Development and Design of Flexible Dolphins
for Jumbo Vehicle Ferry Vessels

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Abstract

To meet the demands of increased commuter traffic on the inland waters of Puget Sound, the Washington State Ferry System (WSF) has initiated a program of building faster and larger ferry vessels. The most recent addition to the fleet is the *Jumbo Mark II* class of vessels. The introduction of these larger vessels has required that many ferry terminals be upgraded.

BERGER/ABAM Engineers Inc. and WSF studied the challenges of accommodating the larger vessels at the existing terminals. One area of concern was the existing dolphins at the terminals. Generally, the existing dolphins were either timber or steel cluster pile dolphins or floating timber dolphins. These dolphins were not positioned to effectively accommodate the new mix of vessels; and, in many instances, the dolphins' capacity to absorb an accidental impact from the larger vessels was not adequate.

Many dolphin concepts were considered for replacing the existing dolphins. The new dolphin had to meet the WSF's requirements for an economical dolphin capable of resisting large impacts and soft and flexible during light impacts for passenger comfort. The dolphin concept selected for use was a flexible steel pile dolphin using buckling rubber fender elements. The dolphin absorbs impact energy primarily through collapse of the rubber fenders and cantilever bending of the plumb reaction piles.

Analysis and design of the new dolphins required development of methods to model the complex interaction between the fender piles, fender elements, diaphragm, reaction piles, and soils. Each element contributes to the total energy absorbed during each impact condition, but at different proportions depending on element properties, tidal conditions, soil conditions, and magnitude of the impact.

Construction of the dolphins has proven to be relatively straightforward. Much of the fabrication is done in the shop, and the design details have proven to be efficient and reasonably easy to build.

Introduction

WSF currently carries over 26 million passengers per year. Because of growth in the Puget Sound area and the desirability of living on Puget Sound's many scenic islands and visits to the Olympic Peninsula, ridership on the ferry system has doubled since 1975. Some routes have experienced a 300 percent increase in passengers. To meet the demands of increased vehicle traffic on Puget Sound, WSF has maintained a program of building faster and larger ferry vessels. During the 1950s, *Steel-Electric* and *Evergreen State* class of ferries had a capacity of 75 to 100 cars and 600 to 1,200 passengers. These vessels were 76 to 95 meters (250 to 310 feet) long and displaced approximately 1,200 to 1,800 metric tons (1,180 to 1,770 long tons). Today, the most recent addition to the ferry fleet is the *Jumbo Mark II* class of vessels that can carry up to 218 vehicles and 2,500 passengers. These vessels are over 140 meters (460 feet) long and have a displacement of 6,280 metric tons (6,180 long tons).

The introduction of these larger vessels into the fleet, plus the increased use of other large vessels on ferry runs that formerly used smaller vessels, has required that many ferry terminals be upgraded to handle the larger vessels and increased traffic. One area of concern at the terminals was the existing breasting dolphins.

Figure 1 shows the typical layout of a ferry slip with the outlines of three different types of ferry vessels at the slip. During relatively calm weather, the ferry vessel enters the slip at a low rate of speed and the bow is brought against the wingwalls at the end of the slip. The vessel then lays against the dolphins on the right or left side of the slip to maintain position during loading and unloading of vehicles and passengers. However, because calm weather conditions are not always the case, vessels also rely on the dolphins to guide them into the slip and act as safety barriers to keep the vessels from entering shallow water or from hitting other structures.

Design Criteria Development

The general design philosophy adopted by WSF for dolphins has been to avoid damage to the ferry vessel. This "Save the Vessel" philosophy is not only to protect the safety of the passengers, but also to avoid the inconvenience to the public that occurs when a vessel must be

taken out of service for repairs and the high cost vessel repairs. Three classes of impacts are considered for dolphin design. They are as follows.

