LARGE DIAMETER FRP MONOPILE DOLPHIN SYSTEMS FOR FERRY BERTHS

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1. INTRODUCTION

The Jamestown-Scotland Ferry is a free vehicle ferry that carries Virginia State Route 31 across the James River near Williamsburg, Virginia. Ferry service was established in 1925 and has been operated by the Virginia Department of Transportation (VDOT) since 1945. The ferry operates 24 hours a day, 7 days a week, and currently transports nearly a million vehicles across the river per year. The ferry berthing slips are primarily divided with timber pile cluster dolphins used to guide the ferries to dock. The ferries bump into the dolphins when off course and the dolphins redirect them into the slip.

2. GENERAL FACILITY DESCRIPTION

Since the original structures were built circa 1925 the docking facilities in Jamestown and at Scotland Wharf have undergone significant structural modifications to accommodate increasing demand. The modifications include structural repairs, facility expansion, and whole scale structural replacements. The Jamestown Ferry terminal was increased from a single slip dock to two ferry slips (Main and Auxiliary), divided by 27 dolphins arranged in three rows. The Scotland Wharf terminal was expanded from a single slip to five slips (Main, Working Lay, Lay, Auxiliary, and Mooring) divided by 54 dolphins arranged in five rows. Both slips at the Jamestown terminal are used for regular loading/offloading of traffic via steel frame movable transfer bridges. Three slips at the Scotland Terminal are used for loading/offloading.

Figure 1: Jamestown docking facility

Typical dolphins at the ferry terminals consist of timber pile clusters wrapped with wire rope and fitted with timber rubbing aprons. Some timber aprons have low friction pads bolted to the timber faces. The head and end dolphins at the vehicle loading slips are stone filled sheet pile with cast concrete caps (three head and three end dolphins on the Jamestown side and four head and four end dolphins on the Scotland side). Head dolphins for all 5 vehicles loading slips are fitted with energy absorbing fender assemblies with ultra-high-molecular-weight polyethylene (UHMW) low friction pads.

A review of historic construction documents dating back to 1956 confirms that dolphin repair and replacement has been a regular occurrence for the life of the facility. At least 20 dolphins have been replaced since 2008. Future dolphin replacements are anticipated to be required at a rate of 4 to 5 every year. The dolphins that require continuous repair and replacement are confined exclusively to the Jamestown and Scotland working slips. The timber dolphins lining the less frequently used lay slips do not exhibit the same premature failure as the working slip dolphins.

Figure 2: Scotland wharf docking facility (Courtesy of VDOT)

3. BACKGROUND AND PURPOSE OF STUDY

In 2014, on behalf of VDOT, WRA initiated a study and design for phased replacement of the existing timber pile dolphins for the Jamestown-Scotland Ferry. The focus of the study phase was exploration of various dolphin replacement options with the goal of reducing the frequency of dolphin replacements and system maintenance costs. The study phase included the following:

- Evaluate current dolphin failures
- Define typical and maximum impact energy absorbed by dolphins during vessel berthing
- Define available dolphin replacement options and fender products
- Determine and compare the performance of each dolphin type based on preliminary analysis
- Evaluate the initial and life cycle cost for each replacement option

Based on results of the study a recommendation was made for a replacement system to be developed into construction documents through the design phase.

Dolphin Failures

The typical dolphin arrangement used for docking slips on each side of the river is shown in the photos above. The most common dolphins are comprised of 37 timber piles as shown; larger 61 pile dolphins exist adjacent to the head dolphins and smaller 19 pile dolphins divide secondary slips at the Scotland terminal. The general condition of the dolphins varies from the extremes of newly installed to severely damaged and in need of full replacement. Dolphins in heavier used areas showed the most damage. From observations above the water surface, environmental degradation appears to be secondary to impact damage.

The condition of piles below the water line was assessed by observing piles removed during a regular dolphin replacement contract. Each of the pulled piles (approximately 20) showed fractured ends where the pile was overloaded to failure. The fractured pile ends were probed with a screwdriver and environmental deterioration was not noted. The fractured ends are visible in Figure 4. Field observations, supplemented with discussions with ferry operators and structural calculations, indicate that the 37 timber pile dolphins do not have sufficient energy absorption capacity to resist higher magnitude vessel impacts over a reasonable period of time. Sufficient strength capable of enduring light ferry impacts may exist; however, higher energy impacts that occur regularly cause one or more piles to fracture within the dolphin. Dolphins with fractured piles have less strength and are susceptible to further damage at an increasing rate.

Figure 4: Broken pile fractured ends

Figure 3: Typical dolphin arrangement (Courtesy of VDOT)

Increases in the rate of dolphin failure likely are due to two factors: the increase of ferry vessel size over the life of the system and the resulting increase in energy during vessel-dolphin collisions, and the more brittle nature of chromated copper arsenate (CCA) treated piles compared to the creosote treated piles used in previous decades. CCA treatment is relatively new and was introduced primarily in response to the environmental regulation of creosote treated timber. CCA has a documented effect of embrittling timber, which effectively reduces the timber's energy absorption capacity, and makes piles more susceptible to damage during vessel strikes.

