NAVAL FACILITIES ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

SPECIAL PROJECT
SP-2317-SHR

LATERAL LOAD CONDITION ASSESSMENT AND FENDER REQUIREMENTS FOR BERTHING AOE-6 CLASS VESSELS AT PIER 2 NAVAL WEAPONS TATION EARLE, COLTS NECK, NJ

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Executive Summary

The Naval Facilities Engineering Service Center (NFESC) was tasked to conduct a structural analysis and condition assessment of Pier 2 and Trestle 2 at the Naval Weapons Station (WPNSTA), Earle. Our structural analysis of Pier 2 concentrated on lateral load assessment with respect to homeporting one and two AOE-6 class ships. The effort included:

- detailed inspection of Trestle 2 and Pier 2 below the deck by Childs Engineering Corporation and reported by NFESC CR-6056-OCN,
- an analysis of lateral loads generated by berthing,
- an analysis of mooring forces generated by wind and current,
- a finite element analysis of the pier response to the berthing and mooring loads as well as dead and vertical live loads,
- design of a foam-filled fender system.

The mooring forces were calculated based on instructions and guidelines of NAVFAC DM 1025.1. The mooring loads were calculated by NFESC's program, FIXMOOR, which is based on data from NAVFAC DM 26.6 and DM 26.4. Mooring analysis considered the ship being oriented with either the bow seaward or the stern seaward and positioned on either side of the pier. We analyzed the mooring loads produced by winds originating from all directions with emphasis on winds that were directed broadside to the ship, 45 degrees off the bow, and from the northeast. Water currents were directed broadside to the ship, or almost parallel to the shore.

The finite element analysis of the lateral loads was performed with ABAQUS. Our finite element modeling accounted for the condition of the piles, bracing, and connections as determined from Childs' inspection. The berthing and mooring loads were applied at the fender stations and points of mooring fixtures on the finite element models. Concurrently with the lateral forces, dead loads plus 500 to 700 psf live load were applied. The higher live load is allowed when the wind velocity is less than 30 mph. Fender and mooring fixture response to lateral loads were compared to the manufacturer's limits of the fenders and current rated limits of the mooring fixtures. Element responses to the lateral loads generated by the finite element analysis were compared to the load limits of the structural members of Pier 2.

Childs reports Trestle 2 to be in good condition. Timber piles are subject to fungal deterioration and some repairs are recommended. Timber bracing is in fair conditions and no repairs are recommended. Two firewalls are missing sections and repairs are recommended. Pilecaps are in good condition and repairs are not recommended. Childs estimates repairs to Trestle 2 will cost $253,000. Childs does not recommend a reduction in service load on Trestle 2. Lateral load limits of Trestle 2 will have no impact on berthing the AOE-6.

Childs reports the general condition of Pier 2 supporting piles is good. The piles have retained most of the original creosote treatment and are still resistant to marine borer attack. Timber conditions above water reflect deterioration due to dry rot. All connections are severely corroded. Except for bracing, timber elements are functioning without distress as originally intended. Childs recommends repair or replacement of piles with 50 percent or more reduction in original cross section. Repairs are not recommended on timber bracing, firewalls or pile caps. Childs estimates the cost of repairs to Pier 2 will be $280,000.

The "best" mooring position for resisting wind loads is on the west side to utilize the upgraded mooring fixtures on that side. The ship should be positioned to avoid using the low rated cleats on the south end of the pier. Mooring fixtures 16, 17, 19, 20, and 21 should be avoided on the west side of the pier. There is a higher probability that these would be overloaded for winds from the east and southeast. When positioning an AOE-6 so that the stern line is on fixture 18, the NFESC recommends doubling the lines on fixture 18 rather than using fixture 16 or 17. When positioning the AOE-6 more shoreward with the stern line on Dolphin 22, the NFESC recommends not using the lower rated mooring fixtures on the south end of Pier 2. Upgrading the mooring fixtures on the west side removes the restrictions of positioning the ship to take advantage of the higher rated bollards.

Low rated mooring fixtures on the east berth restrict resistance to westerly winds. Upgrading the east berth mooring fixtures to the level of those on the west berth would improve resistance to westerly winds and could bring the east berth resistance level up to that of the west berth.

Two AOE-6 ships cannot be moored simultaneously to Pier 2 with winds in excess of 30 mph without risk of structural damage to the pier even with the addition of new fendering. Wind loading on two ships results in excessive forces in the piles.

Fendering limits the capacity of Pier 2 to service a single AOE-6. The fendering installed on Pier 2 is maintenance intensive and does not fit the hull of an AOE-6. Due to the hull curvature and the 54-feet fender spacing, only 3 fenders at most can come in contact with the side of the ship at any given time. This type of fender produces the maximum reaction to the pier because the ship contact point is at the deck elevation. Further, the facing in contact with the ship is prone to heavy damage from padeyes, scuppers, and other appurtenances on the AOE-6 hull. Analysis of AOE-6 berthing yields a design berthing energy of 303 ft-kips and a maximum impact load of 190 kips on the existing Trellex™ Fenders. The manufacturer's recommended maximum absorption energy for each station at 50 percent compression is 306 ft-kips and maximum reaction is 190 kips. The capacity of the fender system in its present state of repair is very low. **Even so, if the system is returned to "new" condition or if the best cells are all relocated to one side, then the reaction from a wind velocity of 30 mph broadside to an AOE-6 is roughly equivalent to the resistance of the fender system.**

The NFESC recommends that the current fendering be replaced by a fendering system consisting of a floating, foam-filled cushion backed by prestressed concrete piles. The foam-filled cushions float on the water and are below the appurtenances that stick out from the AOE-6 hull. The system will be more energy absorbent and the reaction force on the pier structure will be about 30 percent less because the ship/fender contact point on the fender pile at the waterline is separated from the pier reaction point at the deck level. **With improved fendering, the limiting elements are the mooring fixtures and the pile supports. The limiting wind velocity is 60 mph applied broadside (90° and 270°) and from 315° to the AOE-6. The pier response will be within the limits of the mooring fixtures and the lateral capacity of the pier bearing and batter piles.** The cost of the fender system upgrade is $78,000 per fender station. Ten stations on each side of Pier 2 would cost approximately $1,560,000. A preliminary design is presented.

Our finite element analysis showed a great sensitivity to the unbraced length of the piles. The limiting load of each pile is an inverse function of its unbraced length, squared. Even though the braces do not transfer significant forces, they serve to decrease the unbraced length of the piles significantly and increase the limiting load by almost 70 percent. **Pile bracing should be maintained**.

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BACKGROUND

The Naval Facilities Engineering Service Center (NFESC) was tasked to conduct a structural analysis and condition assessment of Pier 2 and Trestle 2 at the Naval Weapons Station (WPNSTA) Earle. Naval Weapons Station Earle provided funding for this project. Our structural analysis of Pier 2 concentrated on lateral load assessment with respect to homeporting one and two AOE-6 class ships. The effort included:

- detailed inspection of Trestle 2 and Pier 2 below the deck by Childs Engineering Corporation and reported by NFESC CR-6056-OCN (Reference 1),
- an analysis of lateral loads generated by berthing at a velocity of 0.52 ft/sec,
- an analysis of mooring forces generated by wind and current,
- a finite element analysis of the pier response to the berthing and mooring loads as well as dead and vertical live loads,
- design of a foam-filled fendering system.

The two AOE-6's scheduled for homeporting at Earle are the USS Supply (Figure 1) in June 1997 and the USS Arctic (Figure 2) in June 1998. The AOE-6 class of fast combat support ships is over 753 feet long and 107 feet across the beam. It has a maximum displacement of over 48,000 long tons with a draft of over 35 feet. The AOE-6 was the first type of deep draft vessels to have gas turbine engines and, at maximum speeds of more than 30 knots, is one of the world's fastest gas turbine driven ships.

Figure 1. USS Supply AOE-6.

Figure 2. USS Arctic AOE-8

Facilities Location

The waterfront of the Naval Weapons Station, Earle is approximately 15 miles south of New York City. The facilities are on the southwest shore of Sandy Hook Bay, roughly due south of the Verrazano Narrows. Sandy Hook Bay is a subdivision of the Raritan Estuary, which also includes the Raritan Bay. Staten Island bounds the estuary on the north, the shoreline of Monmouth County, New Jersey, on the south, and the Atlantic Ocean and Sandy Hook on the east. Pier 2 is part of a 2.9-mile-long pier/trestle complex.

Pier 2 Description

Pier 2 is the most eastern of the pier structures at Earle. The pier has two deepwater berths. The structure was originally built in 1944 and has been inspected three times under the Naval Facilities Engineering Command underwater inspection program (1981, 1987, and 1988)(Reference 2). The condition of Pier 2 in 1987 was considered "exceptionally good." The overall condition in 1988 was "very good" when 97 percent of the piles were undamaged and less than 0.5 percent had damage warranting repair or replacement.

Three concrete mooring dolphins with steel access trestles were constructed in 1986 (Two off the north end of the pier and one off the south end of the pier). The Trellex/Morse® column buckling fendering system was added in 1987. One year later, one fender cell had been broken off and several others had sustained heavy damage from vessel breasting forces. The fender connections were considered inadequate to support their own weight and unable to resist any component of berthing force that is parallel to the pier face (Reference 2).

Pier 2 has a length of 693 feet and width of 136 feet. It is comprised of three sections, NP-1, NP-2 and NP-3, numbered from south to north, and separated by expansion joints. Section NP-1 commences from the north end of Trestle 2. The cast-in-place, reinforced concrete deck is nominally 24 inches thick. Creosote-treated timber pile caps on creosote-treated timber piles support the deck. Steel tension straps are typically located between the concrete deck and timber pilecaps at outside piles, east and west, of each pile bent. An 18-feet wide loading platform is present on both sides of the pier. There are a total of 78 pile bents in Pier 2: NP-1 has 27, NP-2 has 29, and NP-3 has 22. Piles are nominally 14 inches in diameter. Pile bents are typically 9 feet on center. A typical bent has 36 vertical piles. Both longitudinal and transverse batter piles are located between bents. The number of batter piles per bent varies between four and eight. There are a total of 3,334 timber piles supporting Pier 2.

Transverse and longitudinal pile bracing exist below the pile cap on each bent. The height of the bracing is approximately 9 feet. The bracing consists of 3 and 4-
inch by 10-inch horizontal and diagonal timbers. The bracing is connected to the piles and pile caps with 5/8-inch diameter bolts.

Mooring fixtures on the deck consist of bollards, cleats and bitts. The lowest rated fixtures are located on the south end of the pier. The fixtures on the west side of the pier have higher ratings than those on the east side.

Current State of Trestle 2

Childs reports Trestle 2 to be in good condition. Timber piles are subject to fungal deterioration and some repairs are recommended. Timber bracing is in fair condition and no repairs are recommended. Two firewalls are missing sections and repairs are recommended. Pilecaps are in good condition and repairs are not recommended. Childs estimates repairs to Trestle 2 will cost $253,000. Childs does not recommend a reduction in service load on Trestle 2. Lateral load limits of Trestle 2 will have no impact on berthing the AOE-6.

Current State of Pier 2

Childs reports the general condition of the Pier 2 supporting piles is good. The piles have retained most of the original creosote treatment and are still resistant to marine borer attack. Timber conditions above water reflect deterioration due to dry rot. All connections are severely corroded. Except for bracing, timber elements are functioning without distress as originally intended. Childs recommends repair or replacement of piles with 50 percent or more reduction in original cross section. Repairs are not recommended on timber bracing, firewalls or pile caps. Childs estimates the cost of repairs to Pier 2 will be $280,000.

SCOPE OF ASSESSMENT

The methodology for structural assessment of Pier 2 to homeport the AOE-6's is shown schematically in Figure 3. Two independent lateral load assessments were conducted for berthing and mooring. Each process required calculations of lateral forces. Ship impact during berthing generates forces on the pier while wind and water current acting on the ship tied to the pier generate mooring forces. The berthing forces were calculated based on Department of Defense instructions and guidelines. The mooring loads were calculated using computer software based on NAVFAC design manuals. These lateral forces plus dead loads and vertical live loads were applied to finite element models that reflect the condition of Pier 2 as determined by the Childs inspection. Lateral force response of the fendering system and the mooring fixtures were determined and compared with their respective allowable resistance (manufacturer's limits on the fenders, rated limits of the mooring fixtures). Those berthing and mooring responses comparing favorably with mooring fixture or fender ratings were input into finite element model analyses to determine the structural response of Pier 2. The structural analysis provided response characteristics for comparison to structural design limitations. The assessment of the pier and fendering resistance to berthing forces is straightforward. Fenders and the pier structural element responses to AOE-6 berthing are compared to allowable resistance to determine if they are adequate. By early analyses and by inspection it was apparent that the present Pier 2 fendering was marginal for berthing AOE-6's. Therefore, the analyses considered existing and proposed new fendering systems. The assessment of mooring loads was an iterative process to determine the maximum wind velocities and current that the pier structure, fendering, and mooring fixtures could sustain without exceeding allowable or rated resistance.