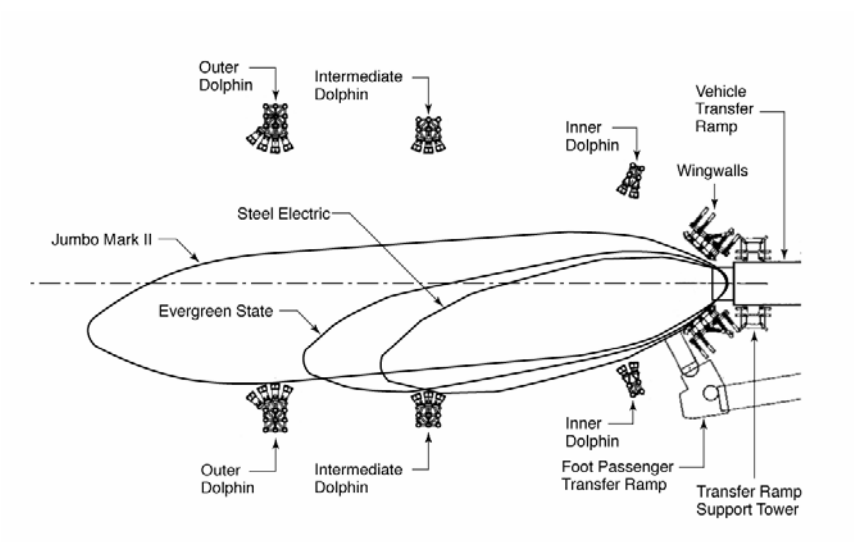

Figure 1: Typical Slip Layout

Type I Impact	No Damage — Dolphin should perform adequately for most berthing events throughout its entire service life. Repairs are limited to normal maintenance.
Type II Impact	Repairable Damage — Dolphin may be damaged by unusually hard berthing events. Repairs are limited to replacement of a portion of the dolphin system. The system may be analyzed to identify probable repair requirements, and contingency plans may be made to accelerate the repair process.
Type III Impact	Catastrophic Damage — Dolphin fender system and its supporting structure may fail during a catastrophic occurrence. If structure yields sufficiently, deceleration forces are limited as vessel is brought to a stop. This would limit injuries and vessel damage. An example of a catastrophic occurrence would be propulsion failure as the vessel applied reverse thrust to stop.

Based on the classifications outlined above, design impact scenarios were developed to determine the design energy for each dolphin, outer, intermediate, and inner. Because the vessels are slowing as they enter the slip, dolphin design energy drops the closer a dolphin is to the wingwalls. Design energy also varies with the type of vessels using the slip. Studies were performed to determine berthing scenarios for the ferry vessels. These scenarios were then used to determine likely interactions between the vessels and dolphins and, thus, develop energy absorption criteria for the new dolphins. Catastrophic scenarios, or conditions where the dolphin could be allowed to fail, were also established. Possible impact angles, vessel speed, and vessel types were all considered in developing energy absorption criteria. Dolphin layout was also

studied to determine the optimum dolphin locations to accommodate all vessels using the terminals. Figure 2 shows a typical impact scenario for an outer dolphin.

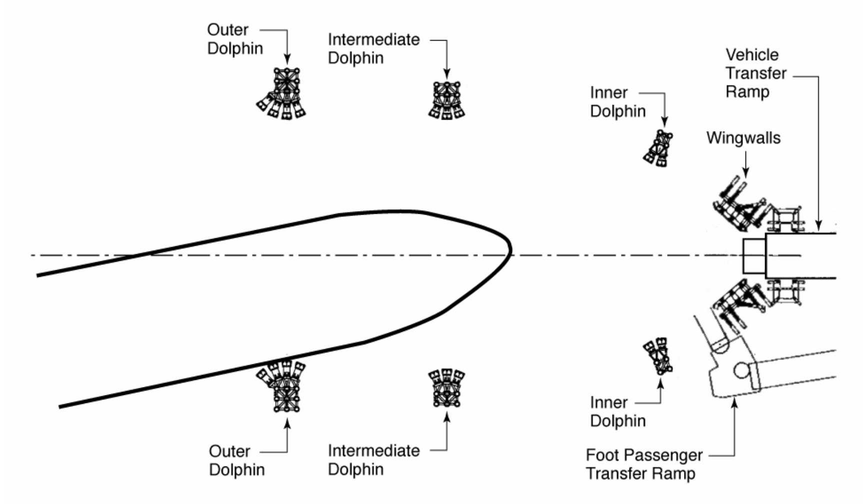

Figure 2: Typical Vessel Impact Scenario

Many scenarios were examined and the worst case was selected for final dolphin design. Considering the *Jumbo Mark II* class of vessels, maximum design energies for a Type I Impact were determined to be:

Outer Dolphin	1,356 kJ (1,000 ft-kips)
Intermediate Dolphin	746 kJ (550 ft-kips)
Inner Dolphin	300 kJ (222 ft-kips)

Dolphin Development

Generally, existing dolphins at the ferry terminals were either timber or steel cluster pile dolphins or floating dolphins. At some terminals, the dolphins were not positioned to effectively accommodate the new mix of ferry vessels using the terminals and, in many instances, the dolphins' capacity to absorb an accidental impact from the larger vessels was not adequate. Figure 3 is a photograph of some typical timber cluster pile dolphins.

