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PROBABILISTIC ASSESSMENT OF ENVIRONMENTAL DEMANDS OF A TIDAL TURBINE DEPLOYMENT SYSTEM

Chao Yang
University of New Hampshire, Durham

PROBABILISTIC ASSESSMENT OF ENVIRONMENTAL DEMANDS OF A TIDAL TURBINE DEPLOYMENT SYSTEM

BY

CHAO YANG

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THESIS

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This thesis has been examined and approved in partial fulfillment of the requirements for the degree of Master of Science in Structural Engineering by:

Thesis Director, Erin Santini Bell, Ph.D., P.E. Civil and Environmental Engineering

Ricardo A. Medina, Ph.D., P.E. Civil and Environmental Engineering

Robert Henry, Ph.D., P.E. Civil and Environmental Engineering

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Abstract

PROBABILISTIC ASSESSMENT OF ENVIRONMENTAL DEMANDS OF A TIDAL TURBINE DEPLOYMENT SYSTEM

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The area of tidal energy conversation has gained increased national and international attention in recent years as society makes strides to decrease reliability on fossil fuels and increase sustainability. Tidal energy installations require significant structural support systems to insure efficient energy conversion. These installations are in areas that experience highly variable and large in magnitude environmental loads due to current speed, wave action and wind gusts.

Performance-Based Design (PBD) was initially developed in response to life safety concerns, costly levels of structure damage, and significant economy lose experience during extreme weather events such as earthquakes, hurricanes, and floods. In the past, PBD was widely used in Performance-Based Earthquake Engineering (PBEE). Decades later, PBD was expended for wind and floods applications. There are still uncertainties for PBD, therefore, a number of methodologies were developed in recent years. The Probabilistic approach of PBD is intended to quantify the uncertainties efficiently, as quantification of uncertainties was originally used and developed for Probabilistic Seismic Hazard Analysis. Similarly, the Tidal Turbine Deployment System (TTDS), investigated as part of this work, is a new design, unlike the normal structure

design, such as office buildings, hospital, apartments, that have specific design code provisions for load development and combinations. The TTDS design process includes uncertainties related to structural demands, for example, the wave load, drag load and wind load. The goal of this study is to use the probabilistic assessment of environmental demands to verify the design, evaluate the impact of highly variable wind and wave load demands on structural performance, and explore the probability of the target anchorage force under a variety of load applications.

Chapter 1 Introduction and Literature Survey

The area of renewable energy technology has gained increased national and international attention in recent years as society makes strides to decrease reliability on fossil fuels and to increase sustainability. This movement includes expanded offshore wind installations, wave energy deployments and tidal turbine installations. Building wind turbines offshore, where strong, steady wind could, in theory, generate large amounts of power, has long been seen as a vital step toward a future based on renewable energy [1]. The converters used for wave energy can produce less noise and barely has impact on ocean life, including birds [2]. The tidal turbines are deployed in areas of high tidal currents and are used to convert tidal energy to electrical energy [3]. While most of the research in this field is related to blade shape and rotor design, these renewable energy installations can be successful only if the structural support system is adequately rigid and structural sound. The renewable energy support structure space an ideal application for the probabilistic demand development, commonly used in performance-based design protocols. This is the focus of this thesis.

1.1 Performance-Based Design

Normally, the current building codes and the minimum design requirements are Minimum design requirements are used to ensure life safety, collapse prevention, and satisfy serviceability criteria. Design is much more than simply provide “sufficient structural capacity”. However, in reality, the structures experience multiple structural demands during an extreme event such as an earthquake, a flood, or a hurricane, which if not properly considered in design could lead to structural failures. Many structural failures occur during these events, which calls for an increased understanding of the environmental demand and the building performance under these demands to perform a safety evaluation of the structure. This scenario was first studied in the seismic design community due to the highly variable and destructive forces associated with earthquakes. In an effort to mitigation losses, in term of human life and economy, performance-based design (PBD) methodologies were developed by research engineers. According to the dictionary, the term of performance is defined as a measure of how effective something or someone is at doing a good job [4]. However, the performance in as PBD defined in engineering terms relates to the building performance during an event, the building's condition after an extreme event and the amount of repair required to maintain the desired level of service for the structure. The PBD is identified by *International Code Council Performance Code for Buildings and Facilities* (ICC PC) [5] as:

> "An engineering approach to design elements of a building based on agreed upon performance goals and objectives, engineering analysis and quantitative assessment of alternatives against the design goals and objectives using accepted engineering tools, methodologies and performance criteria."