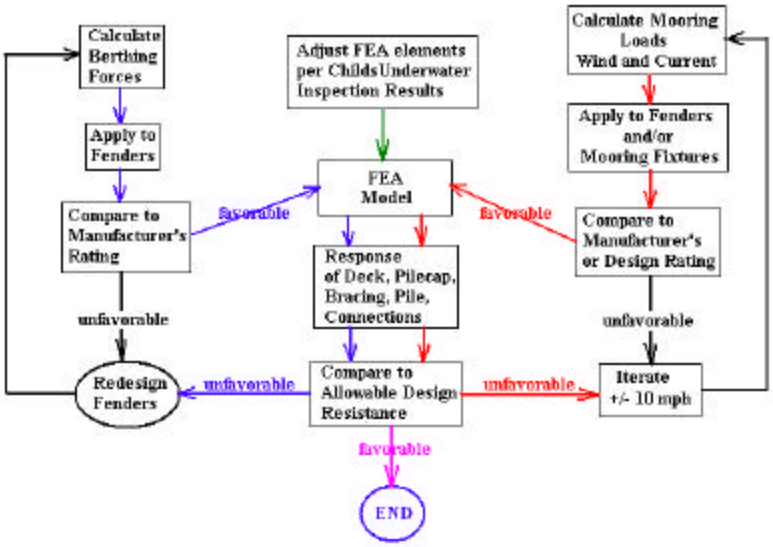

Figure 3. Methodology for pier lateral assessment

PIER LATERAL LOADS

Two independent classes of ship-induced lateral loads on Pier 2 needed to be investigated: berthing forces of an arriving ship and mooring forces of a ship tied to the pier. Lateral loads are transferred into the pier structure through fenders during berthing and through the fenders and mooring fixtures while tied to the pier.

Figure 4 is the layout of the mooring fixtures with rated individual capacities. The bollards on the west side are rated higher than those on the east side. The west side bollards were upgraded for AE ships in 1986.

Figure 5 is the layout of the fender stations on Pier 2. The fender system consists of individual Trellex/Morse® buckling column fenders attached to the deck fascia. The fender stations coincide with pile bents and are spaced at 54 feet on center. Reference 2 reported early damage resulting from several operational problems in the use of the existing Pier 2 fender system. The smooth, high-density polyethylene panels on the outboard face of the fender are subject to damage from ship hull protrusions such as scupper fittings and padeyes. Many of the existing fenders exhibit significant damage or loss of panels. Another problem arises when smaller displacement vessels berth at the pier. At low tide these vessels ride under the suspended buckling column fenders and they impose significant upward shear forces when the tide rises that can lead to fender failure.

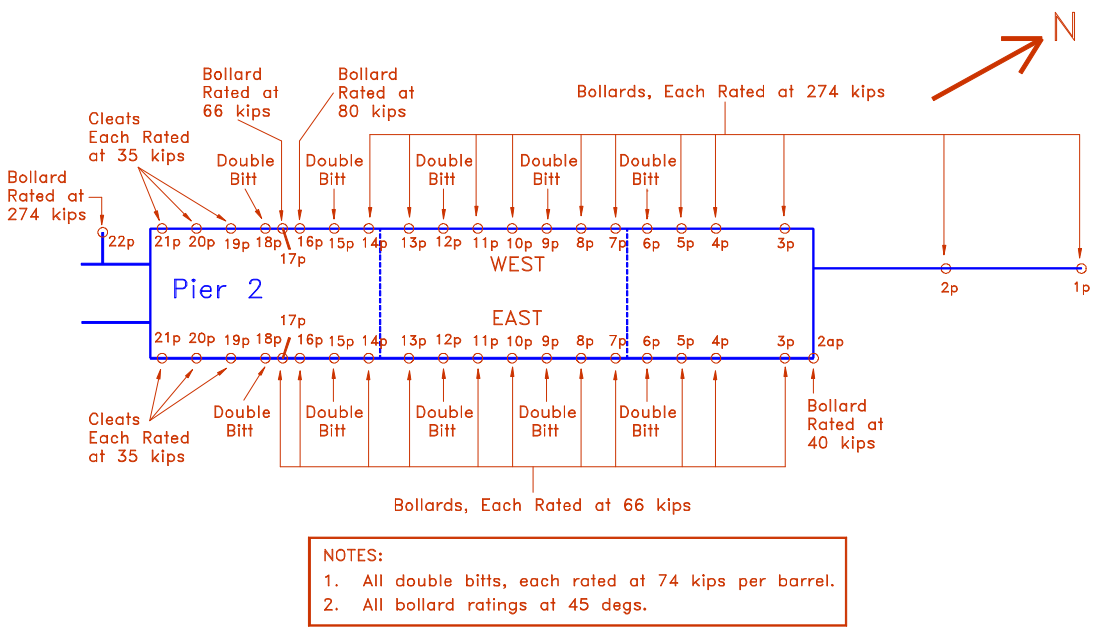

Figure 4. Layout of Mooring Fixtures on Pier 2 with rated capacities.

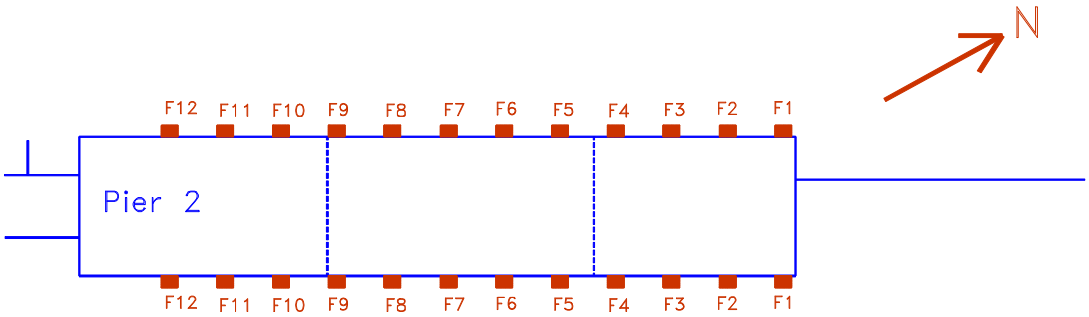

Figure 5. Layout of Trellex/Morse buckling column fenders on Pier 2.

Berthing Impact

Berthing impact loads result from arresting the motion of the berthing ship. The ship approaches the pier, usually at a slight angle, contacts the pier fender system, and rebounds from the pier. A secondary berthing impact occurs from the rebound, the ship's motion is arrested, and mooring lines are deployed to complete the berthing operation.

The physics of ship berthing impact is highly complex and not well understood. Simplified design procedures are available which may lead to inaccuracies in the predicted loads. The NFESC is currently developing an analytical model that will consider the complete physics of the berthing ship problem (Reference 3). Far more accurate results are expected from this model. However, until this model is completed and approved, the NFESC uses the NAVFAC-accepted, and most often used, approach presented in Military Handbook 1025/1 (MIL-HDBK-1025/1) (Reference 4). The MIL-HDBK-1025/1 approach is to estimate the AOE-6 approach velocity, determine the added mass from a simplified MIL-HDBK-1025/1 formula, and compute the resulting ship berthing impact energy from a basic kinetic energy formula.

The most complex concept in predicting berthing forces is the added mass of water in motion during the berthing operation. When the ship decelerates after contact with the pier fender system, the water remains in motion resulting in a apparent increase in mass of the ship. This added mass effect is influenced by water depth, fender stiffness, ship hull geometry, etc; however, the simplified formula for computing the added mass in the MIL-HDBK-1025/1 is modified by an added mass coefficient:

$$C_m = 1 + 2\,(D/B)$$

where

C_m = added mass coefficient
D = draft of the ship (feet)
B = ship beam (feet)

Characteristics for the AOE-6 are:

Displacement:	30,349 long tons (representing light loading condition)
Draft:	26.1 feet
Beam:	107 feet

For moderate to exposed conditions, a berthing velocity of 0.52 ft/sec was selected for the AOE-6 from Figure 45 of MIL-HDBK-1025/1,

The kinetic energy equations for berthing is:

$$E_{fender} = C_b * C_m * E_{ship} \quad \text{(applied to each fender)}$$

where $E_{ship} = 0.55WV^2/g$

C_b is the berthing coefficient, C_m is the ship added mass coefficient, and W is the ship displacement.

$$E_{ship} = 0.5 \times 30{,}349 \times 2240 \times 1/32 \times (0.52)^2$$

$$E_{ship} = 285{,}440 \text{ ft-lb or } 285 \text{ ft-kips}$$

The berthing coefficient is the product of four distinct coefficients:

$$C_b = C_e * C_g * C_d * C_c$$

The eccentricity coefficient, C_e, (from Figure 43 of MIL-HDBK-1025/1) varies between 0.2 and 1.0 depending on the fender contact point as the ship is berthed. C_e typically varies from 0.4 to 0.7. While the value of C_e is larger for a contact point near the ship's center of gravity, the likelihood of impact at the design velocity of 0.52 ft/sec is less and the forces are distributed over more than one fender. It is the judgement of the NFESC that the quarter point impact point has a higher probability of impact at the design berthing velocity and the ship's hull would more realistically impact one fender. C_e is set equal to 0.5 when the ship contacts the fender system at a quarter point. Although C_e is higher for other contact points, the loads on individual fenders are less. The quarter point contact was chosen because it produces the largest individual fender loads. The geometric coefficient, C_g, is equal to 0.95 for quarter point impact. The deformation coefficient, C_d, is set to 1.0 for "soft" fenders such as buckling columns or foam-filled cushions. The configuration coefficient, C_c, is equal to 1.0 for open berths such as Pier 2.

Then, $C_b = 0.475$

The added mass coefficient, C_m, is calculated to be:

$$C_m = 1 + 2\ (D/B)$$

$$C_m = 1 + 2\ (26.1/107) = 1.49$$

So, the energy imparted to each fender is:

$$E_{fender} = C_b * C_m * E_{ship}$$

$$E_{fender} = (0.475)\ (1.49)\ (285)$$

$$E_{fender} = 202 \text{ ft-kips.}$$

MIL-HDBK-1025/1 recommends that the calculated berthing energy be increased by at least 50 percent to account for "accidental" berthing. So the fender system must accommodate 303 ft-kips. From the fender performance curve (Figure 6) received from Trellex/Morse for a Morse buckling column fender E46022 installed on Pier 2, a berthing energy of 303 ft-kips is almost equivalent to the rated capacity of the fender at 49 percent displacement. The corresponding reaction force is 190 kips applied laterally to the deck.

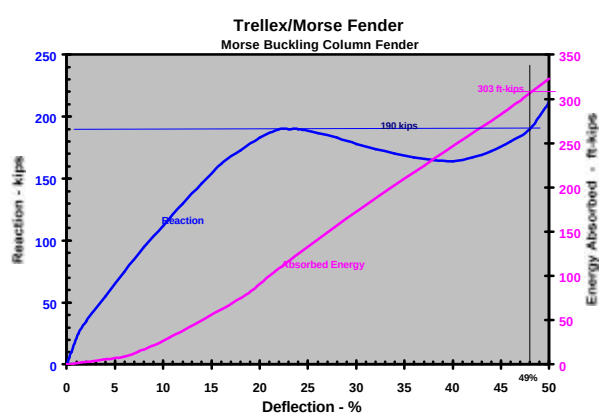

Figure 6. Reaction and energy response of the Trellex/Morse buckling column fender installed on Pier 2. Generated from data provided by Trellex Morse Inc., Keokuk, IA.

The berthing energy calculated above is set for the AOE-6 by MIL-HDBK-1025/1. However, pier response or load transferred into the pier can be decreased through a more efficient fendering system, that is, more energy absorbent fenders and/or by moving the ship reaction point away from the pier deck.

Figure 7 is a photograph of a type of fender system that is gaining acceptance at a number of Navy activities. A group of prestressed concrete fender piles are driven closely in line to provide a backing for commercially available foam-filled fender cushions. The piles are attached to the pier fascia by a steel framework. The foam-filled cushions are more energy absorbent than the buckling column fenders. Figure 8 is energy absorption and reaction force data curves for a 7-feet diameter foam-filled cushion. Since the piles are driven into the harbor bottom and the ship berthing loads are about 12-feet below the pier deck, the lateral berthing forces experienced by the pier will be about 30 percent less than those imposed by the buckling column fenders. This system is similar to Alternative 3 proposed by RBA Engineers in Reference 5. The NFESC has shown that prestressed concrete fender piles, while having a higher initial installation cost, have a lower life cycle cost than steel piles proposed by Reference 5 because of the inherent corrosive nature of steel which will incur higher maintenance costs.

