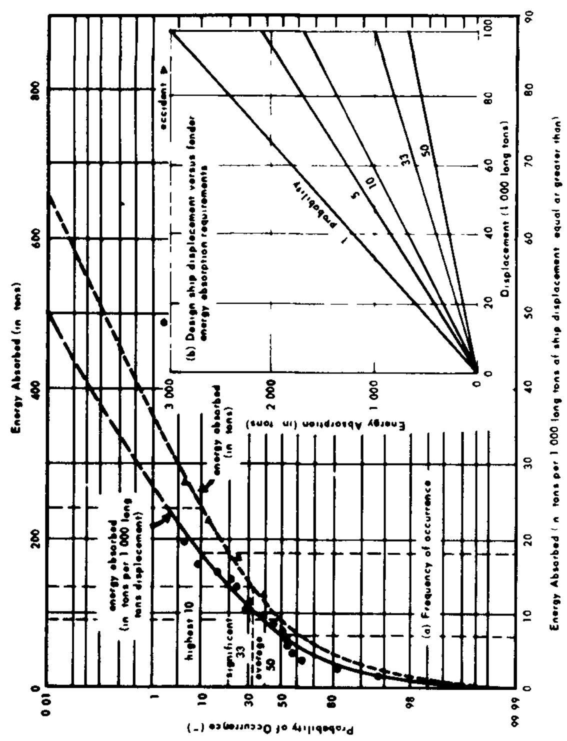
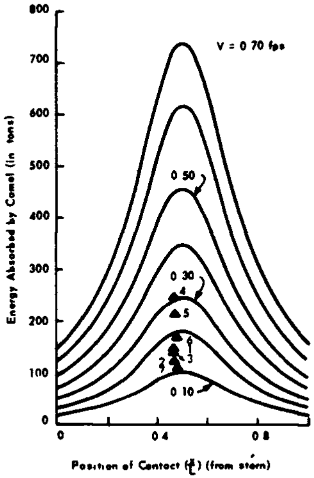


Fig. 15. Frequency analysis of energy absorption.



▲ Measured
—— Computed and adjusted for hydrodynamic and friction effects

Impact No	Average Speed (fps)	Energy Absorbed (in tons)
1	0 15	147
2	0 21	123
3	0 15	140
4	0 30	250
5	0 28	214
6	0 21	170
7	0 24	113

Fig. 17. Predictions versus measurements of energy absorbed by camel in berthing of 15,200-ton USNS General William Mitchell, 22 December 1963.

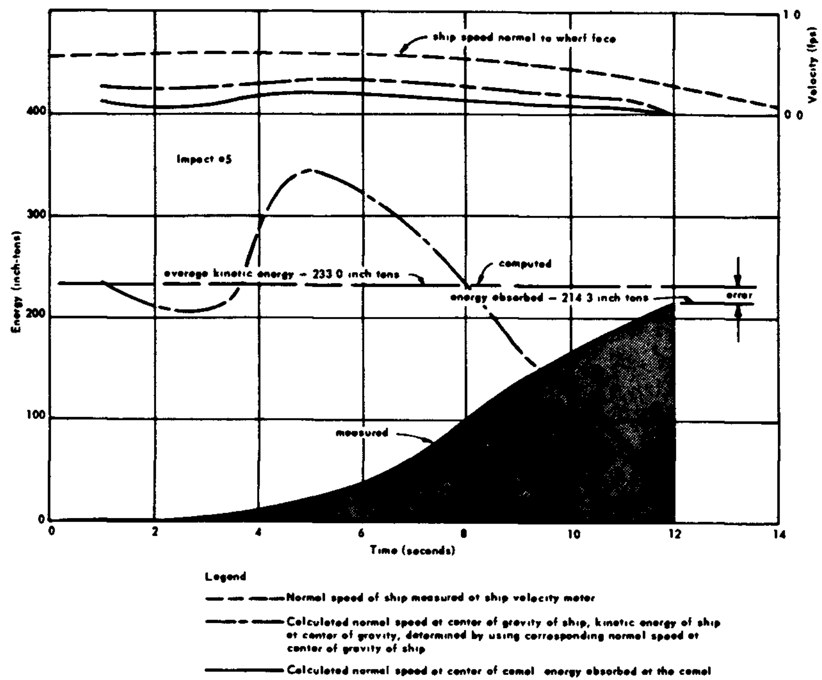


Fig. 18. Precited vs measured energy as a function of time.