Berthing Energy and Preliminary Analysis

The Jamestown-Scotland Ferry fleet is comprised of four ferries, the Virginia, the Williamsburg, the Surry and the Pocahontas, with capacities ranging from 28 to 70 cars. Although design impact energy is driven by the largest vessel, the Pocahontas, the smallest vessel determines other design factors such as layout and maximum spacing of dolphins. Berthing velocities used for the impact energy analysis represent actual observed velocities measured using GPS. Table 1 summarises dimensions, velocity and tonnage for each of the current vessels. Table 2 summarises the impact energies used during the study. After investigating the anticipated impact angles and approach velocities, a berthing energy of 400 kip-ft was established as the design capacity for the evaluation of dolphin replacement options and for the final design of the selected system.

Preliminary designs were performed for each replacement option to a sufficient level to demonstrate feasibility of the system and to proportion system components for cost purposes. Preliminary analyses considered energy dissipation, initial impact stiffness and maximum dolphin deflection at the target energy. For comparison, analyses were also performed for the existing timber dolphins. It is important to note that the design impact energy 400 kip-ft is much larger than what the existing timber dolphins are capable of resisting. WRA calculated that the existing timber dolphins are only capable of resisting approximately 40 kip-ft of energy before undergoing permanent damage. Therefore, all replacement systems considered would have a significantly higher capacity than the timber dolphins currently in place. During the study phase, analyses of the dolphin options utilised geologic mapping and existing subsurface data from borings performed during causeway and terminal design.

Vessel	Length (ft)	Breadth (ft)	Loaded Draft (ft)	Max Berthing Velocity (knots)	Light Vessel Weight (long ton)	Loaded Vessel Weight (long ton)
Pocahontas	263.4	65.3	11	5.6	1074	1635
Surry	199.4	64.8	9.5	6.6	709	919
Williamsburg	200	64	9.9	not available	709	919
Virginia	152	39	6.5	6.6	300	362

Table 1: Ferry vessel characteristic summary

Dolphin Position	Slip Velocity (knots)	Velocity Component (knots)	Impact Energy (kip-ft)	Design Impact Energy (kip-ft)
Bow at Outer Cells	5.6	2.8	212	423**
Bow at Midpoint	4.6	2.3	143	286
Bow at ¾ Point	3.6	1.8	88	175

1. Energy calculation performed in conformance with International Navigation Association (PIANC) Guidelines for the Design of Fenders Systems: 2002
2. Factor of Safety (FS) = 2.0
3. Horizontal angle of impact α limited to 30 degrees

Table 2: Calculated impact energies for the Pocahontas (largest vessel)

Replacement Options

After preliminary engineering, WRA considered seven distinct replacement options capable of absorbing the design energy while having an increased service life over conventional timber dolphins. The preliminary options were:

- cluster of (19) 16-inch diameter solid polymer piles
- cluster of (37) 16-inch diameter solid polymer piles
- cluster of (19) 16-inch diameter hollow composite piles
- cluster of (37) 16-inch diameter hollow composite piles
- steel monopile with donut fender
- steel monopile with fender panels
- FRP monopile with abrasion resistant surface (48" to 72" diameter)

Through cost comparison and client feedback, four of the initial options were eliminated. Three of the cluster pile options were eliminated based on cost. The steel monopile with fender panel option was eliminated due to cost, large size, and low ability to accommodate the type of glancing impacts characteristic of this application. The three remaining options were developed so that upfront and lifecycle cost estimates could be generated.

FRP Monopile with Abrasion Resistant Surface

The FRP monopile with abrasion resistant surface is the simplest of all the replacement options. There are no moving parts, limited mechanical connections, and minimal field installation work after the pile is driven. The option consists of a large diameter FRP pile with a UHWM or high density polyethylene (HDPE) surface for abrasion resistance. This option relies entirely on the deflection of the pile to absorb energy from vessel impacts. To increase the pile's resistance to crushing when subject to a concentrated vessel strike force, the piles are filled with foam or concrete or have internal FRP stiffeners installed in the strike zone. The UHMW or HDPE abrasion sleeve is slightly oversized and is supported by a shelf. This sleeve is replaceable once the surface has been deteriorated by vessel impacts by using a small crane. Between replacements, the sleeves may be repositioned on the pile to allow more uniform abrasion of the sleeve and prolong its service life.

Steel Monopile with Donut Fender

A 48-inch diameter, grade 60 steel monopile with a floating donut fender was determined to be the optimal steel arrangement. Using a higher strength steel (60 ksi yield stress), a reasonable pile diameter was maintained. The floating donut fender stays constantly aligned with the belting around the ferry vessels, allowing the donut to be much shorter and operate more efficiently.

Among the finalists, the steel monopile with donut is unique as it is the only option with an energy absorbing fender. The other two options rely solely on flexing of the piles to absorb impact energy. Although the fender generates the majority of the maintenance cost for this option, it also presents a number of benefits. With two sources of energy absorption the fender may be tuned to different dolphins to accommodate the lower required impact energies towards the head of the slips. Additionally, the nature of donut fenders is to rotate during a glancing impact. The rotation of the donut allows the fender's contact surface to travel with the vessel, greatly reducing abrasion between the dolphin and the vessel decreasing wear on the dolphin and increasing time between maintenance.

Cluster of (19) 16-Inch Diameter Hollow Composite Piles

After evaluating the composite pile clusters, the 19 hollow piles arrangement was the most favourable. The composite cluster is more flexible than the existing timber dolphins. Under a design level vessel impact, the dolphins will deflect laterally approximately 10 feet and then rebound to plumb. The high flexibility and resulting deflections of this system do not damage the dolphin, however, it is possible that the dolphin will deflect into an adjacent slip, striking a neighbouring vessel.

