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Living Docks: Structural Implications and Determination of Force Coefficients of Oyster Mats on Dock Pilings in the Indian River Lagoon

by

Ryan Christiansen

A thesis submitted to the Department of Ocean Engineering and Marine Sciences of Florida Institute of Technology in partial fulfillment of the requirements for the degree of

> Master of Science in Ocean Engineering

> Melbourne, Florida May, 2020

We the undersigned committee hereby approve the attached thesis, "Living Docks: Structural Implications and Determination of Force Coefficients of Oyster Mats on Dock Pilings in the Indian River Lagoon," by Ryan Christiansen.

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Abstract

Brevard County, Florida, is facing rapid population growth and increased pollution entering the Indian River Lagoon (IRL), impairing water quality and damaging the ecosystem. This is problematic not only for public health and environmental stability, but also for the economy. The Living Docks initiative was created to combat environmental degrade in the lagoon and restore natural functions back to the ecosystem. With increased urbanization along coastal systems, there is opportunity for new forms of ecological engineering such as Living Docks, which attaches ovster mats to dock pilings as a means to promote the growth of filter feeding organisms. It is expected that with the addition of oyster mats and biofouling, the forces on the dock piling will increase. In order to analyze the structural effect of the oyster mats as part of Living Docks, a scale model was tested in the Florida Institute of Technology's wave tank. The three main objectives of this study were to: (1) measure forces from a scaled down simulation in a wave tank by use of a strain gauge, (2) determine drag and inertia coefficients from conditions expected in the IRL, and (3) compare calculated forces of Living Docks in the IRL to national design standards. Three phases were tested: a plain piling (phase 1), a piling with a freshly deployed ovster mat (phase 2), and a piling with an ovster mat that has accumulated four months of biofouling (phase 3). Results proved there is approximately a 75%increase in forces by adding an oyster mat to a dock piling, and a 115% increase from a bare piling to one with significant growth. The force coefficients were determined

 $C_d = 1.31$ and $C_m = 1.01$ which can be applied to future designs in any location. There was no indication of hazardous effects on the host dock piling proving Living Docks is a safe and reliable restoration effort that can be easily implemented with any dock.

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List of Variables

Ca	Added Mass Coefficient
Cd	Drag Coefficient
C_{Df}	Friction Drag Coefficient
C _{Dp}	Pressure Drag Coefficient
C _F	Force Coefficient
Cm	Inertial Coefficient
D	Cylinder Diameter
F	Force acting on Cylinder
F _{max}	Max Force
Н	Wave Height
KC	Keulegan-Carpenter's number
l	Length of Piling
m ₁₁	Added Mass
р	Pressure
po	Initial Pressure
r	Cylinder Radius
Re	Reynolds Number
Т	Period
Ú(t)	Horizontal Acceleration Component
U(t)	Horizontal Velocity Component
Um	Max Velocity
ρ	Density
$ au_{ m w}$	Shear Stress
υ	Kinematic Viscosity
\forall	Volume of Displaced Fluid

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1.0 Introduction

The Indian River Lagoon, on Florida's east coast, is significant as a cultural, economic, and environmental resource. However, this large estuary is undergoing major changes that result in fish kills, algal blooms, and detrimental muck accumulation. The Indian River Lagoon, IRL, is a 156 miles long estuary spanning 6 counties, and makes up 40% of Florida's eastern coastline, see Figure 1 (Lapointe et al. 2015). With 3 major water bodies (Mosquito Lagoon, Banana River, and the Indian River) and a limited number of inlets (5) open to the Atlantic Ocean it is classified as a restricted estuary (Smith 1993) and is heavily impacted by anthropogenic and natural inputs. Current attention is focused on restoring natural functions lost due to accumulation of pollution and excess nutrients.



Figure 1: Indian River Lagoon and Inlets

In 2016, Brevard County implemented a tax, half a cent to every dollar, to fund the restoration of the IRL. It is projected to collect 494 million dollars over 10 years, with over 100 million already invested into restoration projects (Tetra Tech 2020). Between the Mosquito Lagoon, Banana River Lagoon, and Indian River, 71% of the Indian River Lagoon's area is surrounded by Brevard County alone (Tetra Tech 2020). Increased development has resulted in additional storm water runoff, wastewater, and fertilizer use which results in excess nutrients and sediments entering the Lagoon (MRC 2018; Grizzle et al. 2002; Weaver et al 2018). These excesses lead to detrimental effects such as algal blooms and the accumulation of muck which makes the lagoon floor inadequate for benthic creatures (MRC 2018; Grizzle et al. 2002; Weaver et al 2018). Efforts to remove the muck and decrease excessive nutrients entering the Lagoon are ongoing. Economically, there is a \$2 billion window of profit resulting from the IRL being restored and an estimated \$4 billion worth of damages if ignored (Tetra Tech 2020). Areas that are at risk due to the decline of the health of the IRL include tourism, recreation, property value, commercial fishing, and the health of residents and tourists along the IRL (Tetra Tech 2020). The "Save Our Lagoon" plan allocates the money raised from the tax and outlines the actions and steps to restore the Lagoon. Many of these projects include fertilizer management, septic and sewer system upgrades, storm water treatment, muck removal, ovster restorations, and living shorelines (Tetra Tech 2020). The

experiment discussed within this thesis is dedicated to help restore the Indian River Lagoon and analyze a current oyster restoration project underway in the Lagoon.



Figure 2: North IRL Habitat and Water Quality Report (MRC 2018)



Figure 3: South IRL Habitat and Water Quality Report (MRC 2018)

Figures 2 and 3 above are provided by the Marine Resource Council (MRC), which conducted a water quality and habitat report of the IRL in 2016. Sections of the Northern and Southern IRL span along Brevard county have considerably low-quality scores (MRC 2018). Banana River, North IRL, and Central North IRL have grades of poor to very poor especially in the Northern region which is caused by minimal lagoon flushing (MRC 2018). There are only two inlets located in the Northern Region that are 100 miles apart, which means the solution to the problem is reducing pollutants entering the lagoon and introduction more filtration systems that have been destroyed (MRC 2018). Restoration efforts aim to bring back natural functions lost to the ecosystem, which will improve habitat and water quality.

The eastern oyster, *Crassostrea virginica*, is considered to be a keystone species and indicator of ecosystem health due to the important benefits they provide (Garvis et al. 2015; Dame 1996). Oysters and oyster reefs positively affect water quality and clarity. However, over the past century, 85% of oyster reefs have been eliminated globally which have prompted different types of restoration efforts (Garvis et al. 2015; Beck et al. 2011). Oyster restoration projects aim to introduce more substrate for the oysters to settle, and sometimes add larvae or spat to the substrate (Garvis et al. 2015). Between 1943 and 2009, mosquito lagoon lost 24% of its oyster reef cover, equating to about 15 hectares; and even greater 40% loss in the Canaveral National Seashore region (Garvis et al. 2015). Being a keystone species for many ecosystems, oysters prove to be imperative for restoration efforts.

In response to the need for restoration efforts, professors and community leaders at Florida Institute of Technology formed the Indian River Lagoon Research Institute, IRLRI. The sole focus of the IRLRI is to combine engineering and science to innovate solutions regarding issues around the IRL, along with providing education and outreach to the community. One of the focus concepts is to engage the community and convert public or private docks into oyster reefs, the project is termed "Living Docks"; Figure 4. Living Docks is an oyster restoration technique designed to create habitat suitable for recruitment of filter feeding organisms in the IRL. Filter feeders such as oysters, barnacles, sea squirts, etc. are benthic organisms that like to settle on hard bottom substrates (Weaver et al. 2018). With the accumulation of soft, silty muck the oyster reefs can be covered, and the oysters suffocated (Weaver et al. 2018; McNally et al. 2018). Muck is comprised 85-95% water by weight with the solid portion containing 10-20% organic matter, 60-80% fine sediments, and 10% shells (McNally et al. 2018; Trefrey 2016; Foster et al. 2017). Muck profiles have been recorded to exceed four meters in height, and excessive accumulation of muck makes the sea floor uninhabitable for new benthic organisms to settle (McNally et al. 2018; Tetra Tech 2020; Weaver et al. 2018). To combat this dilemma, the IRLRI uses dock pilings as a new substrate for these organisms to grow.