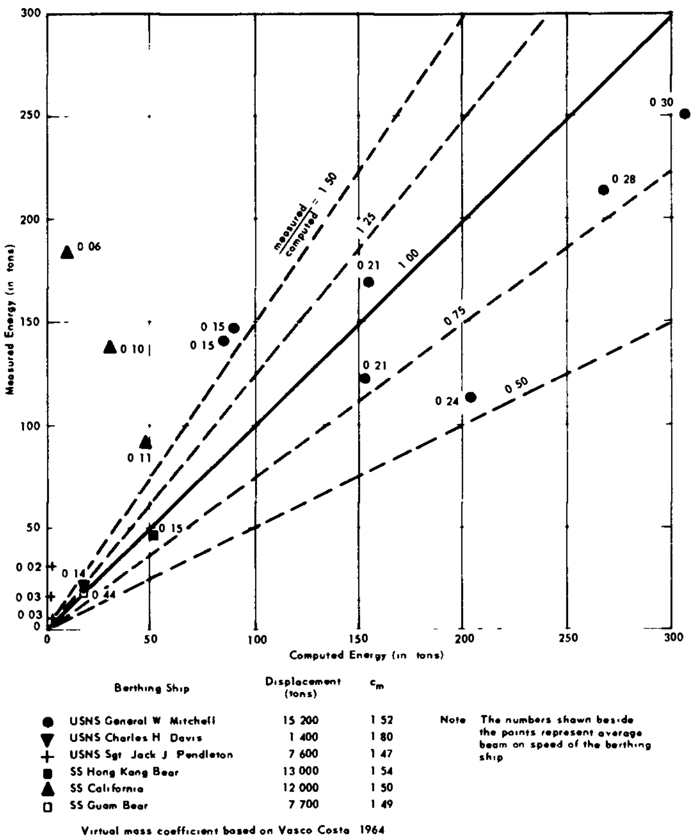


Fig. 19. Relationship of measured and computed (predicted) energy absorption of the hydraulic-pneumatic fender.

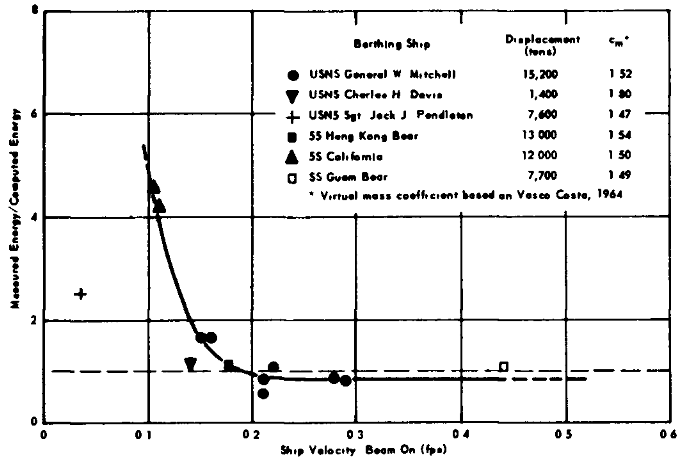


Fig. 20. Ratio of measured and computed energy related to ship velocity during berthing.

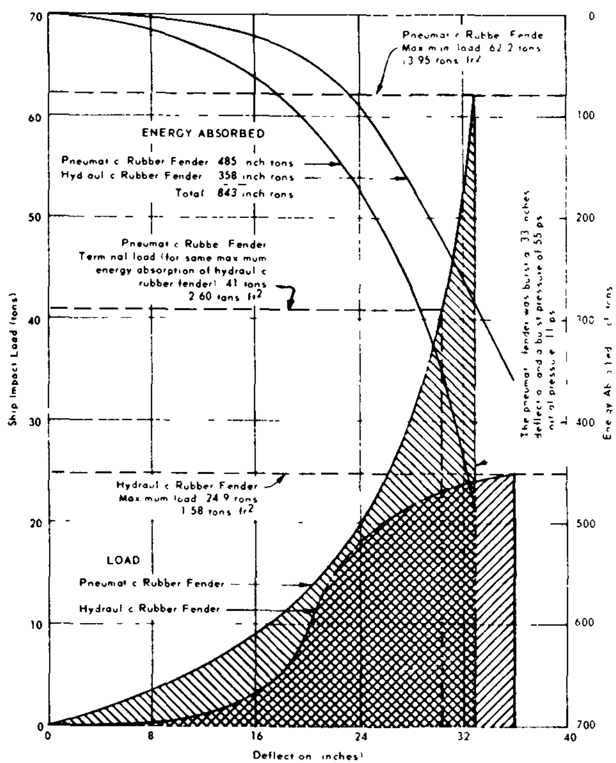


Fig. 21. Load-deflection and energy-absorption characteristics of hydraulic and pneumatic bags, measured during berthing of USNS General Breckinridge on 23 April 1964.

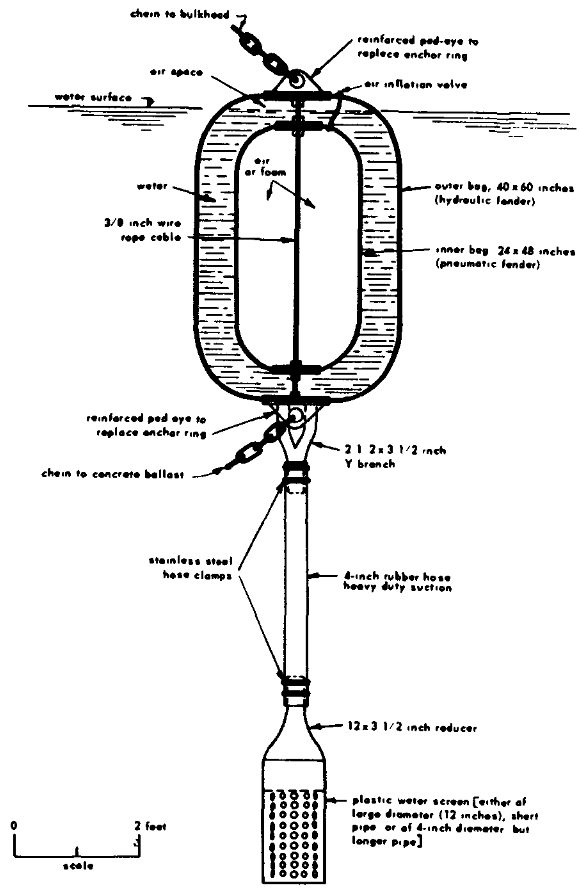


Fig. 22. Proposed hydraulic-pneumatic fender (HYNEU).