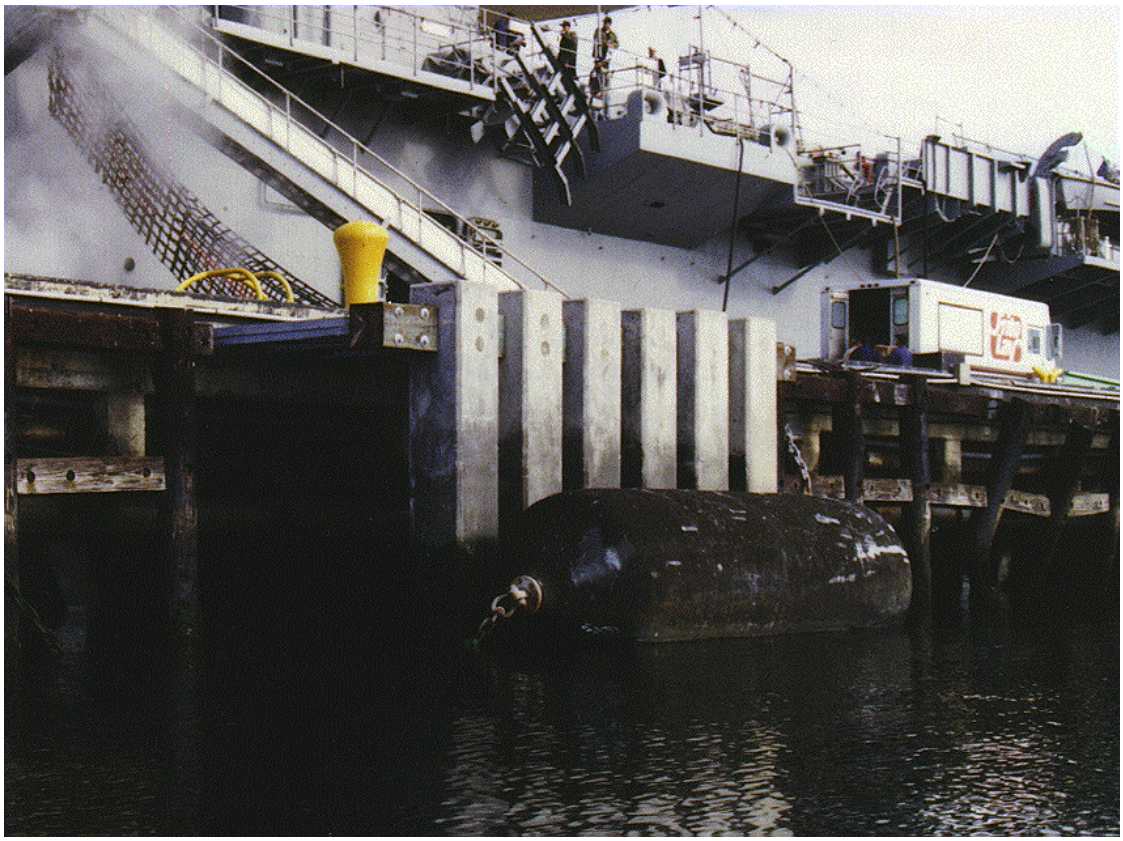

Figure 7. Foam-filled fender system on Pier 12, NAVSTA San Diego.

A berthing energy of 303 ft-kips produces a maximum reaction of 170 kips from a foam-filled fender (7 feet diameter and 14 feet length) at 47 percent compression. This leaves a reserve margin to a maximum design compression of 60 percent and a maximum design reaction of 259 kips. Since the fender reaction is at the water level, the reaction to the pier deck is 120 kips which is 63 percent of the load imposed by the Trellex/Morse fenders.

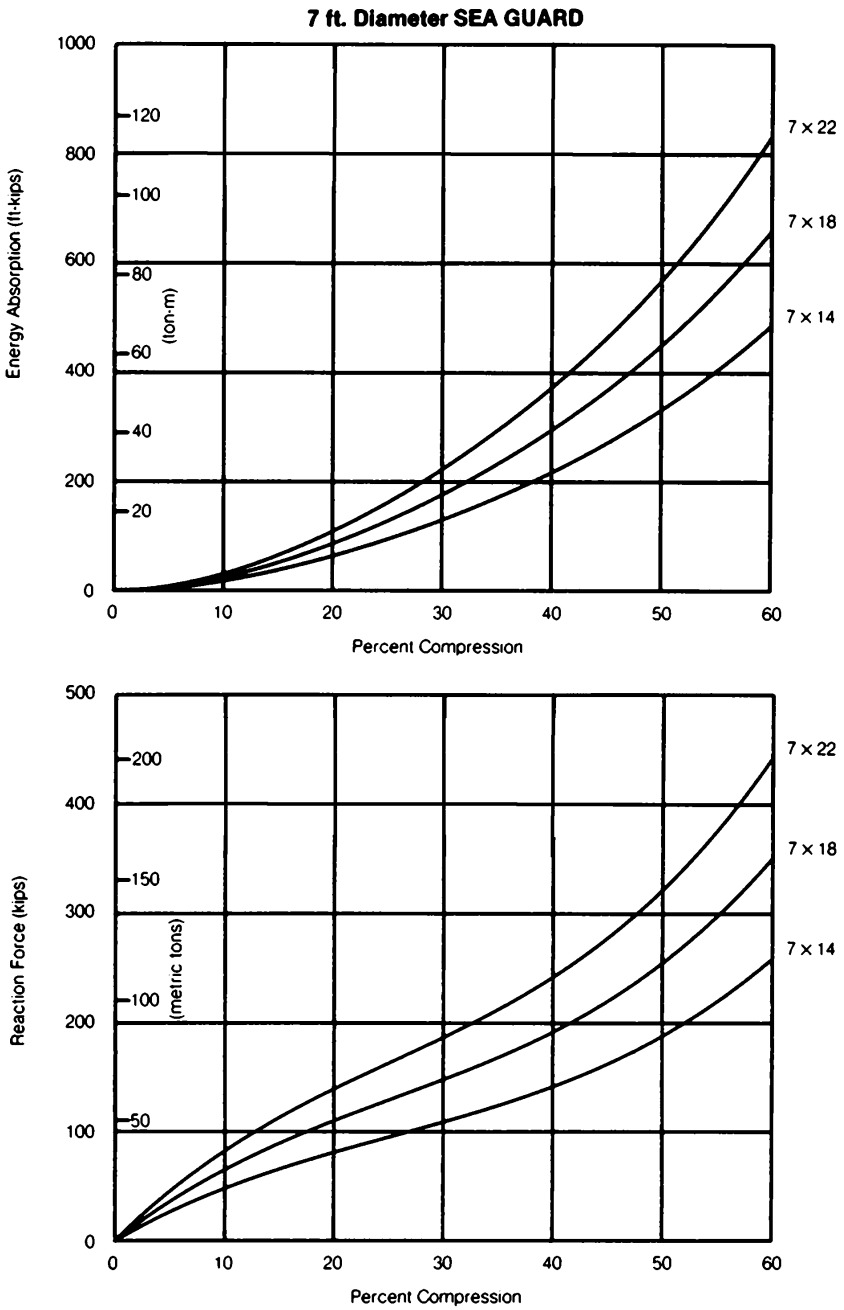

Figure 8. Reaction force and absorbed energy relationships for foam-filled fenders. Reprinted from *Sea Guard Technical Manual*, Copyright by Seaward International, Inc., Falls Church, VA.

Mooring Analyses

AOE-6 Mooring forces on Pier 2 were calculated using the fixed mooring analysis computer program FIXMOOR, version 9/22/91 (Reference 6). FIXMOOR's design procedures and data are based on NAVFAC DM 26.4, "Fixed Moorings," and NAVFAC DM 26.6, "Mooring Design Physical and Empirical Data." (References 7 and 8). FIXMOOR analyzes response to wind and current applied to the ship and determines resulting yaw, sway, and surge motions. These motions are resolved into mooring line, mooring fixture, and fender forces.

FIXMOOR uses two sign conventions: one for the geometric configurations and the second for wind and current (environment) forces (Figure 9). The geometric convention applies to ship chock, pier bollard, and fender locations. The origin is at the ship's center where the x-axis is towards the **bow**, the y-axis is on the port beam, and the z-axis is skyward. The environmental force convention applies to resultant forces (F_x, F_y, and M) on the ship and motions (surge, sway, and yaw) of the ship due to wind and current. The origin is at the ship's center where the x-axis is towards the **stern** and y-axis is on the port beam. Positive yaw moment (M) and yaw motion is counter-clockwise about the z-axis. The angles of wind and current are measured clockwise and referenced from the ship's bow.

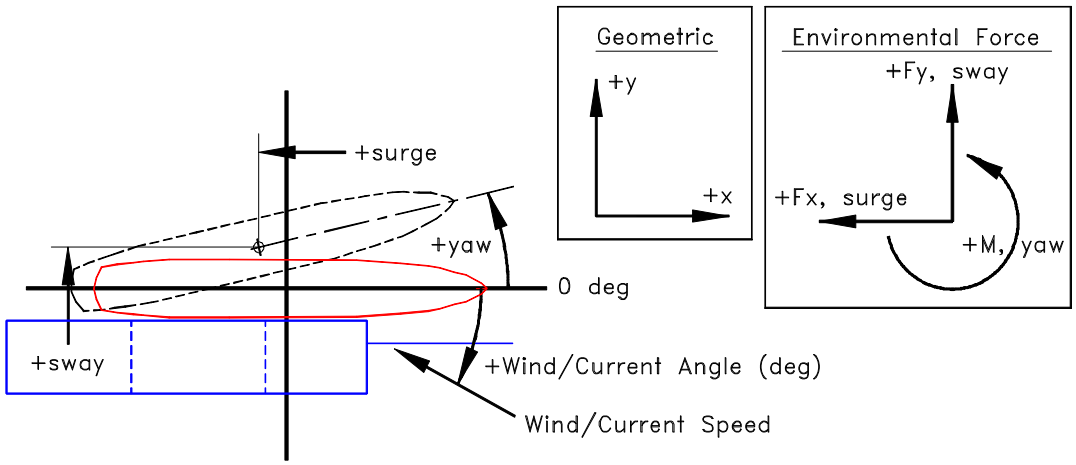

Figure 9. Coordinate systems and sign convention employed by FIXMOOR.

Mooring Configurations

NFESC engineers analyzed four ship-mooring configurations:

(1) west-side bow-out (Figure 10 and 11),
(2) west-side bow-in (Figure 12),
(3) east-side bow-out (Figure 13),
(4) Two ships west/east-side bow-out (Figure 14).

Layout and location of the fenders and mooring fixtures are shown in Figures 4 and 5 respectively. The ship was shifted seaward in the bow-out configurations (Figures 10 and 12) to avoid the lower rated mooring fixtures on the south end of the pier. Figure 11 positioned the ship to take advantage of the high rated bollard 22 off the south end of the pier. Layout and location of the AOE-6 chocks and capstans were obtained from NAVSEA drawings (References 9 and 10). In the FIXMOOR modeling the analyst deployed sixteen mooring lines to resist high winds. FIXMOOR defines mooring lines as tension-only elements attached at the ship chock and to the pier bollard. The basic mooring line is 3-inch diameter nylon line. From NAVFAC DM 26.6, Table 8, a 3-inch nylon line has a breaking strength of 180,000 lbs and a maximum working load of 20,000 lbs. The load-deflection (stiffness) curve for a 3-inch nylon line is resident in FIXMOOR. During the analyses, higher mooring forces dictate that some of these lines are "doubled up" to increase resistance to offset the higher loads. That is, mooring loads of 20 to 40 kips require two, 3-inch lines, loads of 40 kips to 60 kips require three lines, and so forth. Some lines had the equivalent of five, 3-inch lines through the same chock and to the pier bollard. FIXMOOR requires a preload of 3.6 kips on each mooring line for stability. Preloads were adjusted to maintain tension in lines.

NAVFAC Design Manuals and FIXMOOR do not consider the interaction of two ships moored as configured in Figure 14. NFESC analysts used linear superposition of FIXMOOR-derived forces from individual ships (Figure 10 plus Figure 11) to obtain structural forces for the two-ship configuration.