The process used by PBD is to evaluate the performance of the structure under different hazard events, and it account for the uncertainties associated with modeling, analysis methods, material characteristics, etc., which affect the performance of a structure into the consideration [6]. A hazard event has been defined as a source of potential danger or adverse conditions [6]. The main flow of the PBD process is shown in Figure 1.

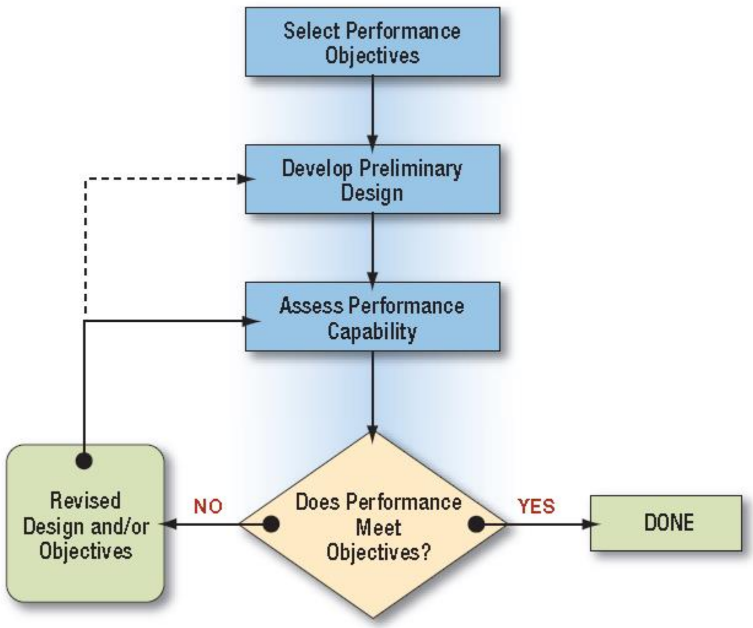

Figure 1: PBD Process [5]

Several major seismic events occurred during the past decades such as Northridge, California (1994), Kobe, Japan (1995), and Wenchuan, China (2008) [7] have indicated life safety related issues, large economic loss, and significant costs for the repair after the earthquakes. Performance-based design in earthquake engineering, performance-based seismic engineering, has been widely used and is rapidly being enhanced as more data is collected related to seismic events. Much of the methodology of performance-based design is under developed by the Pacific Earthquake Engineering Research (PEER) Center [8]. A key focus area is the methodology based upon a deterministic (scenario basis or event) or a probabilistic basis.

1.2 Probabilistic approach of PBD

The performance-based design methodology includes procedures for estimating risks with respect to a specific structural design. The risk is expressed on either a deterministic (scenario basis or event) or a probabilistic basis [8]. Apart from being rare events and having large consequences, earthquake events have large uncertainty associated with them. It is challenging and complicated to make the quantification of performance objectives because of this uncertainty [9]. Probabilistic Seismic Hazard Analysis (PSHA) aims to quantify these uncertainties, and combine them to produce an explicit description of the distribution of future shaking that may occur at a site [10].

The probabilistic approach of the PBD is a broad methodology applied to an earthquake magnitude at many levels. According to PSHA, the probabilistic functions such as cumulative distribution function (CDF) and probability density functions are computed by taking the derivative of the cumulative distribution functions [10]. The CDF can be computed as [10]:

$$F_M(m) = \frac{\lambda_{m_{min}} - \lambda_m}{\lambda_{m_{min}}} \qquad (1)$$

where m_{min} is the minimum magnitude of the earthquake, λ_m is the rate of earthquakes with magnitudes greater than the magnitude m. It is express by the *Gutenberg-Richter recurrence law*:

$$log_{10}\lambda_m = a + bm \qquad (2)$$

where, a and b are constants.

The equation for calculating the probability of exceedance of any PGA level (peak ground acceleration) is related to its mean and standard deviation (equation 3) [10].

$$P(PGA > x|m, r) = 1 - \emptyset\left(\frac{\ln x - \overline{\ln PGA}}{\sigma_{\ln PGA}}\right) \qquad (3)$$

where, $\overline{\ln PGA}$ is the mean,

$\sigma_{\ln PGA}$ is the standard deviation,

m is the magnitude,

r is the source-to-site distance and,

Ø() is the standard normal cumulative distribution function.