Figure 4: IRLRI Living Dock Community Workshop and Deployment

Natural habitats and ecosystem functions are being wiped out due to urbanization and the fact that one third of the total human population lives within 100km of the coastline (Janiak et al. 2018; Gittman et al. 2016). A major part of this urbanization is the installation of artificial or hard structures to fortify and protect against property lost along the shore. These structures guard against erosions, storm, flooding, sea level rise, or are for recreation which has consequences to the local and global ecosystem (Janiak et al. 2018; Dafforn et al. 2015). In the United States, over 14% of the coastline has been modified with the majority taking place in in sheltered lagoons, bays, and estuaries. In most cases the replacements of natural shorelines are built without consulting ecological engineering practices (Janiak et al. 2018; Gittman et al. 2015). As hard structures are accumulating around the world, an interest to convert these structures into habitats for marine organisms is becoming more apparent. In a system dominated with soft sediments, the hard structures provide suitable substrate for benthic species. Artificial structures in the IRL, such as small wooden dock pilings, were concluded to host a greater number of species and diversity when compared to natural mangrove habitats (Janiak et al. 2018). This is surprisingly in contrast to other studies which compared artificial structures to other natural habitats such as rocky shores. The communities found were mainly composed of barnacles, bryozoans, hydroids, and tube-dwelling amphipods (Janiak et al. 2018). Subtropical environments yield better benthic growth on artificial structures than natural habitat, making pilings a great focus area for oyster restorations in the IRL.

Much of the benefits and goals from the Living Docks (Weaver et al. 2018) aligns with the Brevard Oyster Garden restoration project (Tetra Tech 2016), but different in the way it is deployed. This gives the client more options that may be better suited to their specific location. Oyster restorations have been proven to show a net positive result in the removal and processing of excess nitrogen in the water. The three main process oysters use to filter excess nitrogen are assimilation of nitrogen through the shell and tissues, improved burial of nitrogen in the sediments, and the primary method is increased local denitrification rates (Tetra Tech 2020; zu Ermgassen et al. 2016). Even though oyster restorations show minimal impact in the water body as a whole, they have a significant impact on a local scale. Studies have shown the average denitrification effects of oyster reefs can remove 0.04 lbs-N/m², or 161.9 lbs-N/ac, each year (Tetra Tech 2020; Kellogg et al. 2013). Brevard

County's goal is not to restore oyster reefs for the sole sake of bringing back oyster population, but rather to focus on denitrification and improved water quality within the IRL. This is due to the lack of historical data, and the fact that the increase of oyster reefs would compete for space with sea grass which is viewed as a more critical component for the Lagoon system (Tetra Tech 2020). Additionally, the abundance of muck within the IRL continuously releases nitrogen and phosphorous into the water column (Fox et al. 2018). Management of the muck requires removal by means of dredging along with control of nitrogen, phosphorous, and suspended sediments entering the lagoon (Fox et al. 2018). Filter feeders naturally filter the water and remove excess nutrients and fine sediments, making oyster restorations a viable means of contributing to the management and removal of muck in the IRL. Living Docks will increase denitrification with the increase of benthic organisms, while not invading space available for sea grass or interfering with restoration efforts along the lagoon floor. With Brevard's standards in mind, the Living Docks initiative presents a new and innovative approach to oyster restorations while addressing each concern.

With increased anthropogenic structures in the IRL and other estuaries, comes the possibility of converting these into suitable habitat for filter feeding organisms. Living Docks initiative takes advantage of the secure substrate provided by docks and has proven to be an efficient and effective restoration effort. This study is dedicated to advancing ecological engineering techniques and validate the Living Docks as a reliable restoration method. Results will improve Living Dock design by determining the added forces acting on pilings converted to Living Docks, the force coefficients to use in future designs on any dock, and whether or not the addition of oyster mats on pilings will harm the dock.

2.0 Background

Living Docks has the goal of improving water quality by restoring the population of benthic filter feeding organisms lost to over harvesting and eutrophication. Recycled oyster shells are attached to aquaculture grade mesh to make oyster mats, which are secured to dock pilings to provide a substrate for filter feeders to grow. A special chemical cue in the oyster shells signals the other oyster larvae to settle (Chambers et al. 2017), along with the other benthic organisms. This keeps the oyster shells and accumulated growth out of the muck and provides an acceptable hard substance to grow.

2.1 Living Docks

One of the most beneficial results from Living Docks is the filtration capacity of these benthic organisms. Living Docks give a suitable place for these filter feeding organisms to settle and grow, and the diversity of species that grow on these oyster mats provide a wide range of filtering rates. It is estimated that with the successful implantation of 20 miles of oyster reefs, the whole volume of water that falls in the Brevard County limits could be filtered annually (Weaver et al. 2019; Tetra Tech 2020). An individual adult oyster is recorded to filter 50 gallons of water per day; tunicates can filter 23 gallons of water per day; and an individual bryozoan in a colony can filter up to 9 mL of water per day (Weaver et al. 2019; Draughon et al. 2010; Bullivant 1968; Wall et al. 2008). While oysters filter sediments, algae, and other suspended particles, other organisms, like the tunicates, can filter finer particles down to the size of viruses (Weaver et al. 2019). This is beneficial for not only reducing excess nutrients and organic matter entering the IRL, but also for potentially reducing toxins and pathogens (Burge et al. 2016).

For oysters and other benthic organisms to thrive, a suitable substrate much be located away from the fine sediments that can suffocate organisms on the sea floor. For this reason, ideal locations for oyster reefs in the IRL include man-made structures such as docks. Also, with fouling already present on the dock pilings, the mats are supported against slippage (Weaver et al. 2019). Furthermore, permits are not needed since the creation of Living Docks is a modification to an already permitted structure, and since the mats are not on the bottom there is no impact to submerged aquatic vegetation, SAV, habitat (Weaver et al. 2019). In addition to avoiding the muck and being near the surface, the reef should also be located in a region with minimal wave energy away from the shore. By placing the mats on the pilings, the oyster reefs avoid breaking waves where the most energy is created (Weaver et al. 2019). Lastly, using docks as a new habitat, it is easy for deployment and allows for opportunities to include citizen science, education, and outreach.

To have a successful restoration effort the project should be simple, require little maintenance, and be inexpensive. This allows the community to lead in the conservation movement of Living Docks and can be implemented along a privately owned or public dock with the help of volunteers. Once the oyster mat is set, there is no maintenance required, only periodic visual checks that the oyster mats are undamaged. An average oyster can live for more than 10 years, and Living Docks operates by letting nature do the work (Weaver et al. 2019; Cake 1983). The oyster mats are constructed on a 2 ft by 2 ft aquaculture grade mesh. Oyster shells are recycled through community programs that collect and cure oyster shells. The shells are then drilled with a masonry drill bit at the tip near the umbo or thickest part of the shell and are attached to the mesh using UV resistant zip ties. The shells are assembled in a clustered fashion with a goal of 80 shells per mat. A 2-inch border is left around the edges of the mat in order to attach the mat to the dock piling. The size and shape of the oyster mat can be modified according to a structure's specifications but are primarily designed to wrap around and attach to the surface of dock pilings. This will increase to the force acting on the pile due to increased roughness and increased effective diameter. Assembled oyster mats typical for the IRL, ready for deployment, can be seen in Figure 5. UV resistant cable ties secure the mat in position on the piling so that the top of the mat is at mean water level during the seasonal low water (Weaver et al. 2019). Deployments have been implemented already with the help of volunteers and are simple enough for any skill level.



Figure 5: Oyster Mats Ready to be Deployed

Oyster bags are also commonly seen in oyster restorations, so a pilot study comparing oyster mats to oyster bags along the docks was conducted, which concluded that oyster mats are more suited for this restoration project. Bags are too heavy and cumbersome, making it inefficient for the long run due to the bags detaching under their own weight (Weaver et al. 2019). Furthermore, the benthic organisms cemented themselves to the mat and dock adding extra support (Weaver et al. 2019). The pilot test wrapped 36 pilings, and with 50 oysters per mat, it was estimated a Living Dock could potentially filter 36,000 to 57,600 gallons per day or 13 to 21 million gallons per year (Weaver et al. 2019). This estimate focused on oysters and does not account for the other organisms that will settle on Living Docks such as mussels, tunicates (sea squirts), barnacles, bryozoans, and sponges, each of which provide a significant increase in filtering rates within the IRL.