Many dolphin concepts were considered for replacing the existing dolphins. The new dolphin had to meet the requirements for energy absorption and had to be economical to construct, capable of resisting large impacts without damaging the ferry vessels, and, at the same time, be soft and flexible during light impacts for passenger comfort. Concepts considered included rigid dolphins with a flexible fendering system, large cluster pile dolphins, floating dolphins, and flexible pipe pile dolphins.

A rigid dolphin with a flexible fender system is shown in Figure 4. This system is similar to a fendering system on a fixed dock or wharf. The energy from an impact is dissipated by the fender piles and rubber fender elements on the face of the dolphin. This system was found to be capable of absorbing the required energy. However, when elements were sized for the desired energy absorption, the system was stiff and not very flexible during a light impact scenario. Also, once the fender system had collapsed during a Type III impact, the system became very rigid and would likely damage the vessel. Repairs to fixed portions of this dolphin would also be difficult to perform.

Figure 3: Typical Timber Cluster Pile Dolphins

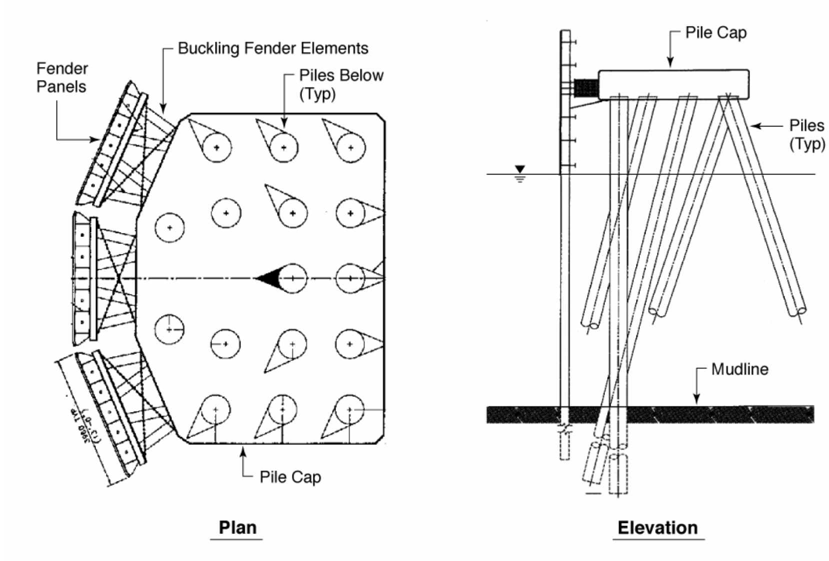

Figure 4: Rigid Dolphin with Flexible Fender System

To meet the demands of increased commuter traffic on the inland waters of Puget Sound, the Washington State Ferry System (WSF) has initiated a program of building faster and larger ferry vessels. The most recent addition to the fleet is the *Jumbo Mark II* class of vessels. The introduction of these larger vessels has required that many ferry terminals be upgraded.

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Many dolphin concepts were considered for replacing the existing dolphins. The new dolphin had to meet the WSF's requirements for an economical dolphin capable of resisting large impacts and soft and flexible during light impacts for passenger comfort. The dolphin concept selected for use was a flexible steel pile dolphin using buckling rubber fender elements. The dolphin absorbs impact energy primarily through collapse of the rubber fenders and cantilever bending of the plumb reaction piles.

Analysis and design of the new dolphins required development of methods to model the complex interaction between the fender piles, fender elements, diaphragm, reaction piles, and soils. Each element contributes to the total energy absorbed during each impact condition, but at different proportions depending on element properties, tidal conditions, soil conditions, and magnitude of the impact.