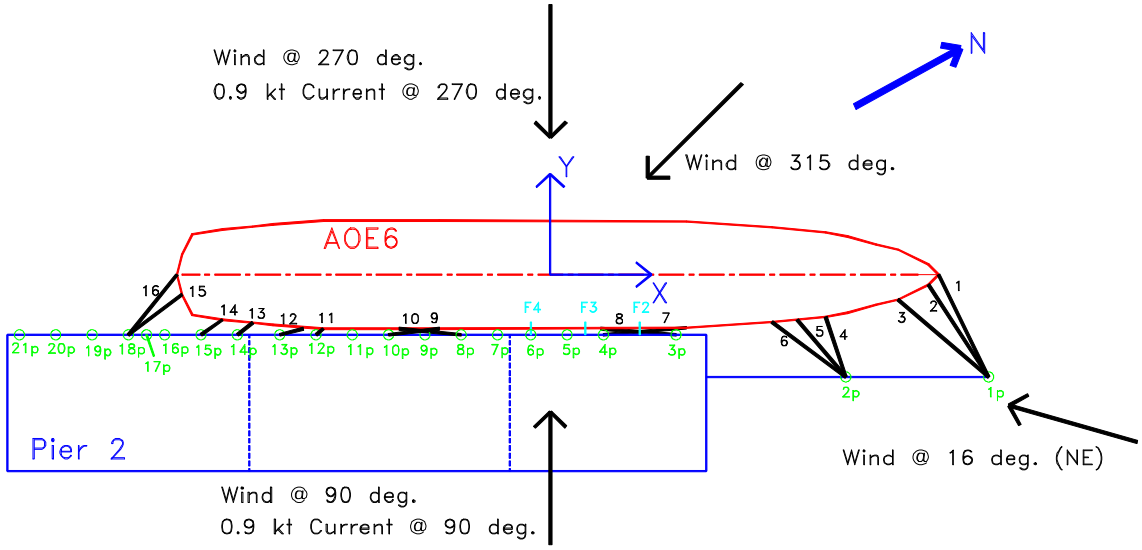

Figure 10. West-side bow-out mooring configuration with stern lines to bollard 18.

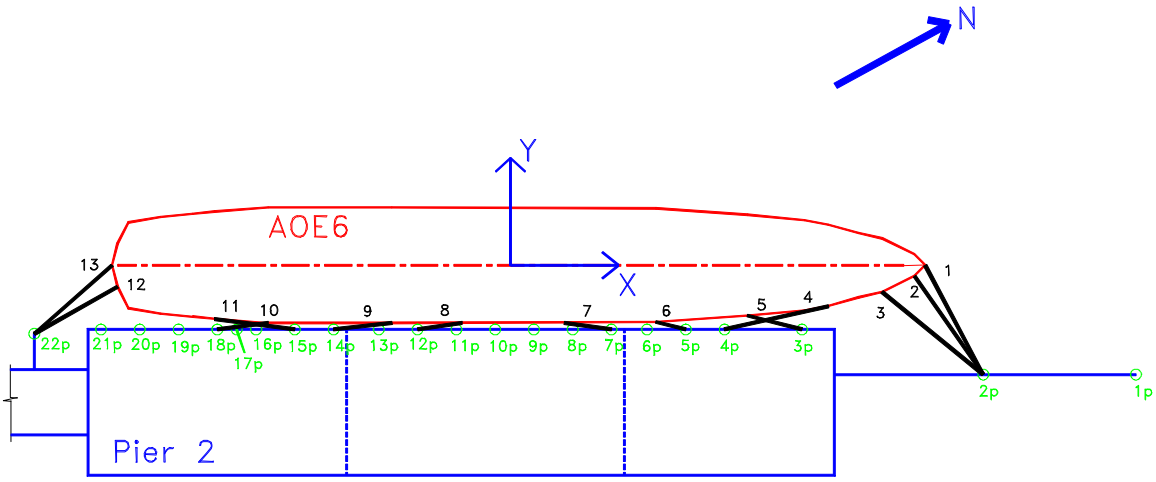

Figure 11. West-side bow-out mooring configuration with stern lines to bollard 22.

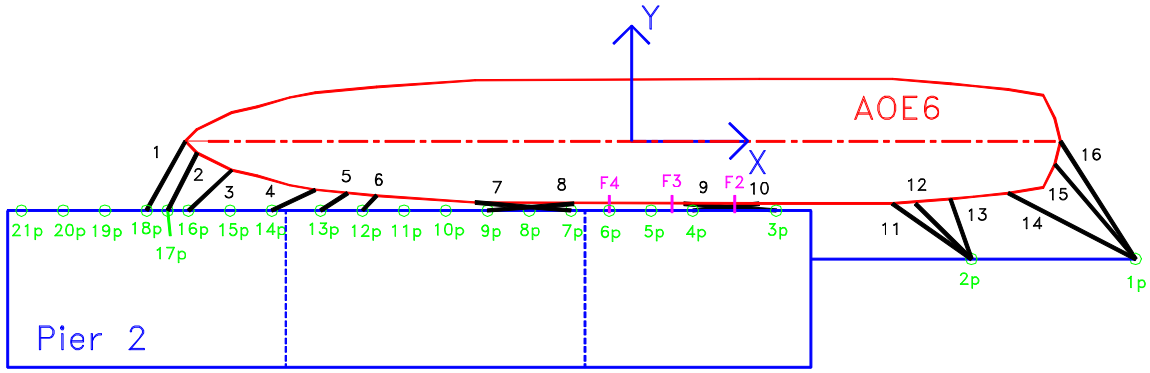

Figure 12. West-side bow-in mooring configuration.

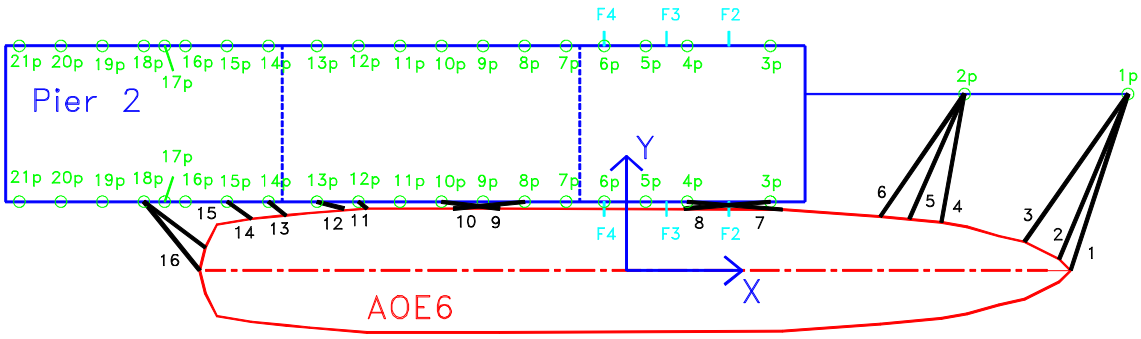

Figure 13. east-side bow-out mooring configuration.

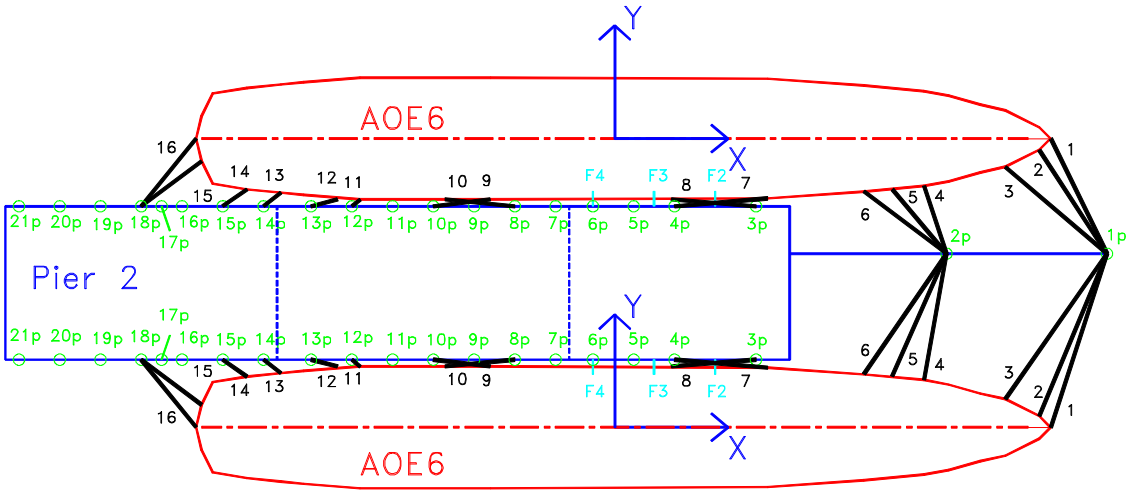

Figure 14. Two Ships with bow-out mooring configuration.

Wind and Current Loads

NOAA was contacted to obtain wind and water current data for the pier site. No water current data was available and the nearest wind gauging station was at Newark. The highest peak sustained gusts for Newark generally range from an easterly to northwesterly direction with maximum wind velocities under 60mph. The along-shore current used in this investigation was 0.9 knots, assumed normal to the longitudinal axis of the pier or roughly parallel to shore. This was the design current used for Pier 4. The area is known for fierce and fast-developing Northeasters.

Our goal in the mooring analysis was to determine limiting wind conditions as a function of wind direction while maintaining a 0.9 knots water current approaching roughly parallel to the shore (either at 90° or 270° whichever provided the worse case loading on fenders or bollards). Initially the analyst applied three current and wind conditions to all four mooring configurations: 1) wind from 315° with a 0.9 knot current at 270°; 2) wind from 90° with a 0.9 knot current at 90°; and 3) wind from 16° (Northeaster) with a 0.9 knot current at 90°. This analysis was followed by "all directions wind" analyses of maximum allowable wind velocities for the west-side berth with the bow out. Water current angles were either 90° or 270°. A similar analysis was completed for east side berth with the bow out. The west side of Pier 2 is more protected from the Northeaster effect and should be the principal berthing. The higher rated mooring fixtures are also located on the west side.

Due to limiting water depth of 32 feet at mean low water (MLW), mooring forces were determined at "minimum load" of 30,349-tons displacement and 26 feet draft. Since a minimum ship displacement

creates a larger sail area, these conditions place higher berthing forces on the pier than a "maximum loaded" AOE-6.

Fenders

The existing Trellex/Morse buckling column fender as well as the alternative foam-filled fender system were evaluated in the mooring analyses. Limiting load and deflection for existing Trellex E46022 buckling column fender was 190 kips and 0.88 feet (50 percent compression). Limiting load and deflection for the alternative, 7 feet diameter by 14 feet long, foam-filled fender system is 259 kips and 4.2 feet (60% compression). Load-deflection curves from Figures 6 and 8 were input to FIXMOOR.

Due to ship hull curvature (Figure 15) and equal-spaced fenders, no more than 3 adjacent fenders can ever make contact with the AOE-6 hull at any time. This characteristic holds for the existing Trellex/Morse fenders on the pier (layout in Figure 5) as well as the proposed foam-filled fenders. Specifically, fenders 2,3,4 or fenders 3,4,5 or fenders 4,5,6, etc. are in contact with the ship hull, depending on the wind and current load case. For example, when winds approach the ship moored bow out at the west berth from 315° (45° off the port bow) and currents are from 270°, the ship yaws in the negative direction (clockwise) "rolling" into the fenders toward the bow. In this case fenders 2,3,4 are the only fenders resisting the compressive ship mooring forces from the wind and current. Similarly, when winds are coming from 225° (45° off the port stern), fenders 4,5,6 are in contact with the ship hull. The pier does not encounter fender loads when the ship is on the west berthing and the wind direction is from 0° to 180°. Similar fender resistance occurs for the east berth.