Adversely, most of these filtering organisms are gregarious and grow on top of each other, thus changing the effective diameter and roughness of the dock piling. Theoretically with an increase of diameter, there should also be an increase in the drag forces on that piling. With the oyster shells and filter feeders on the dock piling, the question that needs to be answered is whether or not these oyster mats will negatively influence the structural design of the hosting dock.

2.2 Dock Specifications in Florida

The Florida Department of Environmental Protection, FDEP, suggests docks be built to specifications outlined in National Design Specification, NDS, Design Values for Wood Structures (Clark 2011). In addition, the Coastal Engineering Manual, CEM, suggests building to a factor of safety of 2.0 with the max forces acting on the piling (CEM 2004). There are two main types of timber used in building docks: Douglas Fir and Southern Yellow Pine; however, other species are commonly used and are grouped into this category. This includes Caribbean Pine, Lodgepole Pine, Red Pine, and Hardwoods (Collin 2016). The production of round timber poles is dictated by ASTM D25 *Standard Specification for Round Timber Piles* (ASTM D25 2017) which establishes physical properties and manufacturing requirements and design parameters by ASTM D2899 *Standard Practice for Establishing Stresses for Round Timber Piles* (ASTM D2899 2017; Collin 2016). The allowable stresses permitted for timber piles are provided in the American Wood Council publication Manual for Engineered Wood Construction (Collin 2016). In addition to pile fatigue, these forces may influence foundation failure. With more exposed pile above the mudline, the more leverage natural forces have to wiggle the pile (Burns 1999). The suggested way to prevent this type of failure is modifying the entire dock design such as digging deeper foundations or adding structural braces between the pilings (Burns 1999). Living Docks may add to the forces that move the piling, but this experiment solely focuses on the stress acting directly on the timber; further research would be needed to understand Living Docks' effects on foundation. Figure 6 shows standard values according to NDS from the American Wood Council, stating that the grouped bending force for pine wood is 1950 psi and compression 1250 psi in accordance with ASTM D2899 (AWC 2018). Figure 6 is calculated for piles in groups, and in a normal load duration (Collin 2016).

Species	Axial Compression (F _c) (psi)	Bending (F _b) (psi)	Shear Perpendicular to the Grain (F _v) (psi)	Compression Perpendicular to the Grain (F _c ⊥) (psi)	Modulus of Elasticity (E) (psi)	
Southern Pine ¹	1250	1950	160	440	1,500,000	
Douglas Fir ²	1300	2050	160	490	1,500,000	
Lodgepole Pine	1150	1700	80	270	1,000,000	
Red Oak ³	1100	2450	135	350	1,250,000	
Red Pine ⁴	850	1350	125	270	1,300,000	
 Southern Pine design values apply to Loblolly, Longleaf, Shortleaf, and Slash Pines. 						

Southern Prine design values apply to Lobiolity, Longrean, Shortean, and Stash Prines.
 Pacific Coast Douglas Fir design values apply to this species as defined in ASTM D 1760.
 Red Oak design values apply to Northern and Southern Red Oak.
 Red Pine design values apply to Red Pine grown in the United States.
 Data in Table above was taken from 2012 National Design Specifications.

Figure 6: Allowable Stresses for Timber Pilings (AWC 2018)

The capacity for compression parallel to the grain of the piling is tabulated in Figure 7. These values are only applicable to piles matching tip standards laid out in ASTM D25 (Collin 2016). The tip is considered to be the smallest diameter of the

piling and weakest point of strength. The following conditions must be present for the values in Figure 6 and 7 to be accurate: piles meet ASTM D25; in-service temperatures don't exceed 100°F; wet service conditions; the piles have been treated with preservatives; the compression members are embedded in soil and fully laterally supported; piles are in a cluster in a dock or pier; and the tip of the piling is the critical location for compression parallel to the grain (ASTM D25 2017; Collin 2016). If the pilings do not meet those criteria, Figure 9 shows correction factors to be applied to the design parameters in Figure 6.

Tinchor	Allowable Pile Capacity in Compression (kips)					
Species	Pile Tip Diameter					
Species	7	8	9	10	11	12
Southern Pine	48	63	80	98	119	141
Douglas Fir	50	65	83	102	124	147

Figure 7: Parallel Compression of Timber Pilings (AWC 2018)

Other factors are in place to increase the maximum bending force in certain conditions. The Size Factor multiplies the bending force by a factor of $C_F = (\frac{12}{D})^{1/9}$ if the diameter is larger than 13.5 inches (AWC 2018). Conditioning treatment factor for marine timber is a value of $C_{ct} = 0.74$ and is multiplied to all design values (AWC 2018). The values in Figure 6 and Figure 7 take these treatments into consideration already and treated in accordance with the American Wood Protection Association standards (Collin 2016). For a group of pilings that act as a single element, such as a

Reference	Number of	C _{ls}	
Design Value	Piles in Group		
	2	1.06	
F _c	3	1.09	
	4 or more	1.11	
	2	1.05	
F _b	3	1.07	
	4 or more	1.08	

dock, a Load Sharing Factor is also considered in the total bending moment and compression force, see Figure 8 (AWC 2018).

Figure 8: Load Sharing Factors for Docks (AWC 2018)

Wood stress is also affected by load duration and in-service temperature. The shorter the duration of the load, the greater the allowable maximum force on the pile (Collin 2016). The values in Figure 6 and Figure 7 are based on short term tests, defined by constant fully stressed piles for 10 years (Collin 2016). Wood at higher temperatures above 100°F for long periods of time can deteriorate quicker (Collin 2016). Figure 9 is a summary of additional factors dependent on the pilings that must come into consideration when designing a dock.

Factors		Compression Parallel	Bending	Horizontal Shear	Compression Perpendicular	Modulus of Elasticity
Load Dura-	δ 10 yrs.	1.0	1.0	1.0	1.0	Na
tion (C _{Id}) > 10 yrs.	0.9	0.9	0.9	0.9	Na
Temp- erature	Tõ100°F	1.0	1.0	1.0	1.0	1.0
(C _t)	100°<Τδ 125°F	0.7	0.7	0.7	0.7	0.9
	125°<Τδ 150°F	0.5	0.5	0.5	0.5	0.9
Untreat- ment Factor (C _u)	Southern Pine	1.18	1.18	1.18	1.18	1.0
	Douglas Fir	1.11	1.11	1.11	1.11	1.0
Size(C _f)		1.0	$C_{f} = (12/d)^{1/9} \le 10$	1.0	1.0	1.0
Load Shar-	Single pile	0.8	0.77	Na	Na	Na
ing (C _{is})	Cluster	1.0	1.0	Na	Na	Na

Figure 9: Adjustment Factors for Timber Pilings (Collin 2016)

When it comes to preserving the timber piles, the expected durability is site specific (Collin 2016). The Federal Highway Consideration, FHWA, has laid out some general guidelines stating: treated piles in freshwater will last five to ten years less than a trestle pile in the same area; treated pile longevity in brackish water should be calculated by site specifics; and marine piles will last about 50 years in northern climates in the United States, and 25 years in southern climates (Collin 2016). Common causes of this degradation are insect damage, and exposure to alternate wetting and drying cycles (Collin 2016). Dock pilings in Florida are inherently affected by many factors that can weaken the piling. Hurricanes and high temperatures are common in the Indian River Lagoon, which constantly degrade docks. With a tropical climate, insect damage and alternate wetting and drying of dock pilings is inevitable.

This experiment uses a pine piling with a diameter of 0.095 m (3.75 in) to represent a piling with a diameter between 0.28-0.30 m (11-12 in) in the IRL. Observing the values in Figure 7, the forces of concern acting on the piling should not exceed a compression range of 119 to 141 kips, or 530 to 627 kPa. Applying the same observation to the values in Figure 6, the experimental piling should not excess a max compression force 1250 psi, or 8617 kPa, and bending force of 1950 psi, or 13445 kPa. If the total force exceeds these values, then oyster mats can be problematic to the structural integrity of the dock.