Construction of the dolphins has proven to be relatively straightforward. Much of the fabrication is done in the shop, and the design details have proven to be efficient and reasonably easy to build.

Figure 5 shows a 200-pile dolphin (salt-treated piles), otherwise similar to the existing dolphins (except creosote-treated piles) at many ferry terminals. The advantages of conventional timber cluster pile dolphins are soft vessel impact characteristics and low technical risks, as both structural and maintenance behaviors are known based on previous WSF experience. The disadvantage of timber is the poor environmental performance of creosoted piles used in the past. As manufactured in the past, creosoted piles leached creosote into the water, which was unacceptable environmentally. The leaching issue led to a propensity of all state and federal users to change from timber to piles of other materials. WSF adopted a policy of not building with timber piles in the water. Also, permitting agencies actively discouraged use of treated timber piles. Since then, new manufacturing procedures have controlled creosote leaching to acceptable levels. Creosote is, thus, theoretically permittable. However, permitting creosote treated piles is uncertain, and likely to take much longer than usual permit review/approval times.

There is an alternative to creosote, which is to pressure treat with metallic salts. This eliminates the creosote and permitting concerns. Salt-treated piles cost about 25 percent more than creosoted. Also, their life is reduced from approximately 25 years for creosote to 15 years for salt-treated piles. This is not a defect for fendering structures, which are expendable, and temporary by nature. However, life-cycle cost analysis indicated this type of dolphin, due to the expected frequent maintenance and shorter life, to cost over 50 percent more that steel pile alternatives.

Cluster pile dolphins constructed with steel pipe piles offered the same advantages as the timber cluster pile dolphin and the additional benefit of requiring fewer piles. However, because of the concentrated wear points at the location where the vessel impacts the pile, frequent fender pile replacement was anticipated with associated high maintenance cost. This made the life cycle cost of the steel cluster pile dolphin higher than the selected alternative.

Figure 6 shows a slip cross section with a floating dolphin and anchors. Performance of floating dolphins is dependent on their anchoring systems. Typical permanent systems use a number of

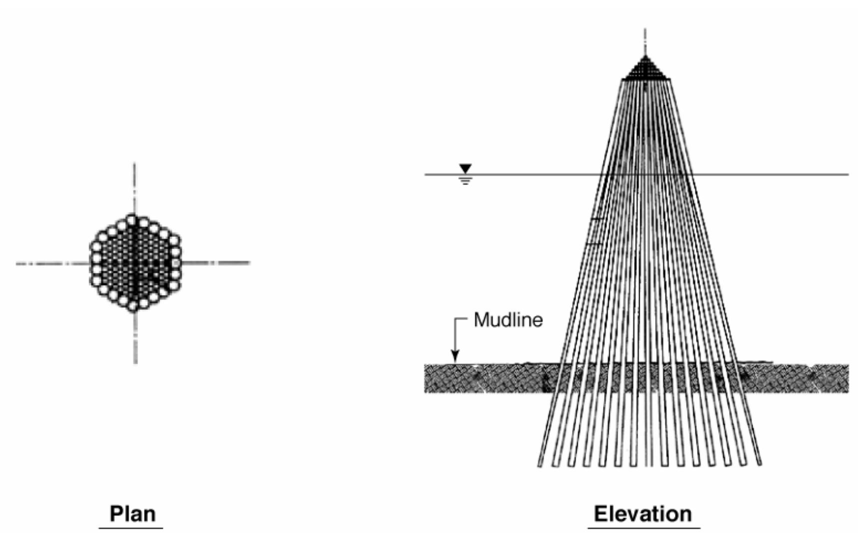

Figure 5: Cluster Pile Dolphin (200 Timber Piles)