From Equation 3, the probability of the peak ground acceleration (PGA) at certain distance, from an earthquake source to a site, can be determined shown in the Figure 2.

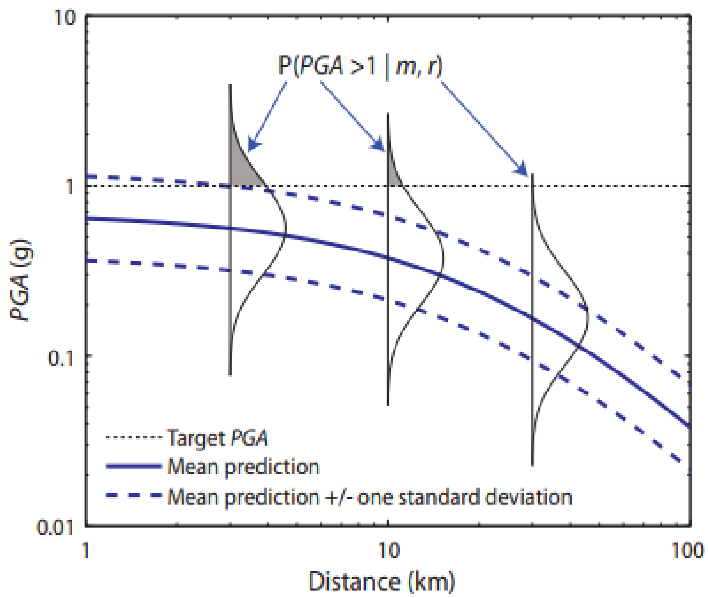

Figure 2: Graphical depiction of the example ground motion prediction model for a magnitude 6.5 earthquake, and the probability of PGA >1g at several source-to-site distances. [9]

The probabilistic approach of the PBD requires analyzing the seismic hazard. It requires to use the actual capacity of the structure to determine the structural damages and failures. However, the application of PBD is limited for the tidal turbine installation, which is the focus of this work, because of the lack of data relating to the environmental demands. Therefore, a range of wind speeds, wave heights and wavelength were considered for this analysis. This range was selected based on input for the marine community, the students and professors in Ocean Engineering Department at University of New Hampshire, for minimum and maximum expected wind and wave characteristics. This information was collected through interviews by the Living Bridge team and does not have statistical basis. Also, the performance criteria used for this study was based on an owner, New Hampshire Department of Transportation, Maine Department of Transportation, and Federal High Way government, requirement to minimize structural impact on the anchor points for the turbine deployment system to the bridge pier. In order to produce probability of the target anchorage force, similar to Figure 2, this study employs a CDF based on an assumed range of environmental demands. The PSHA procedure is adapted to perform a probabilistic assessment of the environmental demands, including wave and wind loadings, for the design of a support structure for a tidal turbine installation.

1.3 Thesis Goals

The main contribution of this thesis work is to provide a decision-making guide for turbine operation with response to environmental demands to ensure that the acceptable force, as determine through discussion with the bridge owner, is not exceeded. The decision-making guide for turbine operation is based on the target probability of exceedance of the target anchorage forces which was determined as 5%. If the probability of exceedance is higher than the target probability, the suggested action would be to stop operation of the turbine or lift the turbine out of water. The potential benefit of decision-making guide for turbine operation to the profession is to avoid damage to the pier cap due to environmental demands in an efficient manner.

As previously mentioned, the initial design of the TTDS (Tidal Turbine Deployment System) was based upon the expected 'worst events' due to the uncertainties associated with the wave loads, drag loads, wind speeds magnitudes and limitations of the design codes application to this structure. The wave loads vary with different wave lengths, wave heights, and the depth of the water passing under the bridge. Different types of structures, for example, a fixed structure versus a floating structure, have different wave loads. Similarly, drag loads vary with speed of the current. For these reasons, quantifying the uncertainties related to the environmental demands, was the main tasks in this study.