In addition to the relatively large horizontal deflection during a design level impact, significant relative vertical displacements of the pile heads are also experienced. Though the cluster should initially rebound undamaged, overtime these relative displacements have the potential to work-loose or damage the through-bolts and wire-wrapping holding the cluster together. Frequent re-wrapping and maintenance of connection hardware for dolphins in high impact areas is a concern.

Cluster dolphin deflections can be reduced by increasing to a 37 pile cluster. However, the increase in size nearly doubles the number of required piles and thus the cost of the system. The high cost takes the 37 pile cluster out of contention with the other replacement options.

A photo of a different VDOT fender system utilising small clusters of hollow FRP piles is presented in Figure 5.

Figure 5: Example of hollow composite pile in small clusters with composite timber walers

Performance Comparison of Dolphin Replacement Options

After the primary evaluation and reduction of options, five dolphin replacement options were studied further.

- cluster of (19) 16-inch diameter hollow composite piles
- steel monopile with donut fender
- FRP monopile with abrasion resistant surface - 48" diameter
- FRP monopile with abrasion resistant surface - 72" diameter

The five dolphin replacement systems were analysed and the performance tabulated and graphed. Figures 6 and 7 plot the impact load vs. horizontal displacement behaviour of the final dolphin options. The charted curves terminate at the dolphins' design strength; loading beyond the curves will damage or permanently deform the dolphins. Though they will be permanently damaged and will likely require replacement, the composite cluster and especially steel monopile options are able to absorb significant energy after initial damage and their respective curves in Figures 6 and 7 terminate.

The performance charts demonstrate that all the considered dolphin replacement options are adequate to absorb the design impact energy without damage. As calculated, the existing timber dolphins, are damaged under even light impacts. The charts also demonstrate that the dolphins' behaviour is dependent on mud line elevation. With a deeper mud line, the dolphins are more flexible and are able to absorb more energy before damage. A diagram of the composite cluster option while at its maximum shallow water deflection of approximately eight feet is included as Figure 8.