By analyzing the total force acting on the pilings we can calculate the nondimensionalized drag coefficient. This drag coefficient will be beneficial in determining if the existing dock can accommodate the extra forces that the oyster mats introduce on the pilings. This will also give insight into if or when the oyster mats are detrimental to the dock, leading to failure. Living Docks is a successful restoration project thus far and projected to not have a significant effect on the total forces acting on the piling. In order to calculate the forces on a piling, the Morison equation is commonly used. This represents the horizontal forces resulting from waves along the length of the piling, and only valid if the piling diameter is small with respect to the wavelength: D/L < 0.05 (Clark 2011). This experiment will analyze a scale model of a typical piling in the IRL using the Morison equation.

2.3 Design Forces

The three primary factors affecting water movement in an estuarine system are freshwater discharge, tidal action, and atmospheric forcing (Weaver et al. 2016; Reynolds-Fleming 2004). However, the tidal component is restricted to the morphology, orientation, and connection of the estuarine system to the ocean (Weaver et al. 2016; Luettich et al. 2002). Some unique features of the IRL system is its longitudinal shape causing partially sheltered bays. Additionally, man-made canals and waterways release excess fresh water into the system due to a statewide water management system. Furthermore, the dredging activity within the IRL has created spoil islands and new channels that affect natural circulation (Weaver et al. 2016). Due to the restrictions present in the IRL, the primary force drivers are meteorological processes (Weaver et al. 2016; Smith 1990). The design conditions for any restoration project must be determined specifically for the area and can be compared to surrounding areas for validation.

The recent release of the town of Palm Beach's *Master Plan for the Town Docks and Accessory Structures* gives insight to expected design parameters for everyday forces acting on dock pilings in a similar area as the IRL. From the Army Corps of Engineers, USACE, the estimated peak current of Lake Worth Lagoon's spring flood tide is between 1 to 1.3 knots and a current of 2 knots entering the marina (Baird 2018). The town used average wind speeds measured at NOAA buoys, concluding most of the wind action originated from the east and south east (Baird 2018). These measured wind conditions can be used to estimate potential wave conditions; the town concluded that at 20 mph, 1-foot waves can be produced (Baird 2018). Another consideration that was taken into effect was the wake resulting from boats and recreational vehicles (Baird 2018). The correlation of windspeed to surface elevation is significant, meaning the changes in predicted surface elevation is dependent on the up and downwind behavior of the wind field (Weaver et al. 2016). This is not unique to the IRL and should be present in any coastal system in general (Weaver et al. 2016). The wave conditions in the IRL can be modeled after recorded weather activities and storms to produce a significant wave height for this experiment.

The wind generated waves exert forces on the dock, but boat wake is the most common cause for destroying oyster reefs. The motion of the water from the wake causes live clusters to pile on top of one another, forcing oysters above mean water line, and causing mortality due to the lack of inundation (Garvis et al. 2015; Grizzle et al. 2002; Wall et al. 2005; Stiner et al. 2008). Compared to wind generated waves, less than 1% of deployed oyster reefs will move in sustained winds of 79 km/hr, 49 mph, with a shell movement of less than 5 cm; however, boat wakes as small as 2 cm can move entire oyster clusters (Garvis et al. 2015; Grizzle et al. 2002; Wall et al. 2008). With Living Docks, the oysters remain in a no wake zone and somewhat protected from excess boat wake. The waves, currents, and water levels that effect the Living Docks are most commonly caused by meteorological

conditions. Although, depending on location, the tidal forcing and boat wakes can also be significant.

2.4 Flow Past a Cylinder

Different effects can be expected due to the flow characteristics around the cylinder in question, see Figure 10. With a low Reynolds number, Re = $\frac{UD}{v} < 1$, viscous affects are felt through a generally large portion of the flow field (Munson et al. 2013). For Re = 0.1 the viscous effects are important within several diameters of the structure. This creates streamlines symmetric about the cylinder that are similar in pattern before and after reaching the cylinder (Munson et al. 2013). As the Reynolds number increases, the region in front of the cylinder decreases in viscous effect while the rear increases. As the flow field loses its symmetry, viscous effects cause the flow field to separate downstream (Munson et al. 2013). As the Reynolds number increases, the flow field separation extends further downstream as the boundary layer thins along the front of the cylinder. This creates an irregular, unsteady, and turbulent wake past the structure (Munson et al. 2013). The turbulent boundary layer structure is highly irregular and complex. The velocity of the flow is random with multiple intertwined eddies and vortices forming in the wake (Munson et al. 2013). The fluid flow outside the boundary layer is inviscid and has a smaller velocity gradient than the flow within the boundary layer and wake zone (Munson et

al. 2013). For this experiment the Reynolds number is expected on the order of 10^5 , meaning the viscous effects are confined to the boundary layer and wake zone.



Figure 10: Boundary Separation Layers in Relation to Reynolds Number (Munson et al. 2013)

Pressure drag, often referred to as form drag, is due directly to the pressure on the object. The form drag is mostly dependent on the shape of the object. D'Alembert's paradox states, "the drag on an object in an inviscid fluid is zero, but the drag on an object in a fluid with vanishingly small (but nonzero) viscosity is not zero" (Munson et al. 2013). In an inviscid fluid, the particles would have no problem traveling around the circumference of the cylinder. However, fluids with any amount of viscosity are affected by the pressure hill. The decrease in pressure from 0° to 90° of the affective flow field is termed the favorable pressure gradient. As to flow travels from the 90° to the 180° mark, the pressure change is termed as the adverse pressure gradient (Munson et al. 2013). Due to viscous effects the particle loses energy in the adverse pressure gradient zone and cannot travel the rest of the circumference of the cylinder. The flow travels as far as it can until it creates a boundary separation layer and lifts off the surface creating the wake field (Munson et al. 2013). Due to the separation layer, the rear half of the cylinder has significantly less pressure than the front, creating pressure drag.

$$C_{Dp} = \int_0^{\pi} C_P \cos\theta \, d\theta \qquad [1]$$

$$C_P = \frac{p - p_0}{\frac{1}{2}\rho U^2}$$
[2]

Where C_{Dp} is the pressure drag coefficient, C_p is the pressure coefficient, p and p_o are the pressure and initial pressure, ρ is desnity of the water, and U is the flow velocity. Friction Drag is the part of drag that is due to shear stress on the surface of the body. Generally, for common flows with high Reynolds number, the percent drag caused directly by shear friction is small.

$$C_{Df} = \frac{\int_0^{\pi} F(\theta) \sin\theta \, d\theta}{\sqrt{Re}}$$
[3]

$$F(\theta) = \frac{\tau_w \sqrt{Re}}{\frac{1}{2}\rho U^2}$$
[4]

Where C_{Df} is the friction drag coefficient, τ_w is shear stress, and *Re* is Reynolds number. Together the friction drag, and form drag create the drag coefficient (C_d) that acts in the direction of flow. The net force is a function of directional components tangential and normal to the body of the object (Munson et al. 2013).

$$C_d = C_{Df} + C_{Dp} \tag{5}$$

The total force acting on a piling consists of 2 components, the inertia force and the drag force. The dynamic force acting on the pile is represented by the equation for drag force in steady state conditions. In non-steady state, the accelerations and deaccelerations must also be considered and accounted for calculating the inertial force (Morison et al. 1954; CEM 2004; Dean et al. 1984). Together the drag and inertial forces are needed for non-steady state systems. Both the drag coefficient, C_d, and inertia coefficient, C_m, must be determined experimentally, and are dependent upon the state of the fluid around the object (Morison et al. 1954; CEM 2004; Munson 2013; Dean et al. 1984). The drag coefficient is influenced by frictional and form drag and related to the steady state flow using the Reynold number. The inertia coefficient does not include hydrostatic forces and is necessary in environments with oscillatory waves and a non-uniform flow field. The total force is determined by integrating force acting on the submerged portion of the piling (Morison et al. 1954; CEM 2004; Munson 2013; Dean et al. 1984). One of the goals of this experiment is to determine drag and inertial coefficient of Living Docks through various stages of growth for future design calculations and failure predictions by using Morison's Equation below.

$$F = \frac{1}{4}\pi\rho D^{2}lC_{m}\dot{U}(t) + \frac{1}{2}\rho C_{d}DlU(t)|U(t)|$$
[6]

Where *F* is total force, *D* is diameter of the piling, *l* is length of the piling, \dot{U} is flow acceleration, C_m is inertia coefficient, and C_d is drag coefficient.