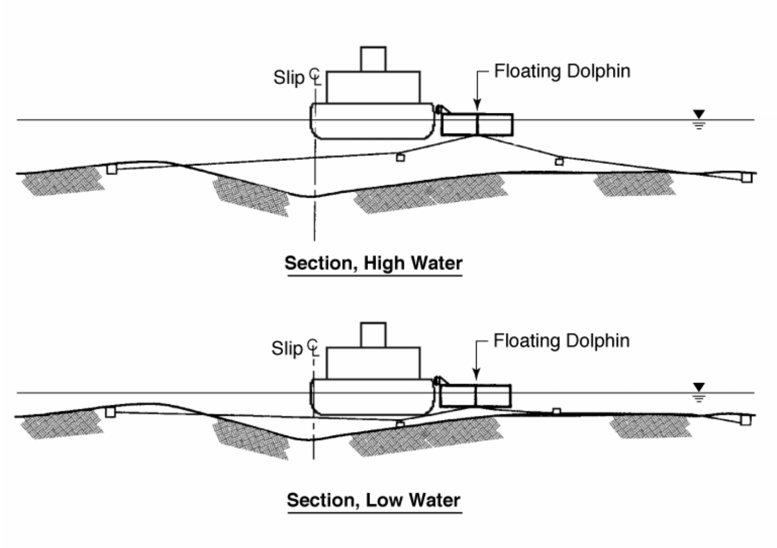

Figure 6: Slip Cross Sections with Floating Dolphin

heavy chains, fixed to the bottom at the far end by concrete gravity sled, ship, or pin-pile-type anchors. The chain is designed long enough so that at highest water level and maximum float excursion, the chain does not lift off the bottom near the anchor, thus assuring the anchor is not pried up and out of the bottom.

This system tends to be very compliant (float motions largest) at lowest water level, as the chain lays down on the bottom, allowing the chain angle up to the float to be more vertical. Clump weights (sinkers), installed in the middle of the chain, are often used to stiffen up the system. It is preferred to locate the clump weights such that they are suspended under all tide conditions. This simplifies the analysis and gives greater confidence in how the floater will respond to external forces.

In shallow water situations, the clump weight can be designed to sit on the bottom and act as an intermediate anchor. However, under extreme forces, the clump weight will pick up to allow greater excursions and energy absorption. The analysis of this type of mooring arrangement becomes much more complicated, with lower confidence in the ability to predict float responses. Conditions favoring good anchor systems include a level bottom with good anchor holding characteristics, and with water deep compared with changes in water depth or float draft. Also important is being able to place anchors a sufficient distance from the float. Mooring line slopes, which is the ratio of horizontal distance to water depth, should be in the 6 to 8 range to avoid significant uplift at the anchor or increase in pretension forces due to tide variation. At many of the terminals, varying bottom conditions would have made use of floating impractical. Also, the high cost of construction was estimated to be over three times higher than the selected alternative. Life-cycle costs were similarly higher.

Working closely with WSF staff, BERGER/ABAM developed a dolphin concept for a flexible steel pile dolphin using buckling rubber fender elements. This concept evolved from a dolphin concept using steel pipe piles fixed at the bottom and pinned at the top. Large diameter fender piles faced with ultra high molecular weight (UHMW) polyethylene are placed on the sides where vessels would impact the dolphin. This type of dolphin is shown in Figure 7. The piles acted as “flagpoles” absorbing energy by bending. This dolphin was found capable of absorbing