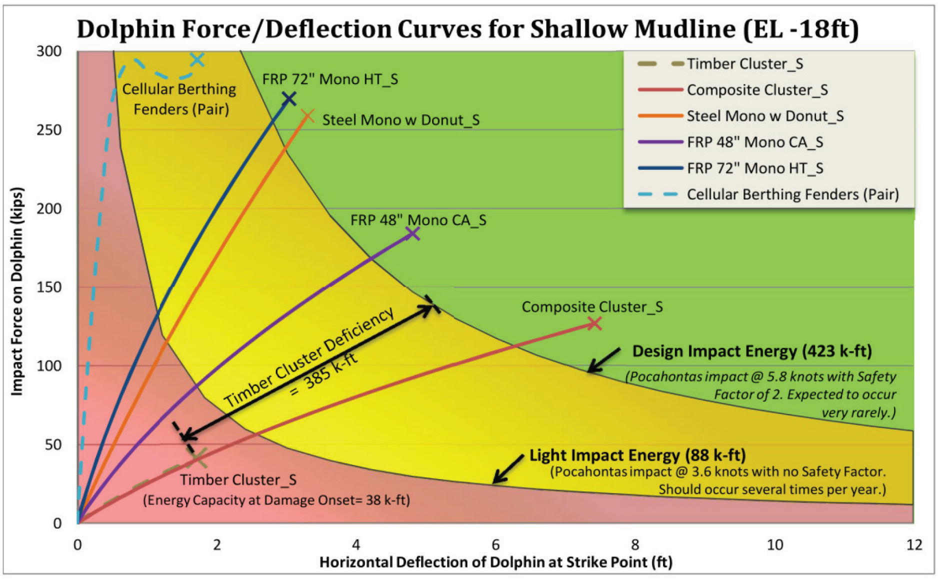


Figure 6: Performance chart of final pptions at shallow mudline

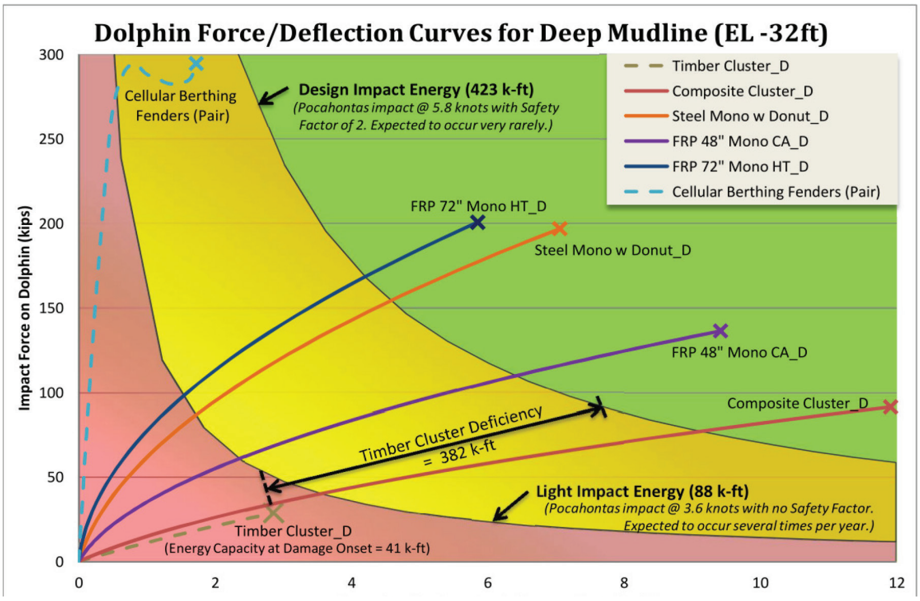


Figure 7: Performance chart of final options at deep mudline

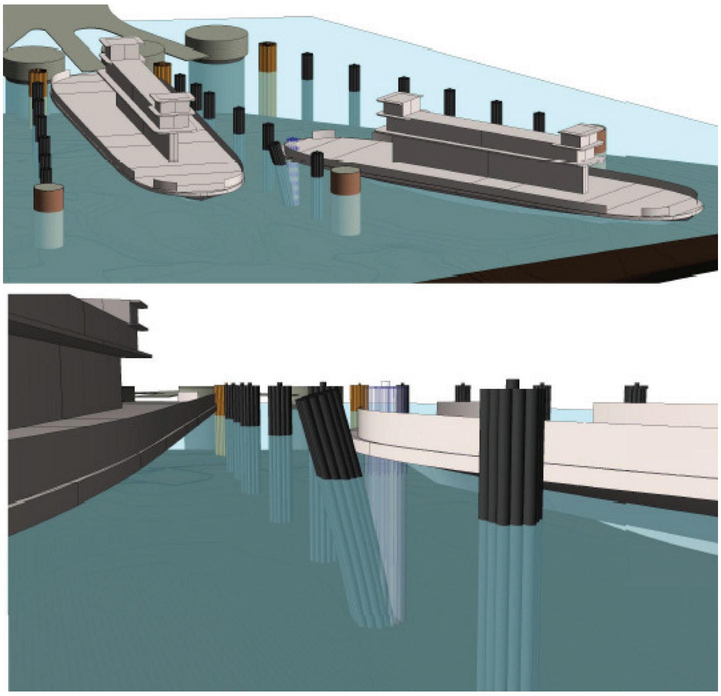


Figure 8: Diagram of composite 19 pile cluster at design deflection

Cost Comparison

For comparison, upfront costs were estimated assuming a one-time full replacement project as described above. Taxes, contractor overhead and profit, bond and escalation were considered in the estimates. All costs were adjusted with area specific material, labour, and equipment factors found in RS Means Building Construction Cost Data. VDOT standard design contingencies and construction engineering and inspection costs were also included. Material costs were obtained directly from suppliers, while RS Means was used to obtain equipment, crew, and labour costs. VDOT's past bid tabulations were used to aid in determining costs associated with removal of the existing timber dolphins, as well as costs of installing new timber dolphins to use for comparison purposes.

A lifecycle analysis approach was used to approximate today's cost of implementation and maintenance of each of the final three options. A total design life of 40 years was considered for each option. Costs for a one-time full replacement of the dolphins were assumed to occur at year zero. For each of the three options, assumed maintenance items were added at 5-year intervals. For comparison purposes, current timber dolphin maintenance costs were obtained from VDOT bid tabulations and considered for the 40-year design life. With direction from VDOT, a timber dolphin replacement rate of five per year was assumed. Figure 9 compares the estimated lifecycle costs for each of the options considered over time. A summary of the lifecycle costs is shown in Figure 10.