The main goal of this study is to verify the design of a TTDS and provide a decision-making guide for turbine operation that is based on expected performance under a range of environmental conditions. The TTDS includes two parts; (1) vertical guide posts (VGP) that are anchored into the pier cap and (2) the tidal turbine deployment platform (TDP) that sides along the VGP with the tides. A major consideration during the verification was to make sure the TTDS did not negatively impact the structure of the pier cap, which include structural damage or increased maintenance needs. In order to achieve the main goals of this thesis, the following tasks were performed:

- Determining the best location of the sensors, strain gages, which will be installed on the A-frame of the VGP of the TTDS.
    - The worst design events were used to determine the locations by identifying the location of the maximum strains
    - This data was not used as part of this work due to delays in sensor installation. However, provision and recommendations for inclusion of the sensors data into this procedure are provided in the Future Work section.
- Developing environmental demands on the VGP and TDP.
    - Collect wave load information and develop the wave load demands
    - Collect wind load information and develop the wind load demands
- Determining the structural impact of the wave loads and wind loads

- Determining the impact of the turbine deployment configuration on the TTDS anchorage system
    - Impact of the turbine operational status and position on the torque and drag loads
    - Impact of turbine status on the load transfer between the turbine at the TTDS
- Determining load conditions that require one the following responses to protect the pier cap
    - Shutting down turbine
    - Lifting the Turbine out of water

Chapter 2 Performance-Based Design Applied to a Tidal Turbine Deployment System

In a traditional structural design procedure, the first step is defining the requirements which include the load demands, structural requirements (the architecture, number of floors, and foundation depth), environmental protection conditions, etc. The second step is design the structure based on the afore mentioned requirements. The third phase of the design includes creating analytical models and verifying the structural design by comparing the predicted structural response to the allowable capacity from the structure design guides or codes. The last step is construction of the structural system. The design flow based upon a probabilistic assessment of environmental demands is different. For this study, the flow chart was created by combining the PBD structural design process (Figure 1) and the probabilistic approach of the PSHA.

2.1 Traditional Structure Design Flow for TTDS

The traditional structural design flow was used for the initial design of the TTDS shown in Figure 3. In step one, the loads (live load, dead load, current drag load on the TTDS, the torque of the tidal turbine, wind loads, and wave loads) were identified and determined by the Living Bridge Research Group. These demands were developed in consultation with local ocean engineering, Duncan Mellor, P.E., the New Hampshire Department of Transportation and the New Hampshire Port Authority.

Step two is to design the support structure for the TTDS based upon the demands identified in step one and the performance requirements based on bridge owner objectives. Then, step three uses SAP2000® [11], a civil engineering structural analysis software, to create a model of the

TTDS, and use the results of the SAP2000® [11] to analyze the TTDS. The step four used the model-based results to verify the structural design, for example, verifying the connection between members. This process is repeated until the design meets the required criteria.

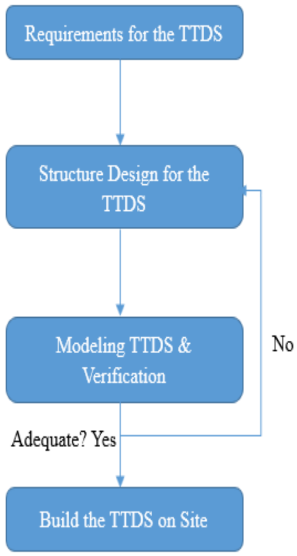

Figure 3: Initial TTDS Design Procedures

2.2 Flow Chart of This Study

A TTDS was built and installed at the Memorial Bridge in 2017. The uncertainties related to the environmental demands, such as, the wave load, wind load, and the tidal current speed, are not included in the initial design procedures, but the uncertainties related to the environmental demands were developed in this study. A range of values was selected for inclusion in this study to represent the expected variation in environmental demand.

A probability-based assessment of environmental demands and the impact of those demands on structural performance provides a basis for turbine operation decision-making with respect to the anchorage limits. In order to confidently avoid the damage of the pier cap, a safety factor of four was used on the strength capacity of each anchor (72 kip [12]) to determine the acceptable anchorage limit per bolt, resulting in an 18-kip performance limit.

However, due to the uncertainties related to the environmental loads, a combined methodology (shown in Figure 4) that includes the general PBD procedures and PSHA procedures that were applicable to this study. This combined methodology uses the general procedures of PBD shown in Figure 1 as the main process. Then, it uses the procedures of the probabilistic approach after the step two of the general process of PBD. This methodology was applied to the TTDS at the Memorial Bridge as part of the Living Bridge Project. The structural models used for the probabilistic assessment of the environmental demands were created in GT-Strudl® [13], but any structural analysis program would be appropriate.