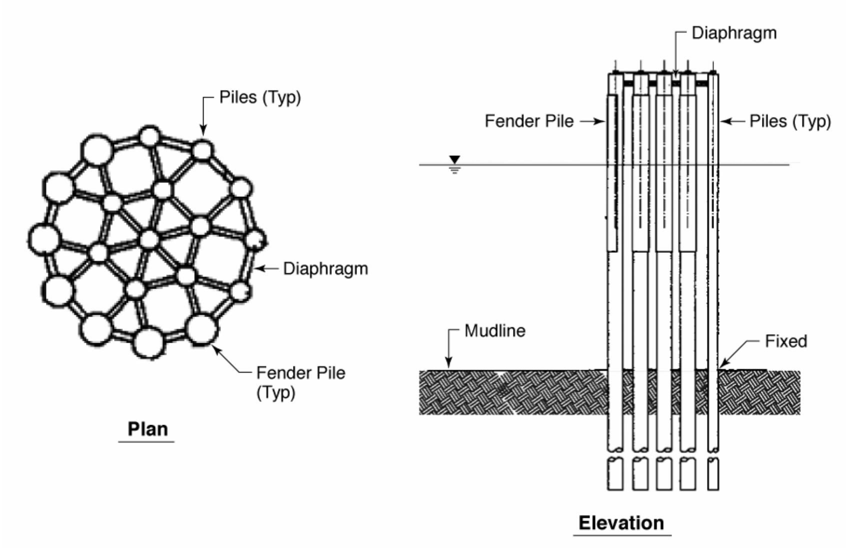

Figure 7: Plumb Pile Dolphin

the energy required, but was somewhat stiff under lighter impacts. To gain flexibility during light impacts, buckling rubber fender elements were added between the fender piles and the dolphin diaphragm. The dolphin absorbs impact energy primarily through collapse of the buckling rubber fenders and cantilever bending of the plumb reaction piles. Heavy wall steel pipe reaction piles connected by a rigid diaphragm are used to absorb the large energy demand from an accidental impact, up to 1,356 kJ (1,000 foot-kips). Fender piles, with UHMW-faced fender panels, are connected to the diaphragm with large buckling rubber fender elements to provide a soft, flexible restraint when the dolphin is lightly impacted under normal use. This dolphin met the ferry system's requirements and was selected for final design. See Figure 8.

Dolphin Design

The UHMW polyethylene fender panels minimize friction between the vessel and the dolphin and provide an easily replaceable wearing surface. These panels also distribute the impact force to prevent local buckling of the fender pile and minimize stress on the vessel rub rail. The fender

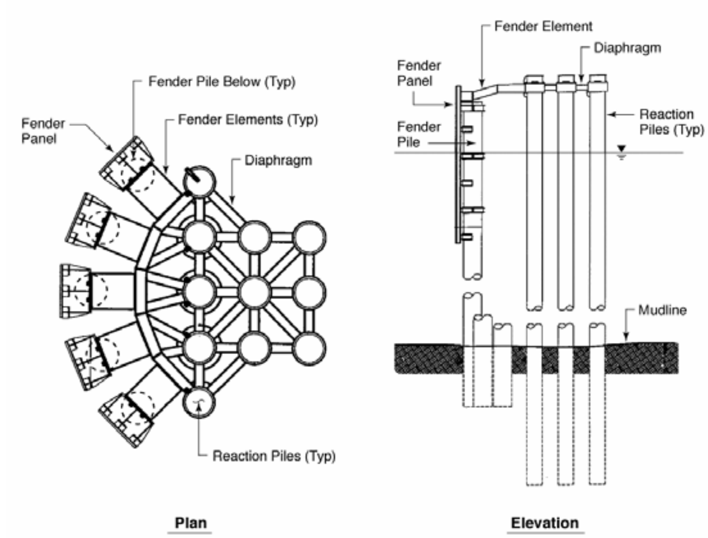

Figure 8: Flexible Steel Pipe Pile Dolphin

panels are connected directly to the rubber fender element at the top to allow them to rotate and conform to the shape of the vessel during an impact. Fender piles are only installed deep enough in the soil to maintain position and are not fixed at the base. This is to minimize stiffness in the fender piles so they can bend and distribute the impact load to the soil below and, through the rubber fender elements and diaphragm, to the reaction piles above. Reaction piles are installed deep enough to develop full fixity. The reaction piles are connected to the dolphin diaphragm at the top with a pinned connection to allow the pile tops to rotate. This increases flexibility of the system and allows large deflections under loading. Depending on the water depth, dolphin deflection under design loading is approximately 1.2 to 1.5 meters (4 to 5 feet).

Varying the number and size of piles and using different fender elements, the dolphin can be modified to accommodate different energy demands due to dolphin location and vessel size. Dolphins using as many as 12 reaction piles and as few as 4 have been constructed. To maximize deflections and energy absorption with the fewest number of piles, high strength steel pipe piles are used. Typically, these piles have a guaranteed minimum yield stress of 415 MPa (60 ksi) and are allowed to approach their yield strength during the design loading.

The failure scenario for the dolphin under a Type III Impact will depend on the manner in which the dolphin is impacted. However, it appears reasonable to assume that the accidental impact will be by impact to the dolphin fender piles first. In general terms, the failure scenario can be described as follows.