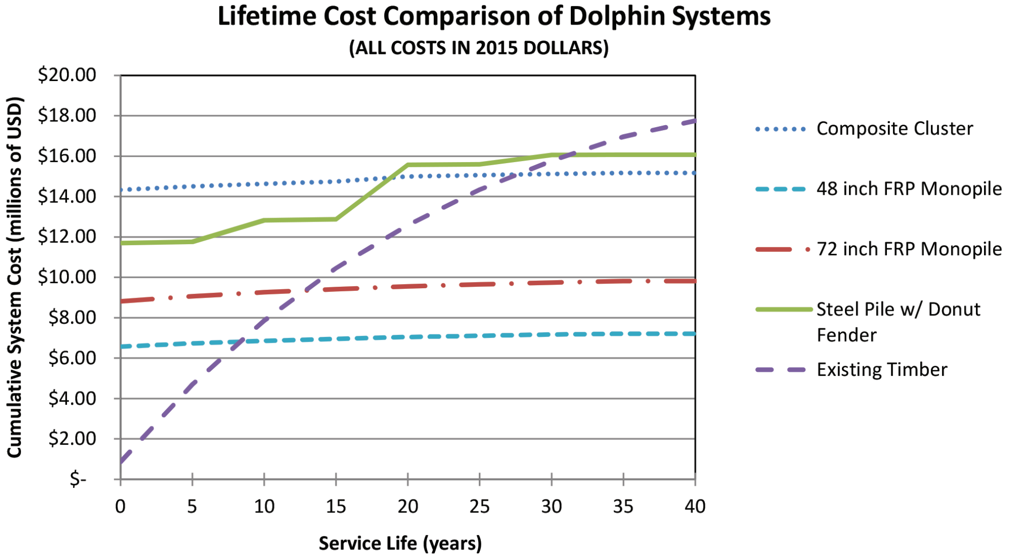


Figure 9: Lifetime cost comparison of dolphin systems

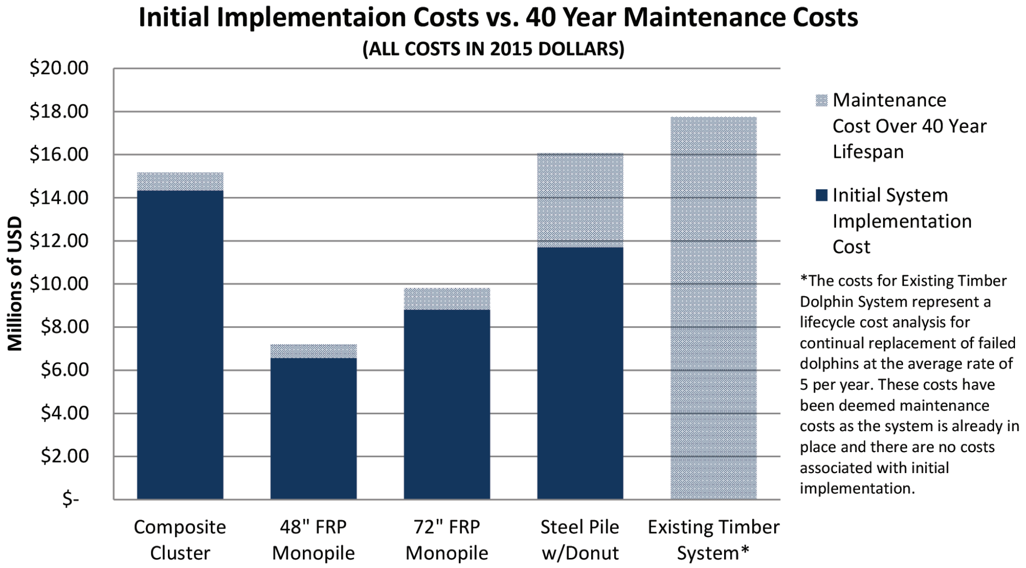


Figure 10: Upfront costs versus 40-year maintenance costs

4. DESIGN PHASE

Based on results of the initial study, VDOT selected the large diameter composite monopile as the replacement option to be fully designed. All three of the final design options were determined to be viable for final design and installation; however, the anticipated life cycle cost of the FRP monopiles was calculated to be only half that of the next least-expensive option. The rationale behind choosing the FRP monopile option was that the savings from reduced first costs and maintenance costs outweighed potentially hidden costs associated with adopting a relatively new system. Even if 50 % of the new FRP dolphins were to require replacement before their expected design life, the overall cost of the system would still be less than the next costly option.

Implementation of Replacement Dolphins

Full replacement of all the working slip dolphins at both terminals requires 34 new FRP monopiles, at a one-time cost of approximately $ 11 million. To fit within the client's annual budget, it was decided to design dolphins for only one ferry terminal at a time. Final design was performed for the Jamestown Ferry Terminal. To further distribute costs, the construction at the Jamestown Terminal was divided into six different phases, each being a separate construction contract to be bid annually. A phasing scheme was developed, optimised to replace dolphins most prone to impacts first while minimising disruptions to ferry operations by keeping replacement work as localised as possible. The average estimated cost per phase is $ 900K.

Furthermore, the new arrangement of dolphins was optimised to reduce the number of dolphins on the Jamestown side from 21 to 17 while improving operations. The smallest current ferry vessel, the Virginia, is to be retired before the end of construction. Following PIANC recommendations, dolphin spacing was increased to suit the next largest vessel, reducing the total number of dolphins required. The new dolphin layout for the Jamestown Terminal is pictured in Figure 11.

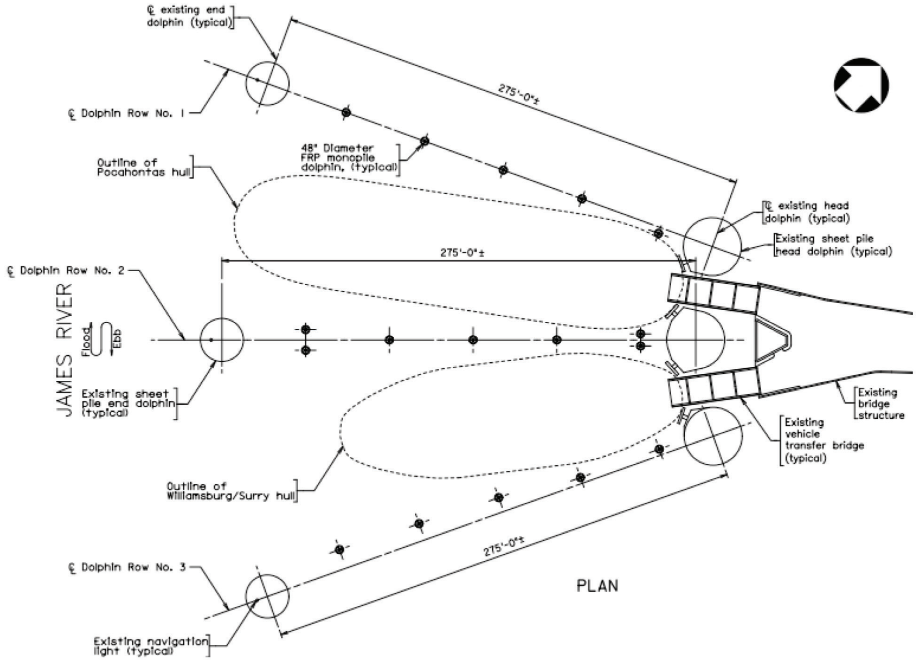


Figure 11: New FRP monopile dolphin layout at Jamestown Terminal working with FRP

The United States based manufacturers capable of producing large FRP monopiles of the necessary dimensions primarily utilise the vacuum infusion process for manufacturing. The vacuum infusion process produces FRP with a high ratio of glass fibres to resin, making high ultimate stresses, on the order of 50 ksi, achievable. The process also permits a high degree of customisation within a single monopile. The high allowable stresses and large pipe wall thicknesses allowed the diameter of the monopiles to be kept within acceptable limits while provided the needed energy absorption capability. Though the same energy capacity can be achieved with even larger diameter piles with thinner walls, the response of the piles would be too stiff when struck by vessels and could hamper ferry operations.