Morison's experiment measured the total forces on cylindrical pilings and will be used as a model to conduct this experiment. The moment on a pile was measured under wave action in the University of California Wave tank. The waves were simultaneously measured for wave height, velocity, and period. Using these parameters, the drag coefficient and inertia coefficient were calculated out (Morison et al. 1954). Our Living Dock experiment used the Morison equation as the central theory in determining the structural influences of oyster mats on dock pilings and was modeled after the laboratory experiment performed by Morison.

Morison's approach was to calculate the force coefficients experimentally. When velocity is at its maximum, acceleration is zero so at that instant the force is entirely drag force (Journee 2001; Newman 1980). When acceleration is at its maximum, velocity is zero and at that instant, the force is entirely inertial (Journee 2001; Newman 1980). Although useful, this can lead to significant phase error if the velocity and acceleration profiles are off by a small amount (Journee 2001).

$$C_d = \frac{2F}{\rho D U|U|} \text{ when } \dot{U} = 0$$
[7]

$$C_m = \frac{4F}{\pi \rho D^2 \omega \dot{U}}$$
 when $U = 0$ [8]

Where $\omega = \frac{2\pi}{T}$ is the natural frequency of the wave.

A later study from Morison's experiment was performed by Garbis Keulegan and Lloyd Carpenter further investigating the inertia and drag coefficients of cylinders in sinusoidal currents (Keulegan et al. 1958). They explored the relationship between the inertia and drag coefficients with Reynolds number and Keulegan and Carpenters period parameter. In the Keulegan and Carpenter experiment, the total forces acting on the object were measured using strain gauges. Calibrating the readings to known weights, a curve was created to formulate an equation to convert the differences into weight in grams. The wave parameters were simultaneously measured to determine maximum velocity using linear wave theory (Keulegan et al. 1958). The magnitude of the forces acting on the cylinder was converted, and the moment was determined about the pivot point, and total force was determined by dividing the moment by the length of the cylinder, which then determined the C_m and C_d (Keulegan et al. 1958). The experiment showed no relation to Reynolds number but there is a relation to the period parameter, or KC number displayed below (Keulegan et al. 1958).

$$KC = \frac{U_m T}{D}$$
[9]

Where U_m is maximum horizontal velocity, and T is wave period.
The results of Keulegan-Carpenter were different between the drag and inertia coefficient. Both started at their respected theoretical level found by Morison and varied as the KC number increased (Keulegan et al. 1958). Both the drag and inertial coefficients are very sensitive to KC values that are below 15, Figure 11. In this range of KC values, the drag coefficient quickly increases, and the inertia coefficient quickly decreases with small changes in KC values. This makes it difficult to accurately select a value for the force coefficients. For this simulation, the KC is expected to be less than 15 so it is important to determine the coefficients experimentally to obtain accurate results. In some cases, the local coefficients differed during different phases of the wave cycle but Keulegan and Carpenter confirmed it is adequate to use average coefficients to describe the magnitude of force at each phase (Keulegan et al. 1958). Using Keulegan-Carpenter's experiment as a guide, the force coefficients of Living Docks can be plotted for research, analysis, and future use.



Figure 11: Drag and Inertia Coefficient with KC numbers (Keulegan et al. 1958)

The force component amplitudes are about equal when KC is in the range of roughly 15 to 20. For small KC values, KC < 3, the inertial forces are dominant and drag can be neglected (Journee 2001). For 3 < KC < 15, drag force can be linearized, and for 15 < KC < 45 drag is nonlinear and Morison's Equation must be used (Journee 2001). As KC approaches infinity, which corresponds to a constant current, drag force is dominate and inertia can be neglected (Journee 2001). This is due to lack of acceleration but based off Keulegan and Carpenter's data that is not apparent and adds to the argument the coefficients should be determined experimentally; see Figure 11. Figure 12 Shows expected drag and inertia coefficients with respect to KC and Reynolds number.

	Rn <	$< 10^{5}$	$Rn > 10^5$		
KC	\mathbf{C}_D	\mathbf{C}_M	\mathbf{C}_D	\mathbf{C}_M	
< 10	1.2	2.0	0.6	2.0	
$\geqslant 10$	1.2	1.5	0.6	1.5	

Figure 12: C_D and C_M with Respect to Re and KC (Journee 2001)

With other methods taken into consideration, determining the pairs of C_M and C_D are inconsistent and not the same and within a tolerance of several percent (Journee 2001). For structures with marine growth and biofouling, the change in diameter is most easily accounted for using Morison's equation (Journee 2001). This raises the question of the most accurate way to calculate both force coefficients.

2.5 Determining CD and CM

The force can be calculated with the Morison equation and can be approximated using coefficients defined in the CEM for large Reynolds numbers, on the order of 10^5 , as $C_d = 0.7$ and $C_m = 1.5$ (CEM 2004). Two derivations of the Morison equation are taken into consideration for this experiment to determine more accurate coefficients that best represent the Living Docks initiative. The first derivation is in perspective of hydrodynamic properties and the second by coastal engineering practice. As stated before, the force results from two components which are C_m and C_d . They are considered the apparent mass and apparent damping coefficients (Newman 1980).

$$C_F = C_m \dot{U} + C_d U \tag{10}$$

Where C_F is the total force coefficient. The coefficients can be predicted theoretically using a comparison of the wavelength from the waves acting on the immersed object to the size of the object. In the case of small wave amplitude and large wavelength compared to the pile diameter, the force is inertia dominated. The force can be approximated with the following equation. (Newman 1980).

$$F \cong (m_{11} + \rho \forall) \dot{U}$$
[11]

Where \forall is volume of displaced water from the piling and m_{11} represents the added mass coefficient for a two-dimensional cylinder and can be calculated by the following equation (Newman 1980).

$$m_{11} = \pi \rho r^2 \tag{12}$$

When the body is small compared to the wave amplitude, then viscous drag forces will be dominate. The force then can be approximated by the equation below. The velocity squared is replaced in form to ensure the drag force acts in the same direction as the fluid velocity (Newman 1980).

$$F \cong \frac{1}{2}\rho D^2 U |U| C_d(Re)$$
[13]

In the intermediate case where the wave amplitude to diameter ratio is of the order 1, the inertial and viscous affects are similar in magnitude, and Morison's equation must be adopted in order to calculate the force (Newman 1980).

$$F = (m_{11} + \rho \forall) \dot{U} + \frac{1}{2} \rho D^2 U |U| C_d(Re)$$
[14]

Since this equation is restricted to a regime where wave amplitude to object diameter is small or large, this Morison's equation must be confirmed with experimental findings (Newman 1980). Following this hydrodynamic approach, the inertia coefficient can be calculated with the added mass coefficient (Journee 2001; Newman 1980).

$$C_m = 1 + C_a \tag{15}$$

Where C_a is the added mass coefficient. For this experiment, C_m was calculated using Chung and Chen's method with the following equation.

$$C_m = 1 + \frac{2\sqrt{2}}{\sqrt{S}} \tag{16}$$

Where $S = \frac{\omega r^2}{v}$ and is related to the added mass coefficient, and v is the kinematic viscosity of water. Equation 16 is applicable when the term S is relatively high (Chung et al. 1976). For this experiment, the value of S was on the order of 10^4 .

The maximum force, which is primarily drag force, can be estimate using figures in the Coastal Engineering Manual. The figures were constructed based off stream-function theory (CEM 2004) and vary with the dimensionless parameter, W; Equation 17.

$$W = \frac{C_m D}{C_d H}$$
[17]

Where *H* is the wave height. Once the value of *W* is determined as 0.05, 0.1, 0.5, or 1.0 then ϕ_m is determined using nondimensionalized wave parameters and the Figures VI-5-131 to VI-5-134 in the CEM. The drag coefficient can then be equated using the following equation once the max force is experimentally determined (CEM 2004).

$$F_{max} = \phi_m C_d \rho g H^2 D$$
 [18]

It is expected that with the addition of oyster mats and biofouling, the forces on the dock piling will increase. It needs to be determined if these added forces will cause damage to the host structure, which was accomplished through three main goals: (1) measure forces from a scaled down simulation in a wave tank by use of a strain gauge, (2) determine drag and inertia coefficients from conditions expected in the IRL, and (3) compare calculated forces of Living Docks in the IRL to national design standards.