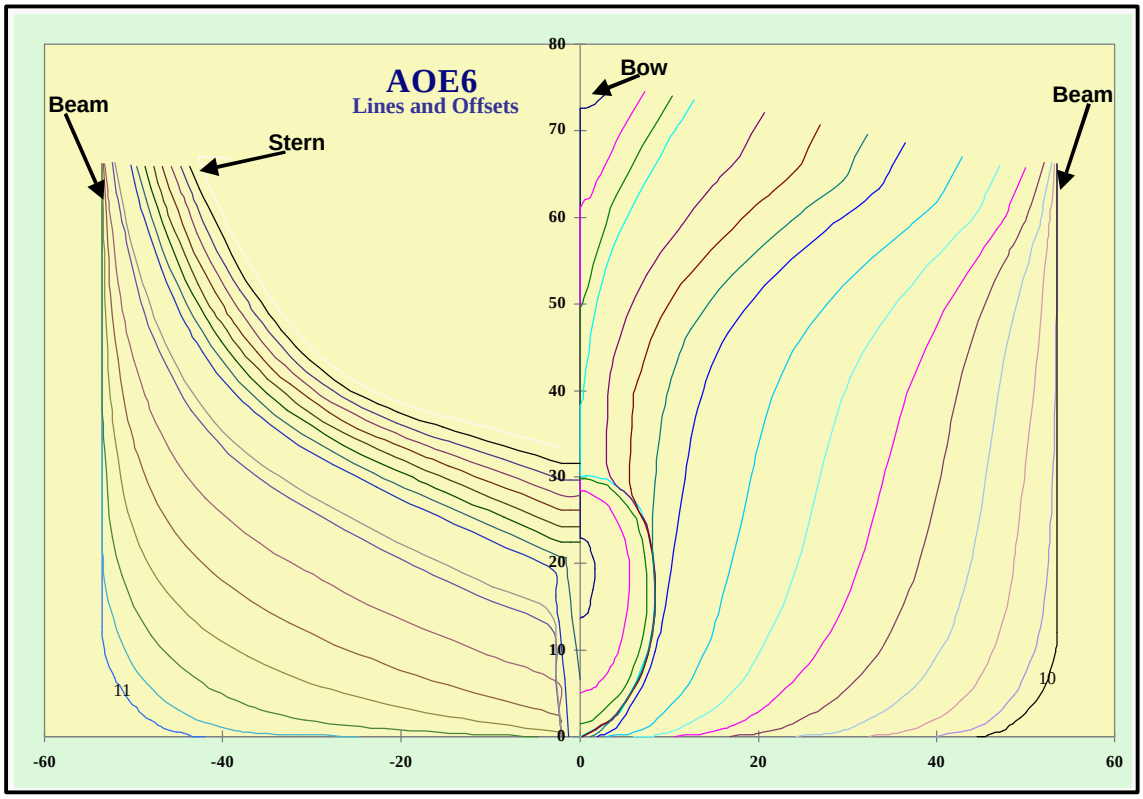

Figure 15. Contours (lines and offsets) for the AOE-6. Stern-to-beam is on left and bow-to-beam is on right. The longitudinal distance between contour stations is approximately 23 feet.

Mooring analyses results
The computed load responses for all cases are tabulated in the Appendix. The forces generated by the analyses were compared to load limitations of mooring fixture ratings and to manufacturer's capacity rating of fenders. Those load cases not in excess of mooring fixture or fender ratings were input into finite element analyses to determine the structural response of Pier 2. The structural analyses provided response characteristics for comparison to structural limitations.

Westerly winds in excess of 30 mph plus water current produce mooring forces in excess of the present fender system capacity on the west berth of Pier 2. Likewise, easterly winds in excess of 30mph plus 0.9 knot current exceed the limitations of the present fender system on the east side.

FINITE ELEMENT ANALYSES (FEA)

A static, elastic analysis was performed on the pier using the computer program ABAQUS (Reference 11). FEA provided a means of efficiently and accurately determining the berthing and mooring load response of Pier 2. Results consisting of deck, pilecap, bracing, and pile reactions to the lateral loading were compared to established limiting stresses which, in turn, restricts the maximum wind and current conditions. Before initiating FEA berthing and mooring forces were compared to the manufacturer's limits of the fenders and current rated limits of the mooring fixtures. Some wind and current configurations cause bollards or fenders to exceed their rated capacities before limits are exceeded in Pier 2 structural members.

NFESC analysts assigned Southern Pine timber properties to the piles, pile caps, and bracing. The timber properties included a modulus of elasticity, E, equal to 1,350,000 psi and an allowable bending stress, F_b, of 2,400 psi. The modulus of elasticity for the concrete deck was taken as E_c = 4,000,000 psi. The concrete deck behaved almost as a rigid body and was insensitive to E_c.

Since Pier 2 consists of three sections (NP-1, NP-2, and NP-3) separated by expansion joints, NFESC analysts modeled each section independently. The modeling allows no forces to be transferred across the expansion joints. Figure 16 is the finite element mesh used for section NP-1. Figures 17 and 18 are elevation and cross section views. Models of NP-2 and NP-3 are similar. The mudline occurs at an average of 25 feet below MLW. The piles were modeled as fixed 5 feet below the mudline (30 feet below MLW).

Childs reported that the steel tension straps connecting the deck to the pile caps were severely corroded and in poor condition. These straps should not be relied upon to transfer any significant tension force from the deck to the pilecaps or piles. The modeling allowed no tension transfer by the tie-down straps. The consequence of discounting the tension straps is that the overturning moment resulting from the mooring loads is resisted entirely by the dead weight of the deck. For this reason the finite element analysis used an iterative approach in which the piles that developed tension forces were deleted in successive runs and the effects were redistributed to neighboring elements. Childs also concluded that about 20-25 percent of the piles are damaged or deteriorated resulting in a 20-90 percent loss in effective cross section. This weakened condition was simulated in the finite element models by deleting 25 percent of the piles (both vertical and batter piles) in uniform fashion.

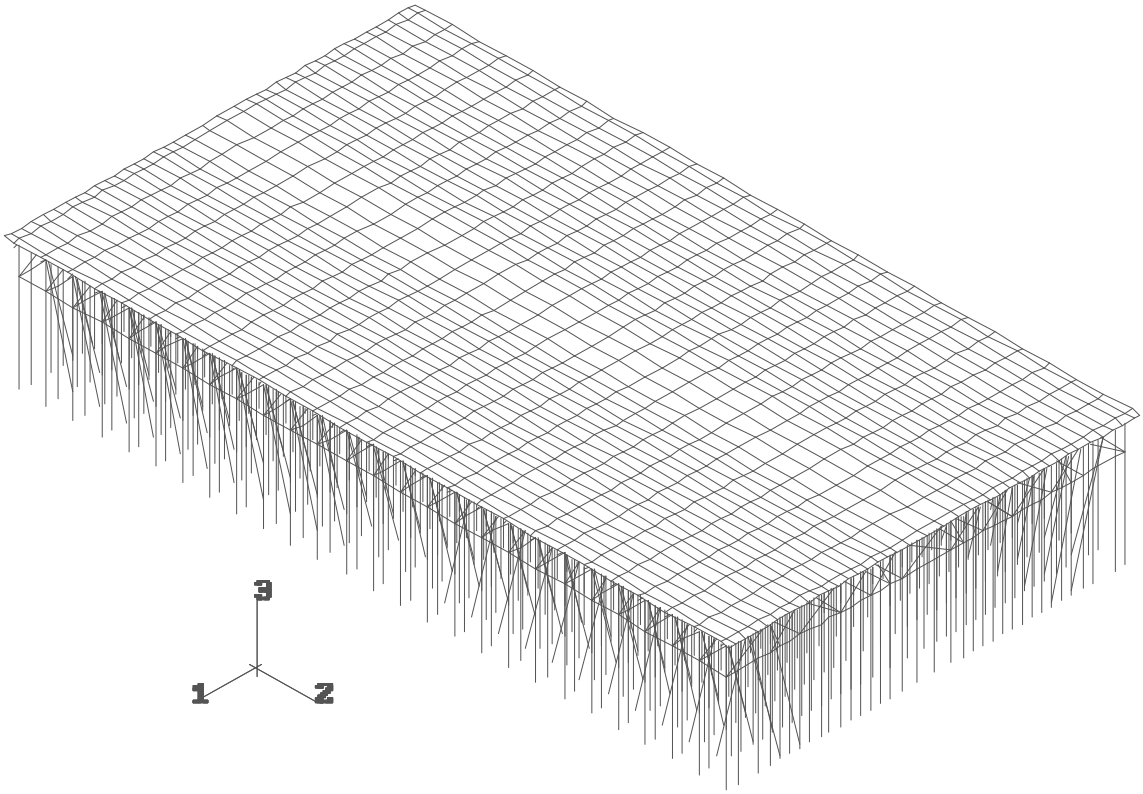

Figure 16. Finite Element Mesh of Section NP-1

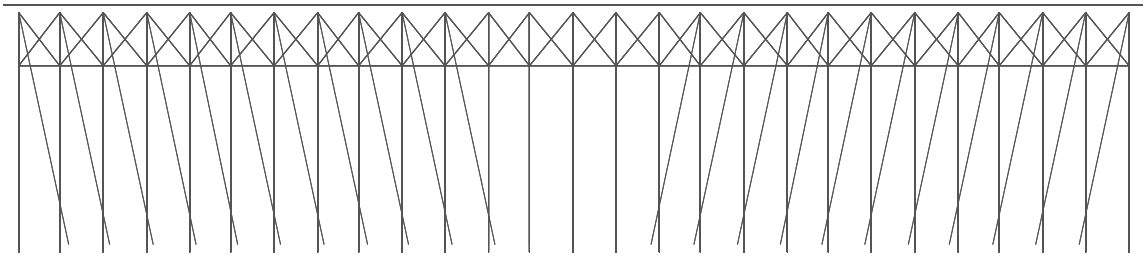

Figure 17. Elevation of finite element model.

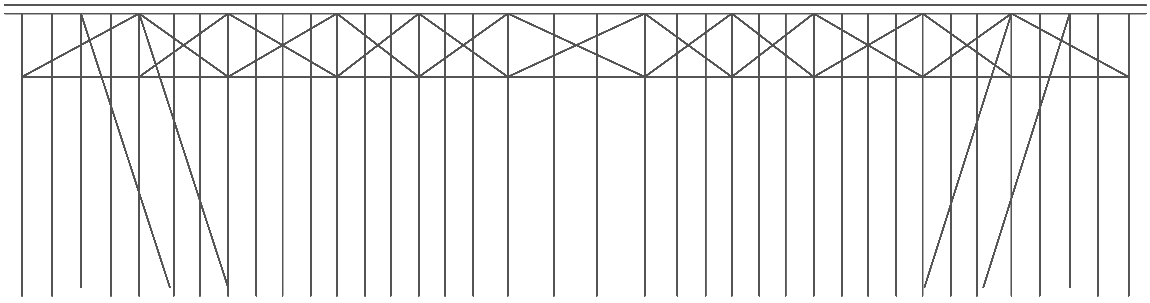

Figure 18. Transverse cross section of finite element model.

The axial compressive stress for the piles is limited by Euler buckling and is given by the following equation (Reference 12):

$$F_c = \frac{.225E}{\left(KL/D\right)^2} \qquad (1)$$

where E = modulus of elasticity
D = diameter of pile
L = unsupported length of pile
K = effective length factor, (K=1 assumed)

The piles are subjected to axial and bending forces when the pier is laterally loaded. Pile response must satisfy an interaction formula that combines the axial compressive stress with the bending stress (Reference 12):

$$\frac{f_c}{F_c} + \frac{f_{bx}}{F_{bx} - J_x f_c} + \frac{f_{by}}{F_{by} - J_y f_c} \le 1 \qquad (2)$$

where f_c is actual compressive stress induced by axial load
f_{bx} and f_{by} are bending stresses about the x and y axes
F_{bx} and F_{by} are design limits for bending stress
J_x and J_y are factors to account for the increase in bending stress caused by the moment induced by the axial load acting away from the centroid of the deflected member and set equal to 1.0 for long piles.

The unbraced length for the piles is 32 feet. Using Equation (1), the allowable axial compressive stress is 405 psi. The relatively low value in allowable compressive stress results from having a large unbraced pile length. Our analysis showed a great sensitivity to the unbraced length of the piles. The limiting load of each pile is inversely proportional to its unbraced length, squared. Even though the braces do not transfer significant forces, they serve to decrease the unbraced length of the piles significantly and increase the limiting service load by almost 70 percent. The pile bracing should be repaired and maintained.

The berthing and mooring loads were applied at the fender stations as compression forces and points of mooring fixtures as tension forces on the finite element models. Concurrently with the lateral forces, dead load plus 500 to 700 psf live load was applied. The higher live load is allowed when the wind velocity is less than 30 mph. Element responses to the lateral loads generated by the finite element analysis were compared to the load limits of the structural members of Pier 2.

Berthing forces do not produce a critical response in structural elements of Pier 2. That is, the responses of all structural elements are well within allowable design stresses (Equation 2). The critical responses (in excess of design allowance) are produced by wind and current while the ship is moored. The wind and current directions that produce the maximum load response on each section for the ship berthed on the west side are given in Table 1. Mooring forces on fixtures and fenders that result from these cases are tabulated in Tables 2 and 3. Wind and currents from these directions will produce forces that exceed the limits of the piles supporting the pier before reaching the limits of the mooring fixtures or the foam-filled fenders. For bow-out mooring configurations the maximum forces into NP-1 and NP-2 are always in response to mooring fixture loads and are independent of the fendering system. The fenders always apply the maximum loads into section NP-3 so the magnitude of the forces in the piles is dependent on the fendering system.