Working with Manufacturers

The properties provided by one FRP Pile manufacturer were used as the basis for the dolphin's design. Close collaboration with the FRP manufacturer was critical, as FRP piles have yet to be standardised like steel and concrete piles. Pile manufacturing processes, and as a result strengths and stiffness vary considerably between producers.

Though the designers worked primarily with one manufacturer, two other manufacturers were identified with the ability to produce dolphins with the same or similar properties to ensure availability and competition. Design decisions were made so the performance requirements were achievable by any of the three manufactures. Dolphin design criteria along with instructions for a competing structural analysis were placed on the contract drawings as means for substituting a competing product. It is critical that the dolphins provided over the phases be consistent in performance and make up. Uniform dolphin construction will permit smoother and more predictable operations of the ferry as well as reduced maintenance costs.

The design benefited from coordination with manufacturers and their FRP production method, vacuum infusion, by being able to vary the orientation of glass fibres along the length of the pile. The glass fibres are what give the FRP nearly all its strength/stiffness. Therefore, altering the fibre orientation allowed pile strength in different regions to be optimised. For example, at the pile's maximum moment region below the mudline, the majority of glass fibres are run in the pile's longitudinal direction to maximise bending strength. Meanwhile, at the vessel impact zone, most of the fibres are run in the transverse direction to maximise pile crushing resistance.

Pile Design at Vessel Impact Zone

Two primary load cases drove the design of the pile at the vessel impact point. The first case is the impulse from the vessel first coming into contact with the pile; the second is when the vessel has displaced the pile to its limit (approximately five feet) and reached the design energy absorption of the system. In the first case, the stationary mass of the pile must be accelerated near instantaneously to the speed of the impacting vessel. The force accelerating the pile is dependent on the vessel velocity, pile mass, and cushioning (stiffness) at the impact point. For most conventional fender velocity, pile mass, and cushioning (stiffness) at the impact point. For most conventional fender systems that are designed with compressible fenders or extra cushioning at the impact point or that are less massive (composite cluster piles), the first load case is generally ignored.

Predicting the response of the pile at the moment of vessel impact was simplified by making a few assumptions: the mass of the pile is insignificant compared to the ferry vessel; only the mass of the top 25 % of the pile acts against being accelerated by the ferry; the resistance of the pile to being accelerated due to flexural stiffness is initially insignificant; the vessel belting is infinitely rigid. After making these idealisations, the scenario becomes a simple elastic collision problem, where the kinetic energy of the bodies is first converted to potential energy associated with a repulsive force between the colliding bodies, then this potential energy is converted back to kinetic energy. This potential energy is created by elastically compressing the HDPE sleeve and pile wall over a small distance. As with the response of the global dolphin absorbing impact energy, a stiffer structural element will result in higher forces but less deflection. To keep the forces within acceptable limits for the HDPE sleeve and vessel belting, the pile wall at the impact point had to remain flexible. Finite element analyses of the pile wall were conducted to predict the crushing stiffness of multiple strengthening concepts, whose results were used to calculate the maximum forces the pile was needed to transfer, see Figures 12 and 13.

To maximise the crushing flexibility of the pile wall in the vessel strike area while maintaining sufficient strength to satisfy load case two, the designers elected to place a slightly smaller diameter piece of FRP pipe within the pile. Any gaps between the two pipes will be filled with a flowable resin to ensure that the interior pipe is engaged to resist crushing of the pile.

Other options the design team considered to increase pile crushing strength was installing interior FRP baffle plates to act as stiffeners as well as filling the pile with foam or concrete. The concentric pipe option was ultimately favoured because the pile wall will tend to flex more with the internal pipe when under load than the donut baffle system or concrete fill. The greater the amount of flex in the pile wall at the impact point, the lower the impact forces in the first load case will be. With the pile concrete filled, the impact forces under load case 1 exceeding those in load case 2 by a substantial margin. By tuning the thickness of the insert pipe, WRA was able to introduce enough flexibility to have the load case 1 and 2 impact forces roughly equal one another. This maximum impact force was approximately 150 kips.

The maximum impact forces were then divided by the anticipated vessel belting contact area to derive the maximum vessel belting contact pressures. These contact pressures were compared against the bearing strength of HDPE and typical acceptable ferry belting contact pressure values to verify that the pressures would not damage the vessel hull or excessively wear the HDPE sleeve.