3.0 Methodology

To accurately calculate the force resulting on the pilings, a scale model was used in the Florida Tech's wave tank. Common practices of designing a dock call for site evaluation for wind and wave loading; however, there are some general guidelines in place. For recreational docks in coastal environments, is it a good assumption to have your design wave with a 0.61 m (2 ft) wave height and a period of 2 seconds and able to withstand a wave as high as 1.31 m (4.3 ft) and period of 2.6 seconds (SunCam "Recreational and Commercial Boating"). The testing conditions were first determined using typical storm conditions expected in the IRL. A significant wave height of 0.68 m (27 in) and period of 2 seconds was determined in a previous Florida Tech Coastal Lab experiment by modelling hurricane Frances, Jeanne, Charlie, and Matthew using ADCIRC+SWAN storm surge and wave model (Weaver et al. 2017). This is the greatest force expected in the IRL and will exceed this limit only in extreme conditions. The wave tank is 8.23 m (27 ft) long, 0.56 m (22 in) wide, 0.91 m (3 ft) deep, and produces waves at various frequencies and heights. The conditions of the IRL were scaled down and recreated in the wave tank to obtain accurate representations of the occurring forces.

A wave tank analysis examined the resulting wave heights at various depths and with different positions of the motor piston. This analysis set the boundary of testing conditions for this experiment. Results from the analysis can be seen in Figure 13. The line drawn represents a 1:3 scale according to the 0.68 m (27 in) storm wave height. An appropriate depth and piston position were selected from this scale to best represent the conditions found in the Indian River Lagoon.



Figure 13: Wave Height and Depth Values from Dimensional Analysis in the Wave Tank

When designing scale model testing, it is important to establish the importance between scaling Froude number and scaling Reynolds number. For incompressible fluid dynamic applications, the Froude number governs the inertial loadings and pressure affects around an object, and the Reynolds number governs dynamic forces around an object (Wolowicz et al. 1979). In this experiment the apparatus was fixed and mounted into place, meaning all the dynamic forces needed to be considered (Wolowicz et al. 1979). Since rigid-body equations of motion already take into account the inertia terms, the Froude number is unnecessary and Reynolds number was scaled (Wolowicz et al. 1979). With accurate scaling, the kinematic properties are preserved from model to *in-situ* conditions (Wolowicz et al. 1979). A general law of Reynolds number scaling is

$$Re_p = \lambda^{1.5} Re_m \tag{19}$$

Where p and m stand for protype and model respectively and λ is the scale factor used in the experiment (Chakrabarti 1998).

It was determined that a 1:3 scale will be used making the storm wave height 0.22 m (9 in), and water depth of 0.37 m (14.5 in) corresponding to the modeled wave height of 0.68 m (27 in) and an average depth of 0.91-1.2 m (3-4 ft) in the IRL. Mimicking a 2 second period, a frequency of 6 hz was used to power the wave tank. This being the most extreme storm condition, the results simulated the greatest force that is expected in the IRL to act on dock pilings. In order to scale a realistic piling used in the IRL, a 0.095 m (3.75 in) diameter pressure treated pine-wood post was used to represent a 0.28-0.30 m (11-12 in) diameter dock piling at the same 1:3 scale. The oyster mats are normally created to be a 0.61 m x 0.61 m (2 ft x 2 ft) square, but for this experiment the mats were scaled down to 0.20 m (8 in) before being attached to the scaled piling.

3.1 Experimental Set-up

In order to measure the forces acting on the piling, a number of different methods were used. Three instruments were used to measure the wave heights impacting the pile, velocity resulting from the waves, and the total bending force acting directly on the piling. Using the parameters under scaled down conditions, the drag and inertial coefficient for different stages of Living Docks were examined. Once these coefficients were obtained and verified through the different data acquisitions, they were applied to *in-situ* conditions.

3.2 Simulation Phases

The experiment went through three phases to simulate the progression of Living Docks. Each phase went through three trials and were averaged at the end. The first phase was a plain dock piling under typical condition found in the IRL. Next phase was a freshly deployed oyster mat. This is the period of time the oyster mat is on the dock piling but has not acquired any fouling. The last phase was with an oyster mat after significant growth. This was accomplished by placing a scaled down oyster mat at another Florida Tech research site, Cape Marina in Port Canaveral marina in Cape Canaveral, FL. The oyster mat was left out for four months and can be seen in Figure 14. Growth is influenced by local factors and some areas may prove to have more or less growth and/or diversity within four months. Organisms found on the oyster mat used in phase 3 included: encrusting bryozoans, arborescent bryozoans, fire sponges, juvenile oysters, barnacles, tunicates, and tube worms. All three phases that were simulated in the wave tank are represented in Figure 15.



Figure 14: Oyster Mat with Four Months of Fouling used in Phase 3



Figure 15: Dock Piling (Phase 1), Deployed Oyster Mat (Phase 2), and Living Dock (Phase 3)

3.3 Construction

The piling was sectioned off for a total length of 0.38 m (15 in). This allowed the whole area to be under the influence of the entire wave from crest to trough. A 0.38 m (1.25 in) diameter hole was cut into the top of the piling to attach the strain gauge. The strain gauge acted as a leg of the piling and was affected in the same manner as the piling. The piling was connected to a frame that clamped to the top of the wave tank, and the pile suspended into the water; see Figure 16. The wave gauge was mounted in front of the piling, which were both placed in a nonbreaking zone. This was to represent the purpose of moving oyster mats away from the shore to avoid breaking waves and increases chances of reef success. The dimensions of the piling experimental set-up can be seen in Figure 17.



Figure 16: Experimental Set-up Showing Pile Attached to Strain Gauge and Mounted to the Florida Tech Wave Channel, and Sonic Wave Gauge Mounted to Tank in front of the Pile.



Figure 17: Dimensions of Experimental Set-up

3.4 Strain Gauge

The strain gauge, Figure 18, was connected directly to the scaled down piling and measured the total force acting on the piling and bending moment resulting from that force. The strain gauge utilized a full Wheatstone Bridge to measure the differences in bending from the wave force acting on the piling; Figure 17. Before testing, the strain gauge had to be calibrated to associate the differences in microStrains from the Wheatstone Bridge to newton force. By relating the change in voltage to its associated force, the magnitude of forces were determined similarly to Keulegan and Carpenter's experiment.



Figure 18: Strain Gauge and Piling in the Florida Tech Wave Tank

The strain gauge measured 0.45 x 0.02 x 0.03 meters (17.72 x 0.75 x 1.0 inches) which used Arduino and a HX711 ADC to process then output the difference in strain along the resistors in the Wheatstone Bridge. The processing unit was housed in a protective box and contained a 12 v battery power source; Figure 19. The load cell hosted the Wheatstone Bridge sealed in a 3-D printed case on the aluminum bar; Figure 19. The readings were compiled and displayed using a serial port terminal application called CoolTerm.



Figure 19: Strain Gauge and Processing Unit

3.5 Sonic Wave Gauge

The sonic wave gauges, same ones used for the wave tank analysis, use a sonic beam to measure relative surface elevation. The sonic wave sensor was purchased from Ocean Sensor Systems and can be seen in Figure 20. The signal was interpreted using functions in Matlab to find the significant wave height. The signal was plotted and the method of zero-up crossing was used to calculate wave height of each wave. From there the significant wave height ($H_{1/3}$) was calculated. Using linear wave theory, velocity and acceleration were calculated as well.



Figure 20: Ocean Sensor Systems Sonic Wave Gauge

3.6 <u>Velocity</u>

The velocity used to design the docks are mostly estimated from the wind driven waves, similar to Palm Beach County's dock plan mentioned previously. The particle velocity of the incoming waves was measured using a particle image velocimeter (PIV) program in order to validate the accuracy of using linear wave theory. For the PIV study Matlab's PIV tool was utilized to dissect videos of particles traveling around the piling. Bright particles were used to visualize the flow field and recorded by GoPro camera. The program tracked the particles frame- by- frame and used relative distances to create a vector field. After obtaining the vector field, different areas of the video were analyzed to obtain recorded u-components of velocity.