Figures 19 through 21are example results showing the piles that exceed 75 percent of the design limit for the worst case loads on sections NP-1, NP-2, and NP-3 respectively (Table 1). The responses are for 60 mph and 0.9 knots with deck live load of 500 psf. The models included effects of simulated damage reflecting the Childs inspection and with foam-filled fenders installed. The piles shown in Figures 18 through 20 should be given a higher priority during future inspections and maintenance projects.
Since the current analyses simulated the present condition of the piles, if degraded piles are repaired or replaced so that all piles are fully effective, the maximum allowable wind can be increased to 70 mph for those case discussed above and others where the pile limitations are exceeded.

TABLE 1. Wind and Current Conditions For Critical Structural Response		
SECTION	**WIND DIRECTION**	**CURRENT DIRECTION**
NP-1	120°	90°
NP-2	120°	90°
NP-3	315°	270°

Table 2. Pier 2 West Side Berth - Fender and mooring reaction forces for 60 mph wind from 120° and a 0.9 knot current from 90°.

Bollard WEST	Reactions X (LBS)	Y (LBS)	Z (LBS)	Resultant (KIPS)	Rating (KIPS)	Check
Dolphin 1	-63339	88257	32036	113	274	OK
Dolphin 2	-111047	152550	53359	196	274	OK
3	-14935	1200	1599	15	274	OK
4	0	0	0	0	274	OK
5	0	0	0	0	274	OK
6	0	0	0	0	148	OK
7	0	0	0	0	274	OK
8	-19758	1921	1281	20	274	OK
9	0	0	0	0	148	OK
10	0	0	0	0	274	OK
11	0	0	0	0	274	OK
12	34696	28517	104562	114	148	OK
13	16187	4168	2779	17	274	OK
14	131830	103396	103396	197	274	OK
15	63066	44413	35530	85	148	OK
16	0	0	0	0	80	OK
17	0	0	0	0	66	OK
18	49318	49774	15611	72	148	OK
19	0	0	0	0	35	OK
20	0	0	0	0	35	OK
21	0	0	0	0	35	OK

Table 3. Pier 2 West Side Berth - Fender and mooring reaction forces for 60 mph wind from 315° and a 0.9 knot current from 270°.

Bollard WEST	Reactions X (LBS)	Y (LBS)	Z (LBS)	Resultant (KIPS)	Rating (KIPS)	Check
1	0	0	0	0	274	OK
2	0	0	0	0	274	OK
3	0	0	0	0	274	OK
4	0	0	0	0	274	OK
5	0	0	0	0	274	OK
6	0	0	0	0	148	OK
7	0	0	0	0	274	OK
8	0	0	0	0	274	OK
9	0	0	0	0	148	OK
10	0	0	0	0	274	OK
11	0	0	0	0	274	OK
12	0	0	0	0	148	OK
13	1601	412	275	2	274	OK
14	6392	5014	5014	10	274	OK
15	8769	6176	4940	12	148	OK
16	6233	14411	5764	17	80	OK
17	0	0	0	0	66	OK
18	7049	8756	2335	11	148	OK
19	0	0	0	0	35	OK
20	0	0	0	0	35	OK
21	0	0	0	0	35	OK

Fender WEST	Hor Reac[1] (lbs)	Check
2	224252	OK (b)
3	176172	OK
4	132135	OK

[1] Maximum Fender Capacity:
a) Existing Fender (Trellex E46022): 190 kips
b) 7x14 Foam-filled: 259 kips at 60% Compression

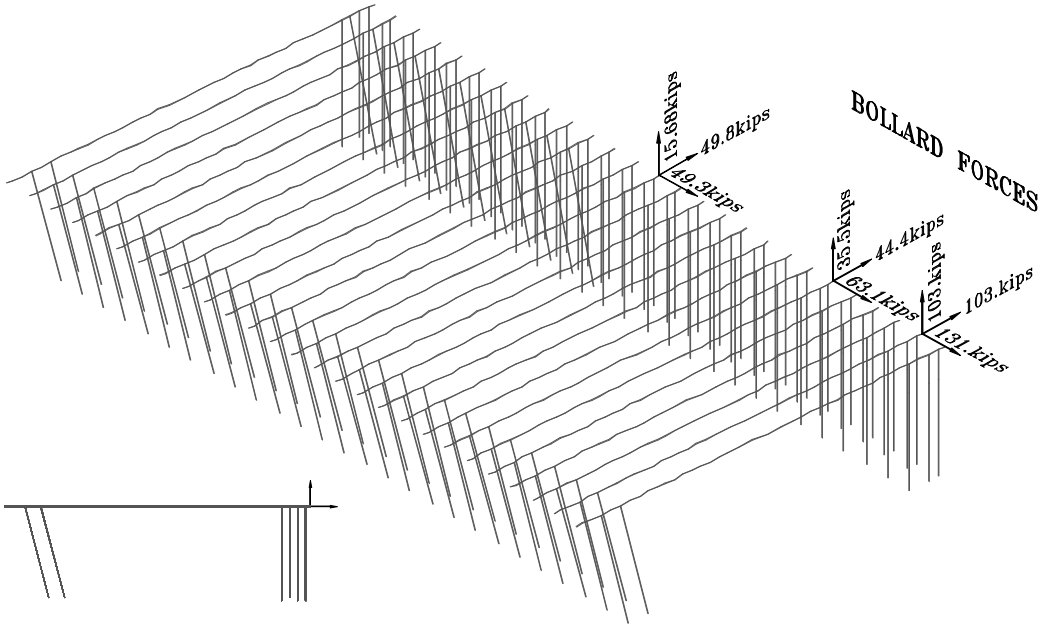

Figure 19. Section NP-1 Piles that exceed 0.75 of the design limit. Wind equals 60 mph at 120°, and current equals 0.9 knots at 90°.

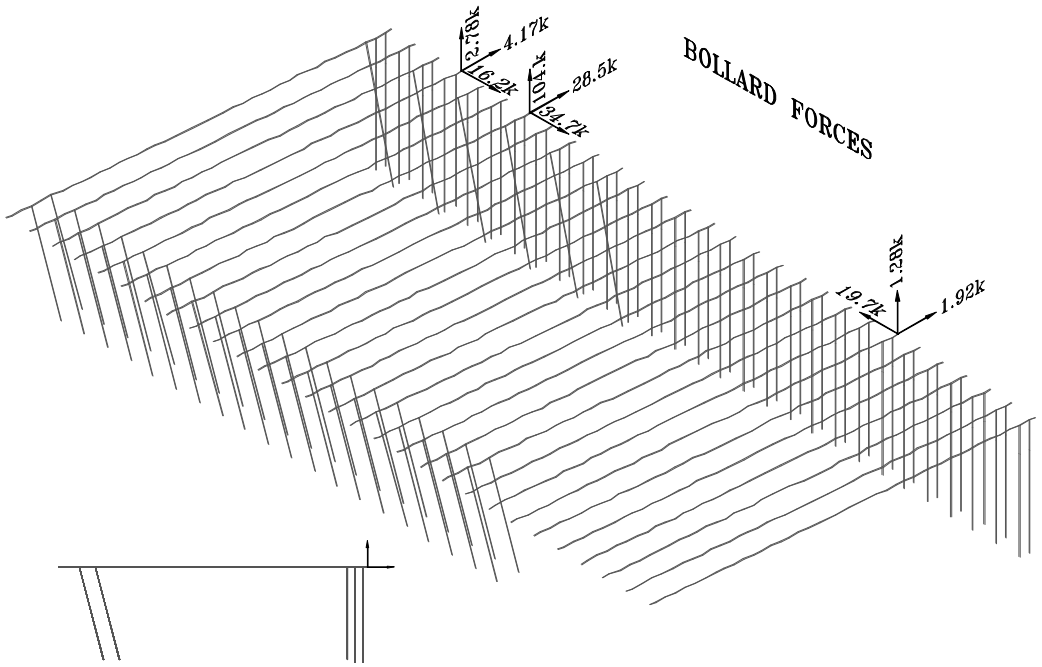

Figure 20. Section NP-2 Piles that exceed 0.75 of the design limit. Wind equals 60 mph at 120°, and current equals 0.9 knots at 90°

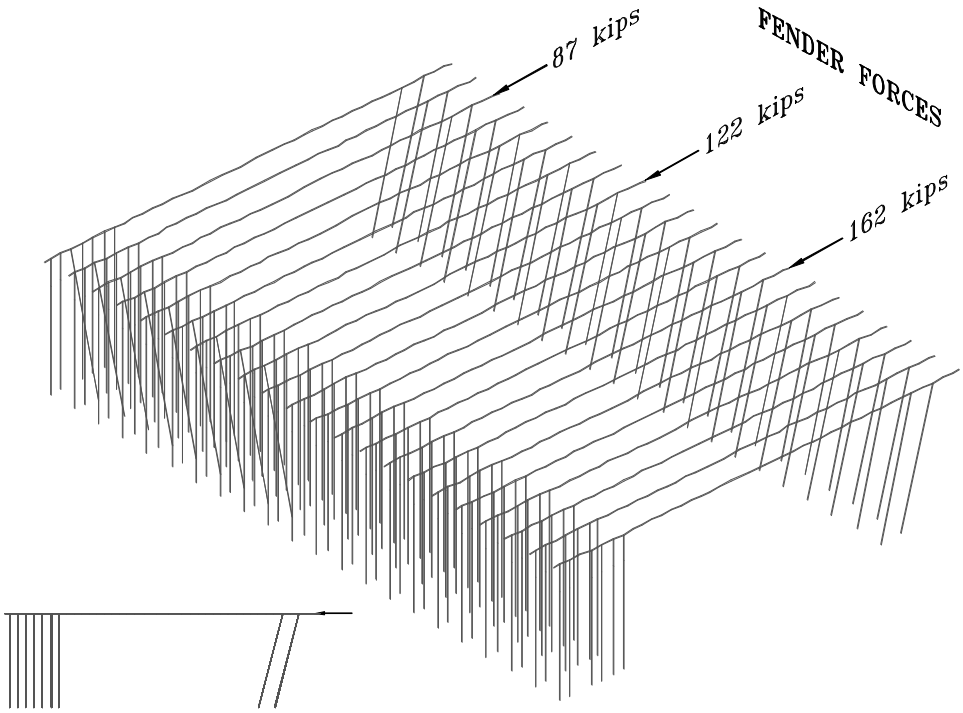

Figure 21. Section NP-3 Piles that exceed 0.75 of the design limit. AOE-6 moored on west side with Wind equal to 60 mph at 315°, and current equal to 0.9 knots at 270°.

BERTHING AND MOORING ASSESSMENT

The berthing requirements were simplified using NAVFAC DM 25.6 guidelines. The results are straightforward. Pier 2 in its present condition and with the present fendering is just barely adequate for berthing AOE-6's. The limiting elements are the fenders.

The analyses of mooring is more complex than berthing. The wind and water current sources for loading the pier produce a wide range of responses depending on direction. Polar plots summarizing limiting wind velocities were derived for single ship on the west and east side, bow-out mooring (Figures 22 and 23 respectively). These plots represent the maximum allowable wind velocities from all directions (360°) about the ship. The longitudinal centerline of the ship toward the bow is the direction 0°. The dashed line plot applies to the existing Trellex/Morse buckling column fender and the solid line represents wind limits if a foam-filled fender system is added to Pier 2. While the limiting feature for the dashed line is the existing fender system, the limiting feature of the solid line plot fluctuates among the mooring fixtures, structural piles, and fenders depending on the wind and water current direction.

Two AOE-6 ships cannot be moored simultaneously to Pier 2 with winds in excess of 30 mph without risk of structural damage to the pier. Wind loading on two ships generates excessive forces in the piles and would not be significantly improved by addition of new fendering.

Although the existing Trellex/Morse fenders severely limit the resistance of the west side berth from northwesterly winds (Figure 21), it is better suited for resisting Northeasters than the east side. In its present state the fender system or one or more mooring fixtures would exceed their allowable rating before the pier structure is overloaded for winds from all directions except the southeast. Piles in Section NP-1 and NP-2 limit the wind loading from the southeast. Removing the existing fenders and adding a foam-filled fender system would improve Pier 2 west side berth resistance to westerly winds. With a foam-filled

fender system, westerly winds can be almost doubled wherein piles in section NP-3 approach limiting capacity before the fenders and are the limiting elements (see Figure 20 of the finite element analysis above).