Pile Design for Energy Absorption

To develop a better subsurface profile and determine soil strength values, additional soil test borings, pressure meter (PMT) and laboratory testing were performed. Table 3 is a design profile for a 25-foot water depth. Lateral pile analyses were performed using LPILE software by Ensoft Inc. Load at the pile- head was increased until the moment developed in the pile was beyond the plastic

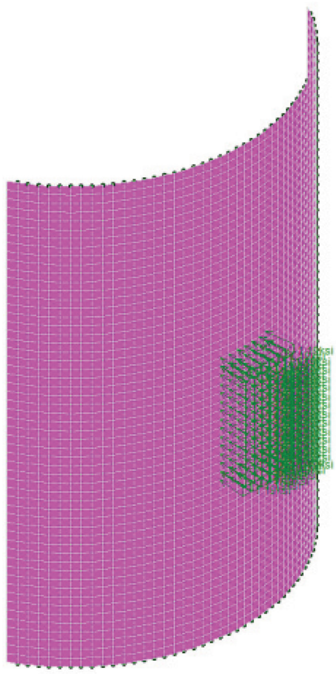


Figure 12: Application of force to FEA plate element model of pile wall (only quadrant of pile shown for clarify)

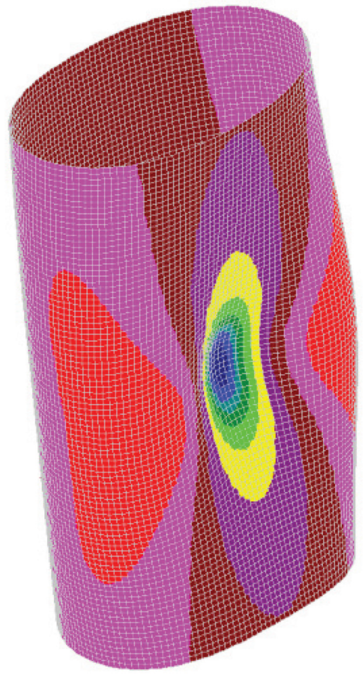


Figure 13: Deflected shape of pile with magnification of 40. Colours are bending stress contours in circumferential direction

moment capacity of the section. The analyses used soil load-deflection (p-y) curves generated from pressure meter test results according to Briaud et al. (1984) and Felio and Briaud (1986). Pile reaction and deflection results from the lateral pile analyses were charted and fit with a hyperbolic curve. The curve was integrated to determine energy dissipation for each increment of increasing deflection. The maximum energy dissipated before reaching the maximum moment capacity for each dolphin pile was determined for the initial (static) and repeated (cyclic) impacts. Figure 14 shows pile reaction and cumulative energy dissipated for the FRP pile and 25-foot water depth.

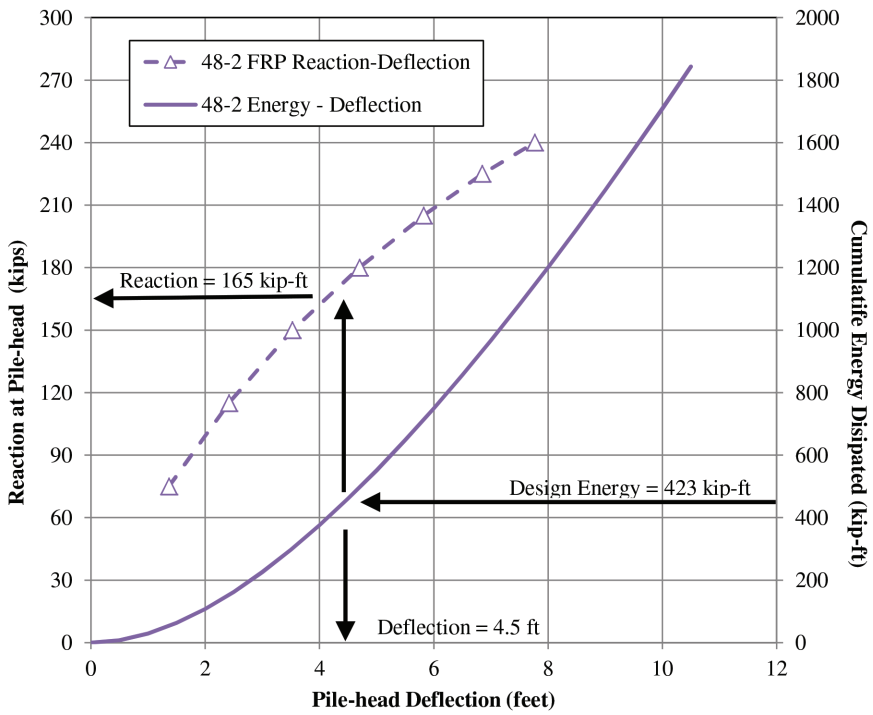
Top of Pile Design

The top of each pile is required to have a mooring device and abrasion resistant sleeve. A sleeve consisting of a large stock-diameter HDPE pipe is placed around the top of the pile. A shop installed FRP shelf around the pile keeps the sleeve in place, and is designed for the weight of the sleeve combined with down drag forces from rocking vessel hulls. The HDPE sleeve is expected to wear out over the course of time and is replaceable. See Figure 15 for elevation view of HDPE sleeve.

Ferry operators regularly moor vessels in the working slips. In the event of mild storm conditions with winds less than 50 knots, for which the mooring are designed, the ferry vessels will be moored in the working slips. Plain mooring posts rather than cleats or bollards were selected to for the ease of attaching and removing lines. Depending on tide, the top of the mooring post can be up to nine feet above the deck of the ferry. The favoured method of removing lines is to jerk them upwards quickly, causing the end at the mooring to flip upwards and off of the post. This quick and easy method would be hindered by bollards with horns and impossible with cleats.