4.0 Results

A pilot study was conducted as a proof of concept. The wave heights were recorded alongside the strain acting on the piling. A scaled down oyster mat was used to simulate a Living Dock and tested under typical storm conditions found in the IRL. When compared to a bare piling, the addition of an oyster mat approximately doubles the forces on the piling. The forces measured in newtons of both the dock piling and Living Docks can be seen in Figure 21.



Figure 21: Living Dock Force Comparison Pilot Study

Using the wave parameters for this trial, the KC number was calculated to be 12, meaning it is in the range of variable drag coefficients.

4.1 Wave Analysis

Sonic wave gauges were used to record wave heights influencing the simulated piling in the wave tank. The wave signal for three trials, Figure 22, are each processed in Matlab using a zero-up crossing method in order to find the significant wave height for each signal. The period was also determined as part of the zero-up crossing method. The wave height and period were used to calculate other wave parameters using linear wave theory equations found in the CEM and is seen in Table 1. The wave height is within range of the desired wave height of 0.22 meters.



Figure 22: Wave Signals Measured in Wave Tank from Experiment Simulation

Wave Parameters					
	Wave	Wave	Particle	Particle	
	Height (m)	Period (s)	Velocity (m/s)	Acceleration (m/s ²)	
Trial 1	0.19	2.10	0.52	1.55	
Trial 2	0.19	2.02	0.53	1.66	
Trial 3	0.20	2.32	0.53	1.44	
Average	0.19	2.14	0.53	1.55	

Table 1: Measure and Calculated Wave Parameters

To validate the accuracy of calculating velocity and acceleration using linear wave theory, a PIV study was conducted. The appendix contains full frame images of the water column vector field forming with a passing wave, the u-component results of which were compared to the calculated particle velocity in Table 1. The average u-component of most of the vector field (0.50 m/s) and the average u-component in the fastest part of the vector field (0.61 m/s) were determined through the PIV study; Figure 23. The calculated velocity from linear wave theory (0.53 m/s) agrees with the results from the PIV study.



Figure 23: PIV Study Results with Average u-Components (Frame 4)

4.2 Strain Gauge Forces

A calibration curve was created in order to convert microStrains, the original units resulting from the Wheatstone bridge, to Newton force by applying known masses to the strain gauge. This is needed in order to analyze total force of each phase and trial. The calibration curve, Figure 24, was used to create Equation 19 which is used to convert the raw strain gauge data to force. The masses were hung from piling while connected to the strain gauge at the point of the resulting force from the flow field. The known masses were multiplied by gravity before calculating the equation in order to convert the readings into newtons. The following equation was used to convert the strain gauge data.



$$Newtons = 0.000131 * microStrain - 5.58$$
 [19]

Three trials were performed for each scenario: piling without an oyster mat, a piling with a freshly deployed oyster mat, and a Living Dock piling wrapped in an oyster mat with four months of biofouling. The diameters for each phase increased with the addition of oyster shells and fouling. These diameters were 0.095 m (3.75 in), 0.20 m (7.75 in), and 0.22 m (8.75 in) respectively. The raw converted data for each trial in each phase using the strain gauge is provided in Figures 25-27.



Figure 25: Strain Gauge Data for Bare Piling



Figure 26: Strain Gauge Data for Piling After Deployment



A selected trial overlaid from each of the three test cases is plotted in Figure 28 and is an overall view of how the forces acting on the piling increase with each successive stage. After the strain gauge data was converted using Equation 19, the signal was processed using a zero-up crossing method to obtain the significant force for each trial. All the forces processed from each trial are in Table 2.



Figure 28: Force Comparison from Each Phase of the Simulation

Strain Gauge Forces (N)					
	Piling Deployment Living Docks				
Trial 1	13.06	29.66	40.61		
Trial 2	12.74	28.58	37.52		
Trial 3	12.97	28.60	37.54		
Average	12.92	28.95	38.56		

Table 2: Strain Gauge Values

4.3 Drag and Inertia Coefficients

The drag and inertia coefficients were determined using the experimental values that represent *in-situ* conditions of the Indian River Lagoon. Using both methods mentioned in Section 2.5, either the C_m or C_d was calculated first and the other coefficient was determined using the strain gauge force and newly calculated coefficient.

The coastal engineering approach used the max force method laid out in the CEM and followed Equation 18. To determine W from Equation 17, C_m and C_d were approximated for large Reynolds numbers using the CEM, and W was determined to be approximately equal to 1.0. Using Figures VI-5-130: VI-5-134, ϕ_m was determined to be 0.42. Once C_d was determined, Morison's equation, Equation 6, was used to back out C_m . See Table 3 for the coefficient values using the coastal engineering approach.

Coastal Engineering Approach						
	Drag Coefficient (C _d)					
	Piling	Piling Deployment Living Docks				
Trial 1	0.89	0.98	1.19			
Trial 2	0.87	0.95	1.10			
Trial 3	0.89	0.95	1.10			
Average	0.89	0.96	1.13			
Inertia Coefficient (C _m)						
Piling Deployment Living Docks						
Trial 1	2.03	1.08	1.16			
Trial 2	1.99	1.04	1.07			
Trial 3	2.02	1.04	1.07			
Average	2.01	1.06	1.10			

Table 3: Coastal Engineering Approach Coefficient Values

The hydrodynamic approach used a coefficient related to added mass to calculate C_m , Equation 16. After calculating C_m , Morison's equation, Equation 6, was used again to determine C_d . See Table 4 for the coefficient values using the hydrodynamics approach.

Hydrodynamic Approach						
	Inertia Coefficient (C _m)					
	Piling Deployment Living Docks					
Calculate	d	1.0)3	1.0	2	1.01
Drag Coefficient (C _d)						
	Pi	Piling Deployment Living Docks				
Trial 1		0.87		1.10		1.48
Trial 2		0.80		0.99		1.22
Trial 3		0.85		0.99		1.22
Average		0.84		1.03		1.31

Table 4: Hydrodynamic Approach Coefficient Values

4.4 Forces in the Indian River Lagoon

To relate these forces to the IRL, we must check that the coefficients can be transferred from the lab scale to the field scale. Examining the Reynolds number scaling mentioned in the methodology, Equation [19], there is a 15% difference between the Reynolds numbers in IRL conditions and the scaled conditions in the wave tank; see Table 5.

Table 5: Reynolds Number in IRL Conditions

	Theoretical Reynolds number $(\lambda^{1.5} Re_m)$	Experimental Reynolds number (Re_p)
Piling	2.62×10^5	3.58x10 ⁵
Deployment	5.72x10 ⁵	4.85x10 ⁵
Living Docks	6.08x10 ⁵	5.17x10 ⁵

With the scaling analyzed, the coefficients determined from the lab simulations were applied in the Morison's equation to the full scale parameters for storm conditions (see Section 3.1), wave height (H = 0.68 m), and pile diameter (D = 0.29 m). Table 6 shows the max forces expected on the dock piling for each phase of Living Docks calculated with coefficients approximated in the CEM, and determined experimentally through the coastal engineering and hydrodynamic approach.

Table 6: Max Forces Exp	ected in the IRL (N/m²)

IRL Force Conditions (N/m ²)				
	*Theoretical	Coastal Eng. Approach	Hydrodynamic Approach	
Piling	1920	2534	1607	
Deployment	3257	2808	2818	
Living Docks	3644	3389	3428	
*C _d and C _m approximated for large Reynolds numbers using CEM				
$(C_d = 0.7 C_m = 1.5)$				

The percent difference of both approaches compared to the theoretical approximation

was also calculated in Table 7.