Low rated mooring fixtures severely limit the resistance of the east side berth from westerly winds while the existing Trellex/Morse fenders limit easterly wind resistance (Figure 22). In its present state, either the fender system for easterly winds or one or more mooring fixtures for westerly winds would exceed their allowable rating before the pier structure is overloaded. Removing the existing fenders and adding a foam-filled fender system would improve the east side berth resistance to easterly winds. With a foam-filled fender system, piles in section NP-3 approach limiting capacity before the fenders and are the limiting elements (see finite element analysis above). Upgrading the east berth mooring fixtures to the level of those on the west berth would improve resistance to westerly winds and could bring the east berth resistance level up to that of the west berth.

A foam-filled fender system should be chosen to closely match the strength of the pier, specifically that of section NP-3. In its present state, 7 feet diameter by 14 feet length foam cushions best match the pile capacity of Pier 2. If all the piles identified in the Childs' report (Reference 1) are repaired, then 8 feet diameter by 16 feet length foam cushions can match the strength of the pier structure. The larger size fenders will increase the northwesterly wind resistance of the west berth and the easterly wind resistance of the east berth up to 70 mph. The larger cushion costs approximately 45 percent more than the smaller cushion.

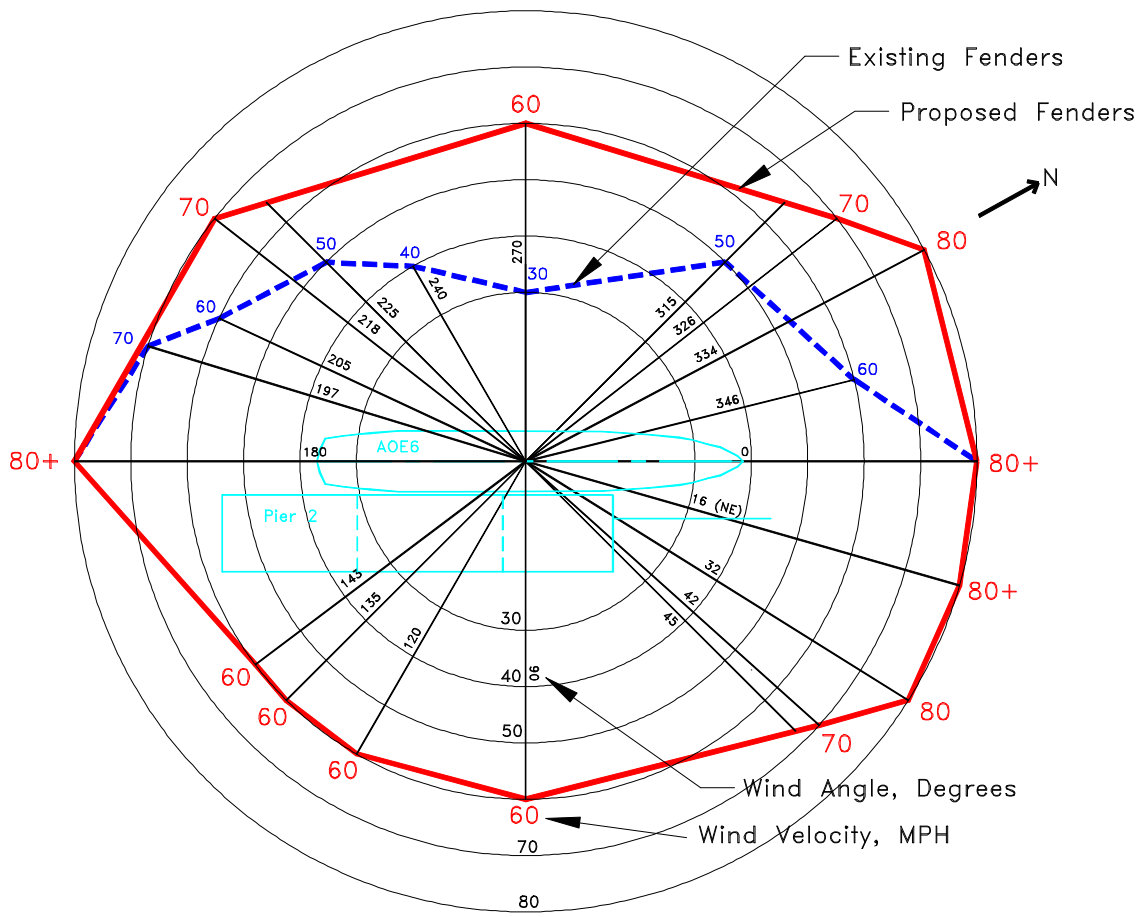

Figure 22. Maximum allowable wind velocities for Pier 2 west side mooring.

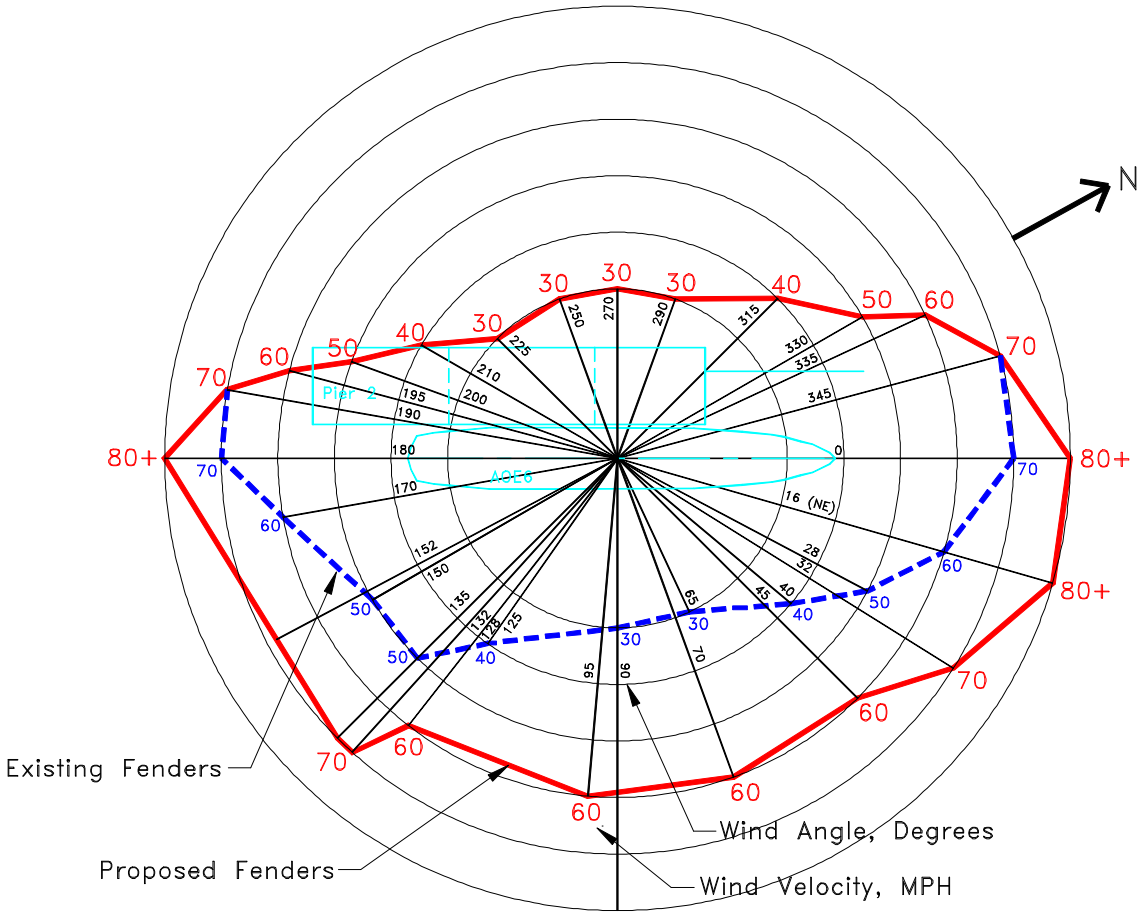

Figure 23. Maximum allowable wind velocities for Pier 2 east side mooring.

PROPOSED FENDERING DESIGN

The Trellex/Morse fender system presently installed on Pier 2 is inadequate for use with AOE-6 class vessels. The berthing energy analysis shows that the rated energy capacity of the buckling column units barely meet MIL-HDBK-1025/1 standards for an AOE-6. Use of the buckling column fenders is limited to wind velocities considerably less than 60mph for westerly winds on the west side berth and for easterly winds on the east side berth. In addition, the fenders are prone to damage from hull protrusions and smaller displacement vessels berthed at the pier. Replacement of the high density polyethylene panels on the outboard face is a continuous maintenance problem.

The NFESC has demonstrated the advantages of the foam-filled fender systems in our analyses and recommends that a foam-filled fender system be selected to serve the ships at Pier 2. This system is an adaptation of a system first proposed by the Naval Civil Engineering Laboratory (Reference 13) and was subsequently used extensively at the Naval Station, San Diego, to berth a wide range of surface combatants, amphibious ships and auxiliary ships. The system includes commercially available foam-filled, elastomer-covered cushions that provide a resilient and energy absorbing fender. The cushions transfer reaction loads to a series of closely spaced 24-inch square prestressed concrete piles. The system offers several advantages over systems anchored to the pier deck. Since the fender reaction loads occur at water level, the loads experienced at the pier fascia is significantly lower, for equivalent berthing events, than those imposed by the buckling column fender. The floating foam fender contacts the side of the AOE-6 at an

elevation that is free of hull appurtenances and it adapts readily to the berthing requirements of smaller vessels. The use of proven commercial fender cushions and prestressed concrete fender piles results in a robust and low maintenance fender system. In the event that a cushion should be damaged, it can be easily removed for repair and replaced by a spare cushion (Reference 14).

Figures 24 through 26 provide a preliminary design of a foam-filled fender system for Pier 2. The cost breakdown for one fender station is as follows:

1. 7 x 14 foam cushion	**$25,000**
2. Cushion hardware	**$ 1,000**
3. Prestressed Concrete piles (6)	**$28,000**
4. Plastic chocks/wales	**$ 8,000**
5. UHMV polymer panels and bolts	**$ 8,000**
6. Steel wale truss	**$ 8,000**
Total	**$78,000**

Larger, 8 feet diameter by 16 feet long cushions cost approximately $36,000 and would increase the total to $91,000 per station. The estimate does not include costs of demolition and removal of the existing fender system or repairs to the pier fascia to accept the new system. The NFESC recommends that the new fenders be placed at the existing fender stations for fender locations F1 through F7 and at locations F9, F11 and F12 (See Figure 4). Thus, ten fender stations on both sides of Pier 2 would result in a total cost of $1,560,000. The NFESC recommends top priority be given to placing the fendering on the west berth.

A potential problem for the recommended fender system is the effects of wave loading in unprotected water on the cushions and the cushion restraining hardware. Heavier chains and shackles may have to be employed at Pier 2 to better resist the Northeasters. While open exposure presents a risk in using the recommended system, a heavier design is doable. We recommend using 1-3/4 in. stud link chains, 1-3/4 in. shackles, 1 in. diameter bolts, and 1 in. padeye plates to connect the cushion to the pier fascia.

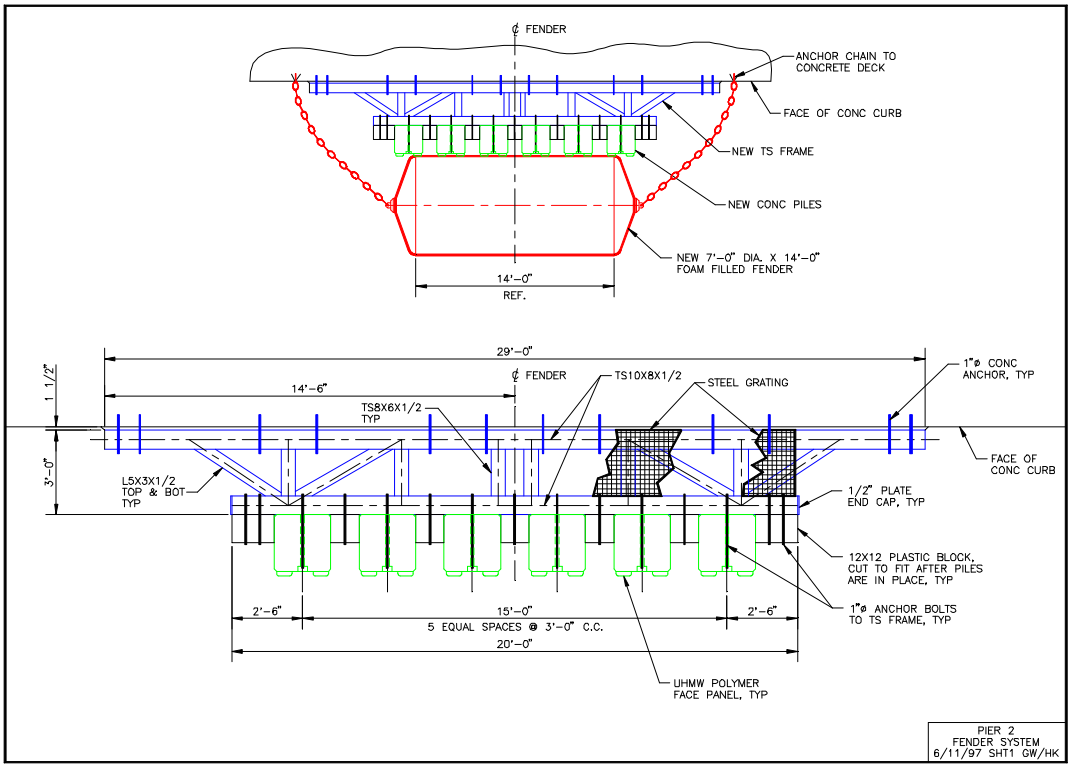

Figure 24. Plan views of proposed foam-filled fender system for Pier 2.