Depth Below Impact FROM-TO (Feet)	Layer Type	Effective Unit Weight, γ (pcf)	Friction Angle, φ (degrees)	Undrained Cohesion, c (psf)	Strain Factor, ϵ_{50}
0 – 5	Impact to Water Surface	--	--	--	--
5 – 25	Water	--	--	--	--
25 – 40	Stiff Clay with Free Water	42.6	0	1000	0.04
40 – 50	Sand	57.6	38	0	--
50 – 105	Stiff Clay with Free Water	47.6	--	2200 – 3600	0.015
105 – 120	Dense Sand	67.6	45	0	--

Table 3: Design profile for lateral analyses – Jamestown Terminal, 25' water depth



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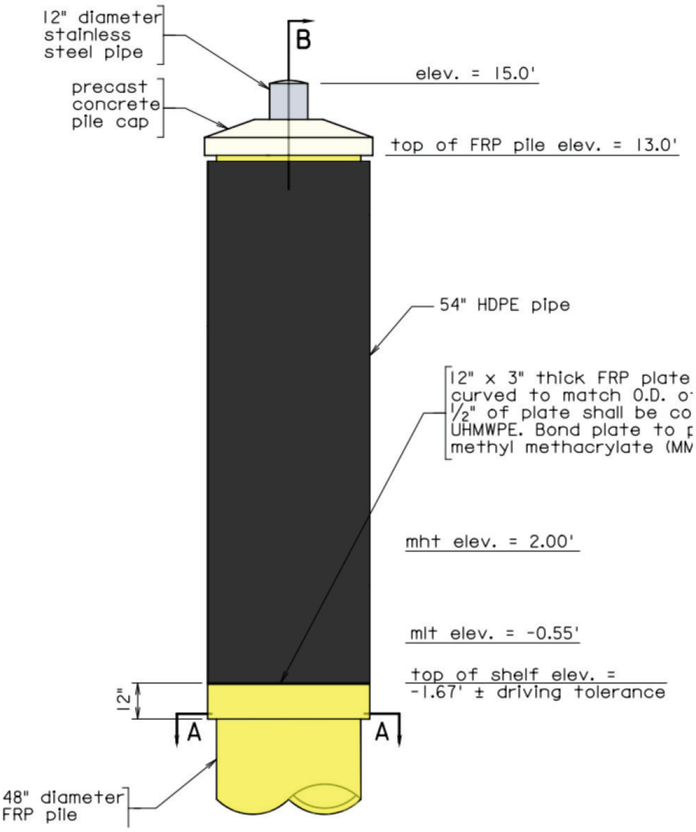

Figure 15: Elevation of pile at top

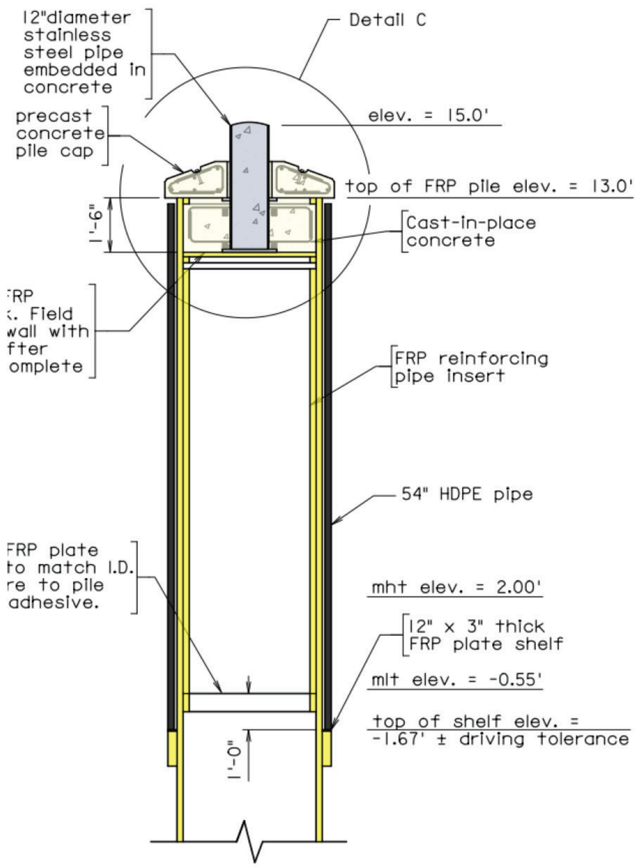

Figure 16: Section through pile at top

An 18-inch thick plug of reinforced cast-in-place concrete is used to anchor the mooring post to the pile. FRP plate ledges adhered to the pile wall interior keep the concrete plug from being pulled out of the pile by mooring forces. The depth of the concrete plug was kept to a minimum to reduce weight and improve flexibility. The concrete filled section of pile has a very high crushing stiffness compared to the rest of the pile in the impact zone. Minimising the depth will prevent vessels from striking near the concrete edge and causing differences in stiffness compatibility between the two sections overstressing the pile wall. The pile is capped by a reinforced precast concrete cone that keeps debris out of the annular space between sleeve and pile. See Figure 16 for section through mooring post and concrete cap.

CONCLUSION AND RECOMMENDATIONS

Design of the FRP monopile dolphins for the Jamestown terminal concluded in 2015 and installation of the dolphins will begin in 2016. FRP monopiles are a burgeoning construction technique with a great deal of potential. WRA found the FRP monopile to be a cost-effective alternative to other steel and composite system for midsize ferry vessels. FRP monopiles could also be suitable for much larger vessels if berthing velocities and geotechnical conditions result in similar energy demands. Additionally, monopiles are well suited to be outfitted with donut fenders, increasing the range of possible applications. The authors recommend that FRP monopiles be included when considering replacement dolphins systems for similar facilities.

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