% Difference				
	Coastal Eng. Approach	Hydrodynamic Approach		
Piling	32%	16%		
Deployment	14%	13%		
Living Docks	7%	6%		

5.0 Discussion

The 1:3 (0.33) scaling was applied to the diameter of the piling, wave height, and depth of the water. The ratio of D:H is considered relative when comparing the force components and follows the equation below (Dean et al. 1984).

$$\frac{H}{D} = \frac{(C_m)}{C_d} \pi \tanh(kh)$$
[19]

The drag and inertia coefficient are related to the diameter and wave height while also affected by the type of wave, which is determined by depth. By scaling down the main factors influencing the force, the coefficients that represent the IRL were able to be obtained using the parameters in the wave tank. Translating the forces measured by the strain gauge to a scaled-up version is not possible due to the diameter factors in Equation 6. Where the drag force factor uses only one multiple of diameter (D), the inertial force factor uses two (D^2), both terms of the equation would have different scales to multiply the measured force. However, the drag and inertia coefficient are solely dependent on the state of fluid motion around the piling (Morison et al. 1954; Munson et al. 2013; CEM 2004), meaning that since the Reynolds numbers were accurately scaled within 15%, the force coefficients are the same and can be translated from simulation to *in-situ* conditions. To determine expected forces in the IRL, the coefficients experimentally determined are necessary in conjunction with the parameters determined for the IRL to calculate scaled up forces.

When calculating force on a piling with Morison's equation, the CEM recommends using a constant diameter through the length of piling to calculated total maximum acting on the piling (CEM 2004). It also recommends using linear wave theory to calculate the particle velocity and acceleration for small amplitude wave in shallow water (CEM 2004). In order to validate the linear wave theory for the experiment's test conditions, a PIV study was conducted to more thoroughly analyze particle velocity. The video used was analyzed and the section found in Appendix was used to summarize the results. Figure 23 shows the particle velocity at an average and a maximum value of a vector field formed by a wave. The linear wave theory calculated the particle velocity to be 0.53 m/s which falls between the average value of 0.49 m/s and max value of 0.62 m/s. It was determined linear wave theory gives an accurate representation of particle velocity and acceleration after conducting the PIV study.

5.1 Force Comparison

There is an increase of forces with every phase of the simulation, Figure 28. Experimentally there is a 125% increase by adding an oyster mat to the dock piling and 200% increase after significant growth on the oyster mat according to the values in Table 2. However, when using the coefficients to calculate expected forces in Table 6 for lagoon conditions, the results differ. Using the coastal engineering approach, there is a 10% increase in force by adding an oyster mat and 35% increase after the oyster mat has accumulated growth. The results from using the

hydrodynamic approach shows an increase by 75% and 115% respectively. This experiment examined Living Docks after four months of deployment, and since fouling is relative to geographical location and duration as previously mentioned, results may differ over time and region. Even as growth may vary, the roughness of the piling remains relatively the same due to the encrusting nature of the benthic communities. The initial increase in diameter is from the oyster mat, and the fouling added thickness on the surface of the oyster shells. The fouled oyster mat used in phase 3 of the simulation was good representation of living docks because it was so diverse and included a wide range of organisms common in the IRL. Most of the mat was encrusted with bryozoans, sponges, and barnacles while the rest also had protruding organism such as arborescent bryozoans, tunicates, tube worms, and oysters. The growth represented both extremes of possibilities; some growth that did not increase the effective diameter drastically and some growth that increased the diameter. Another consideration in future designs is the limit of growth before the organisms fall under their own weight.

Looking at the difference in coefficients used in Table 6, the coastal engineering approach of calculating drag and inertia coefficients produced larger values for phase 1 of the experiment than the ones used in the theoretical and hydrodynamic approach calculations, leading to smaller percent increases. The differences between percent increase for the experimental values and calculated values may be due to the scaling being geometrically similar but not dynamically similar. For this reason, the coefficients were determined solely from the simulation and then used to calculate total force on a realistic piling.

The coefficients that were determined from this experiment share similar trends for both approaches. The drag coefficients increase with the added oyster mat and increase again after the oyster mat has accumulated growth. The inertia coefficients from the coastal engineering approach drop and with the addition of an oyster mat and increase again after fouling has occurred. The inertia coefficients from the hydrodynamic approach consistently decrease but remain around the same number. The dip in inertia coefficient in the coastal engineering approach is similar to an experiment conducted by Jedid et al. that showed pilings with triangular protrusions had decreased forces due to narrower wake caused by the protrusions (Jedid et al. 2018; Zeinoddini et al 2016). Phase two of the experiment involved loose shells, when an ovster mat is deployed the shells are only connected at the top of the shell, and the shell is able to orient itself with the flow, explaining the decrease in that coefficient. Phase 3 does not see this happen because the fouling cements and encrusts the oyster mat. The hydrodynamic approach results smaller inertia coefficients due to the very large S-term, Equation 16, and in turn has higher drag coefficients. However, we do not see the same decrease in phase 2 like the coastal engineering approach. The data follows the expected trend of increased drag and decreased inertia as the diameter of the piling increases, and on examination of Table 3 and Table 4 the system is drag dominated which is common for intercoastal water

ways. This means for future designs incorporating Living Docks, the force should be determined with a drag coefficient of 1.31 and inertia coefficient of 1.01 for conservative measures. These coefficients can be used for future calculations with the expected thickness of Living Docks being approximately 0.064 m (2.5 in).

5.2 Structural Impacts

As far as not exceeding force limits laid out in figure 6, the forces from Living Docks will not compromise the structural integrity of the dock. The bending limit for the types of timber typically used range from 1950 - 2050 psi and the compression limits perpendicular to the grain range from 440 - 490 psi. Table 8 below contains the expected force values found in Table 6 converted into pounds per square inch.

IRL Force Conditions (psi)				
TheoreticalCoastal Eng. ApproachHydrodynamic Approach				
Piling	0.28	0.37	0.23	
Deployment	0.47	0.41	0.41	
Living Docks	0.53	0.49	0.50	

Table 8: Max Force Expected in the IRL (psi)

It is clear even with the addition of oyster mats and the fouling they attract, the increased forces are far from exceeding limits the American Wood Council has published. Other influences can affect the structural integrity of the dock such as marine borers. There are five main organisms of concern that are either identified as crustaceans or mollusks: piddocks, ship worms, limnoriids, sphaeromatids, and

chelurids (Rajapakse 2008). These organisms can either eat and deteriorate the wood from the outside causing weak points, or weaken the pile from within, leaving no traces of damage on the surface but a hollow interior (Rajapakse 2008). Since the main objective of Living Docks is to recruit additional fouling and benthic creatures, it is possible Living Docks may influence the structure through its recruitment rather than its placement. While the oyster mats can create habitat for marine borers to thrive, it may also deter them whether it be through filtering the larvae out of the water or encrusting the oyster mat enough to armor the dock. Pilings that are treated with creosote are generally protected as the pesticides prevents infestations, however, marine borers can still pose a threat for any piling (Rajapakse 2008). More testing would need to be performed to determine the biological effect on the dock structure.

6.0 Conclusion

Living Docks is an innovative and simple new approach to oyster restorations in coastal estuaries. In addition to contributing to restoring the oyster population, the recruitment from Living Docks naturally filters water removing excess nutrients and suspended solids which help reduce effects of increased runoff and eutrophication. This experiment advances research in ecological engineering by proving Living Docks as a safe and reliable restoration effort. As urbanization increases along the coast, hard structures are being introduced more into the environment. There is protentional to implement restoration efforts that take advantage of the structures, such as providing suitable substrate for oysters in a secure location on dock pilings. After simulating storm conditions typical for the IRL, force coefficients for a plain piling, a piling with a freshly deployed oyster mat, and a piling with an oyster mat with significant accumulated growth were determined. Comparing the max forces expected in the IRL from Living Docks to the standard set out by the American Wood Council, the Living Docks initiative poses no threat to the dock's structural integrity. Out of the two approaches used in this experiment, both approaches to determine the coefficients were accurate; however, the hydrodynamic approach should be used in future experiments determining forces from Living Docks. The recommended coefficients of $C_d = 1.31$ and $C_m = 1.01$ from the hydrodynamic approach for conservative measures, and thickness of 0.064 m (2.5 in) for Living Docks, can be used to calculate expected forces in any location for future designs.

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Appendix: PIV Study

The following figures are taken from PIV lab that analyzed the velocity resulting from the waves. Frames 1-4 shows the progression of the wave and formation of vector field.