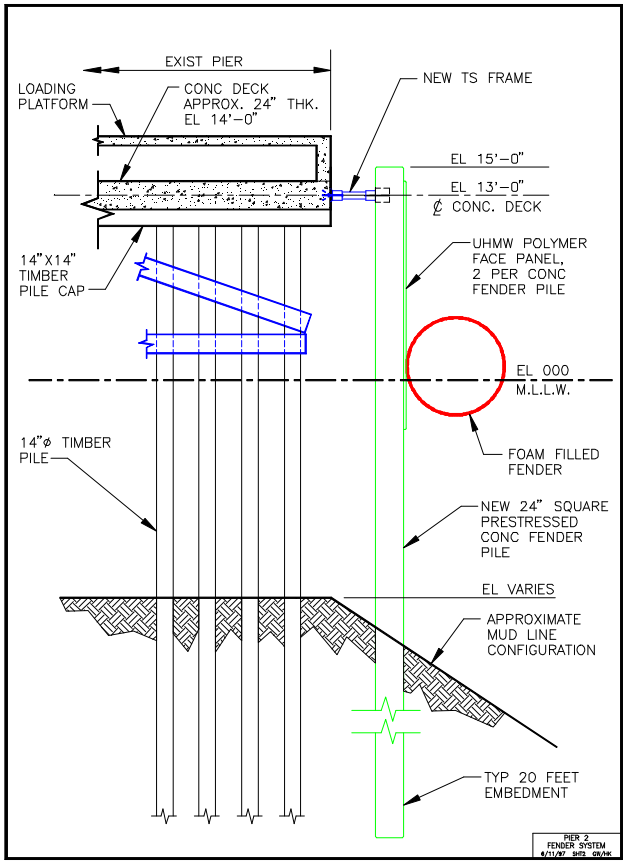

Figure 25. Elevation view of foam-filled fender system.

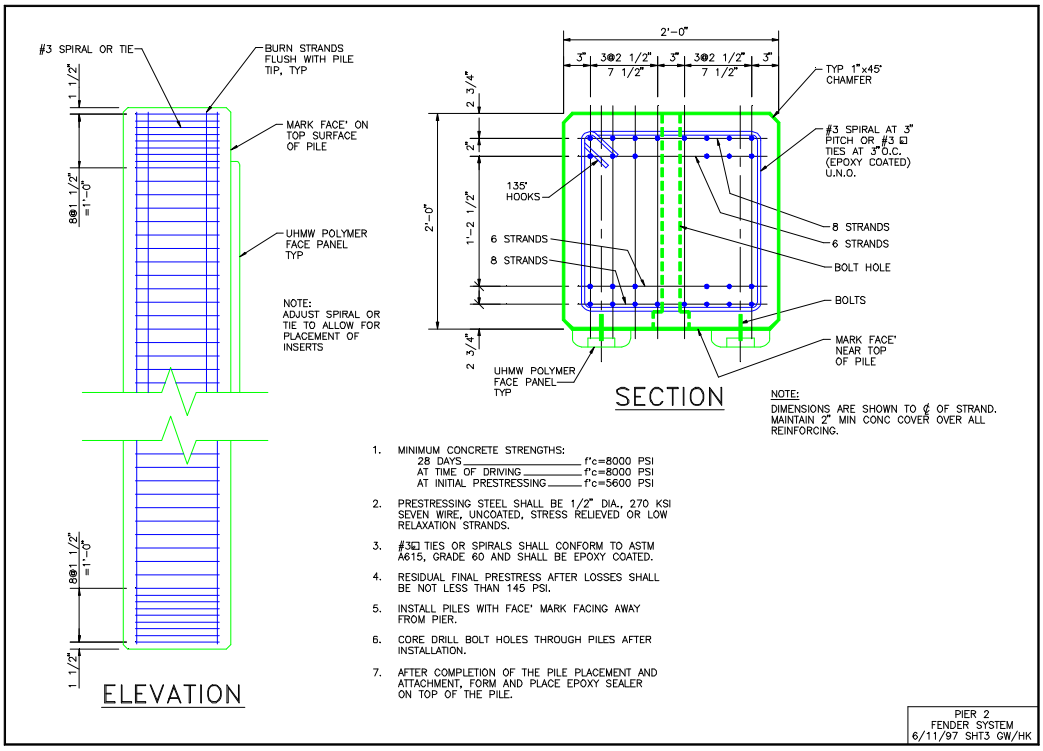

Figure 26. Prestress pile for backing foam-filled cushion.

SUMMARY AND CONCLUSIONS

The Naval Facilities Engineering Service Center (NFESC) was tasked to conduct a structural analysis and condition assessment of Pier 2 and Trestle 2 at the Naval Weapons Station (WPNSTA), Earle. Our structural analysis of Pier 2 concentrated on lateral load assessment with respect to homeporting one and two AOE-6 class ships. The effort included:

- detailed inspection of Trestle 2 and Pier 2 below the deck by Childs Engineering Corporation and reported by NFESC CR-6056-OCN,
- an analysis of lateral loads generated by berthing,
- an analysis of mooring forces generated by wind and current,
- a finite element analysis of the pier response to the berthing and mooring loads as well as dead and vertical live loads,
- design of a foam-filled fender system.

The mooring forces were calculated based on instructions and guidelines of NAVFAC DM 1025.1. The mooring loads were calculated by the NFESC's program, FIXMOOR, which is based on data from NAVFAC DM 26.6 and DM 26.4. Mooring analysis considered the ship being oriented with either the bow seaward or the stern seaward and positioned on either side of the pier. NFESC engineers analyzed the mooring loads produced by winds originating from all directions with emphasis on winds that were directed broadside to the ship, 45 degrees off the bow, and from the northeast. Water currents were directed broadside to the ship, or almost parallel to the shore.

The finite element analysis of the lateral loads was performed with ABAQUS. Our finite element modeling accounted for the condition of the piles, bracing, and connections as determined from the Childs inspection. The berthing and mooring loads were applied at the fender stations and points of mooring fixtures on the finite element models. Concurrently with the lateral forces dead loads plus 500 to 700 psf live load were applied. The higher live load is allowed when the wind velocity is less than 30 mph. Fender and mooring fixture response to lateral loads were compared to the manufacturer's limits of the fenders and current rated limits of the mooring fixtures. Element responses to the lateral loads generated by the finite element analysis were compared to the load limits of the structural members of Pier 2.

Childs reports Trestle 2 to be in good condition. Timber piles are subject to fungal deterioration and some repairs are recommended. Timber bracing is in fair conditions and no repairs are recommended. Two firewalls are missing sections and repairs are recommended. Pilecaps are in good conditions and repairs are not recommended. Childs estimates repairs to Trestle 2 to cost $253,000. Childs does not recommend a reduction in service load on Trestle 2. Lateral load limits of Trestle 2 will have no impact on berthing the AOE-6.

Childs reports the general condition of Pier 2 supporting piles is good. The piles have retained most of the original creosote treatment and are still resistant to marine borer attack. Timber conditions above water reflect deterioration due to dry rot. All connections are severely corroded. Except for bracing, timber elements are functioning without distress as originally intended. Childs recommends repair or replacement of piles with 50 percent or more reduction in original cross section. Repairs are not recommended on timber bracing, firewalls or pile caps. Childs estimates the cost of repairs to Pier 2 to be $280,000.

The "best" mooring position is on the west side to utilize the upgraded mooring fixtures on that side. This position is "best" resisting wind loads and does not consider operational considerations. The NFESC assumes that off loading and loading operations will not commence during strong winds. To protect the ship and the pier structure during strong winds, the ship should be positioned to avoid using the low rated cleats on the south end of the pier. Mooring fixtures 16, 17, 19, 20, and 21 should be avoided on the west side of the pier. There is a higher probability that these would be overloaded for winds from the east and southeast. When positioning an AOE-6 so that the stern line is on fixture 18, the NFESC recommends doubling the lines on fixture 18 rather than using fixture 16 or 17. When positioning the AOE-6 more shoreward with the stern line on Dolphin 22, the NFESC recommends not using the lower rated mooring

fixtures on the south end of Pier 2. Upgrading the mooring fixtures on the west side would remove restricting the positioning the ship to take advantage of the higher rated mooring fixtures.

Two AOE-6 ships cannot be moored simultaneously to Pier 2 with winds in excess of 30 mph without risk of structural damage to the pier. Wind loading on two ships results in excessive forces in the piles and is not significantly improved by additional fendering.

Fendering limits the capacity of Pier 2 to service a single AOE-6. The fendering installed on Pier 2 is maintenance intensive and does not fit the hull of an AOE-6. Due to the hull curvature, only 3 equally spaced stations at most can come in contact with the side of the ship at any given time. This type of fender produces the maximum reaction to the pier because the ship contact point is at the deck elevation. Further, the facing in contact with the ship is prone to heavy damage from padeyes, scuppers and other appurtenances on the ship's hull. Analysis of AOE-6 berthing yields a design berthing energy of 303 ft-kips and a maximum impact load of 190 kips on the existing Trellex™ Fenders. The manufacturer's recommended maximum absorption energy for each station at 50 percent compression is 306 ft-kips and maximum reaction is 190 kips. The capacity of the fender system in its present state of repair is very low. **Even so, if the system is repaired to "new" condition or all the best cells are relocated on the west side, then:**

- **AOE-6 berthing impact loads are equivalent to the manufacturer's recommended resistance of the fender and**
- **The reaction from a wind velocity of 30-mph broadside (270°) to an AOE-6 is equivalent to the resistance of the current fender system.**

The NFESC recommends that the existing fendering be replaced by a fendering system consisting of a floating, foam-filled cushion system backed by prestressed concrete piles. The foam-filled cushions float on the water and are below the appurtenances from the AOE-6 hull. The system will be more energy absorbent and the reaction force on the pier structure will be about 30 percent less because the ship/fender contact point on the fender pile at the waterline is separated from the pier reaction point at the deck level With new improved fendering the limiting elements are the mooring fixtures and the pile supports. With a 0.9 knot current, the limiting wind velocity is 60 mph applied broadside (90° and 270°) and from 315° to the AOE-6 berthed on the west side. The pier response will be within the limits of the mooring fixtures and the lateral capacity of the pier bearing and batter piles. Resistance to easterly winds on the west berth is limited by the strength of mooring fixtures and the pile supports while resistance to westerly winds is limited by the fendering system. Northeasterly winds are resisted on the east berth by the fendering while low rated mooring fixtures restrict resistance to westerly winds. Upgrading the east berth mooring fixtures to the level of those on the west berth would improve resistance to westerly winds and could bring the east berth resistance level up to that of the west berth.

The cost of the fender system upgrade is $78,000 per fender station. Ten stations for the west side of Pier 2 would cost approximately $780,000. If the east side is upgraded the cost will double. The cost estimate does not include demolition and removal of the current fender system.

We found from the finite element analyses that the single most important factor governing the response of the pier structure is the slenderness or unbraced length of the piles. Any planning for future dredging to increase draft must take into account that allowable load is a function of the unbraced length, squared. For example, an increase in draft of 5 feet will decrease the allowable pile loads by approximately 25 percent and an increase of 10 feet decreases the allowable by 40 percent. Further, if the bracing is not replaced and properly maintained, the allowable pile response is cut by more than 40 percent. **Pile bracing should be maintained**. Even though the braces do not transfer significant forces, they serve an important function to decrease the unbraced length of the piles. Repair and maintenance costs for the bracing are not included.

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