Upon accidental contact with the fender system with an impact energy significantly above the design energy, 1,356 kJ (1,000 foot-kips) for an outer dolphin, the dolphin will deflect beyond the point of yield on certain critical piles. Particularly in the case of a high elevation impact, the support piles are the critical elements as the fender piles have a significant amount of reserve capacity for this condition. In the case of a low hit, the fender pile capacities are more closely balanced with the bending capacities of the structural piles. However, calculations indicate that the first yield, even at a low hit, will be by the reaction piles. As the yielding of the structural support piles will be by bending at the base of the piles, a significant amount of soil/structure interaction will occur. It is possible that a certain amount of yielding in the soil will take place prior to yielding in the steel pipe piles. When this soil or pile yielding occurs, the load imparted to the structure remains relatively constant, and other elements will approach or exceed their yield capacities. This process is accompanied by a large deflection of the structure, which will absorb a large amount of energy that in turn will continue to resist the accidental impact. If this is the case, the structure will in all probability rebound partially, but exhibit a permanent set as some of the elements or soil connections have been stressed beyond yield. If the permanent set is not too excessive, it may be possible to continue to use the structure without any repair, although the energy capacity will be reduced. If the structure does not rebound then repairs to the yielded elements may be required. It may be difficult to determine with certainty which of the elements will require repairs. Assuming this can be done, it may be possible to remove the piles, perform the repairs, and reinstall. We believe that, due to the required reaction pile penetrations for fixity, extraction of any damaged piles may be difficult. An alternative may be to cut the damaged pile off at mudline and drive a repair pile adjacent to the old pile. This would also require modification of the diaphragm.

In the case of an extreme accident where the vessel cannot be arrested while the dolphin is still standing, it is expected that the vessel will push the entire structure over as either the piles have all yielded, or the soil has failed. In this instance, the piles will bend over away from the vessel and should pose no great danger to inflict major damage to the vessel. It should be emphasized that a significant amount of energy is required to cause this total failure. Based on calculations considering yield of all support elements, we estimate that the ultimate energy capacity of the outer flexible dolphin is approximately 20,340 kJ (15,000 foot-kips).

Analysis and design of the new dolphins required development of methods to model the complex interaction between the fender piles, fender elements, diaphragm, reaction piles, and soils. The new flexible dolphin is a system of energy absorbing elements. Each element contributes to the total energy absorbed during each impact condition, but at different proportions depending on element properties, tidal elevations, soil conditions, and intensity of the impact. Because of the complexity of the dolphin system, a direct solution for the energy absorbed for each loading condition is not practical and a series of iterations is required to converge on the solution.

To quickly evaluate the performance of different combinations of piles and fender elements and to expedite the design process once elements are selected, a series of spreadsheets and computer programs are used. The LPILE, Version 3.0, computer program is used to analyze the soil/pile interactions, determine depth to pile fixity, pile tip elevations, and develop pile deflection curves for various levels of loading. Microsoft Excel spreadsheets are used to determine load distribution through the fender piles, energy absorbed by the fender piles, fender elements and reaction piles, and the total dolphin energy capacity. The RISA-3D computer program is used to determine final forces in the reaction piles and to analyze the dolphin diaphragm.

Construction

Construction of the dolphins has proven to be relatively straightforward. Much of the fabrication is done in the shop, and the design details have proven to be efficient and reasonably easy to build. Fieldwork consists of driving reaction and fender piles, welding of diaphragm supports and bearings, placing of the prefabricated diaphragm, and placing of the prefabricated fender panels and rubber fenders. Fieldwork to construct one dolphin has been accomplished in as few as five working days. Minimizing fieldwork is important to WSF because many times new dolphins must be installed while the ferry slip remains active.

Conclusion

To date, approximately 20 of the new flexible steel dolphins have been constructed and some have been in service for two years. The dolphins have performed well and only one has required repair. The dolphin requiring repair was an outer dolphin impacted almost directly head-on by a *Jumbo Mark II* ferry attempting a landing during a dense fog. The vessel speed was not known, but the dolphin arrested the forward motion of the ferry without injury to passengers and without damaging the vessel. Damage to the dolphin consisted of three fender piles being displaced, one bent fender panel, and three torn rubber fender elements.

Recently, the first double-sided flexible steel dolphins were put into service at the Kingston Ferry Terminal. This concept uses one dolphin to guide vessels at two side-by-side slips.

The flexible dolphin design is a radical departure from any dolphins WSF had previously used. WSF was actively involved in the design process and assisted in the selection of materials and methods of construction. WSF's experience with ferry vessel operations and terminal construction was invaluable in developing the new dolphin. We anticipate that as service experience with the dolphins is gained, the design will be improved and modifications developed to minimize maintenance and repairs.