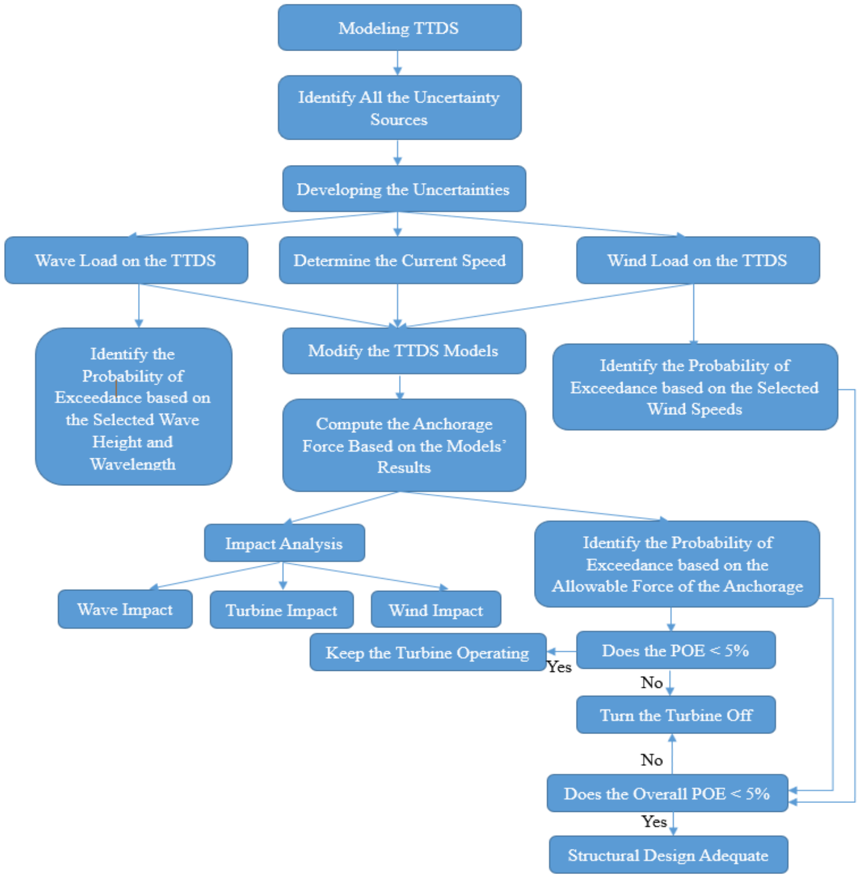

Figure 4: Flow Chart of Probabilistic Assessment of Environmental Demands on the TTDS

As shown in **Error! Reference source not found.**, developing the uncertainties is the main step i n the flow chart. In order to have an accurate and reasonable development of the uncertainties, a case study of the TTDS and the environmental loads for the TTDS are specifically discussed in Chapter 3 and full developed Chapter 4.

The wave load and wind load were developed independently for this work, but there are dependencies between wind and wave load that should be included in future applications. For instant, the wave height is much higher during a hurricane than the wave height under a normal wind speed. The relationships between wind and wave were not developed in this study, but it will be developed once field data is available.

Chapter 3 Case Study for Living Bridge Project

The Probabilistic Assessment of Environmental Demands (PAoED), as shown in Figure 4, was implemented for the design verification and operational decision-making of the TTDS at the Memorial Bridge in Portsmouth, NH, as part of the Living Bridge Project. The Living Bridge Project is funded by a combination of state and federal agencies to create an example of the future of smart, sustainable and user-centered transportation infrastructure. This project includes a structural health monitoring system for in-service condition assessment of the innovative gusset-less connections and the tower design [14]. This project is funded by the National Science Foundation's Partnerships for Innovation: Building Innovation Capacity program (#143260), the New Hampshire Department of Transportation's Research Advisory Council, The Federal Highway Administration program for Technology and Innovation Deployment Program and the Department of Energy.

3.1 Living Bridge Project

The Memorial Bridge in Portsmouth, NH is the focus, the Living Bridge Project. The bridge is on US Route 1 and connects Portsmouth, NH to Kittery, ME (Figure 5). The Memorial Bridge is a smart bridge as it is instrumented with structural sensors to allow for self-diagnose and self-report structural response related to the current condition of the bridge [14]. The collected information can be used to verify the structural design of the bridge, to calibrate the computer model, and measure the bridge excitation for decision relating to the lift operation of the bridge [14]. A Tidal Turbine Deployment System (tidal generator) is used to supply energy to the sensors.

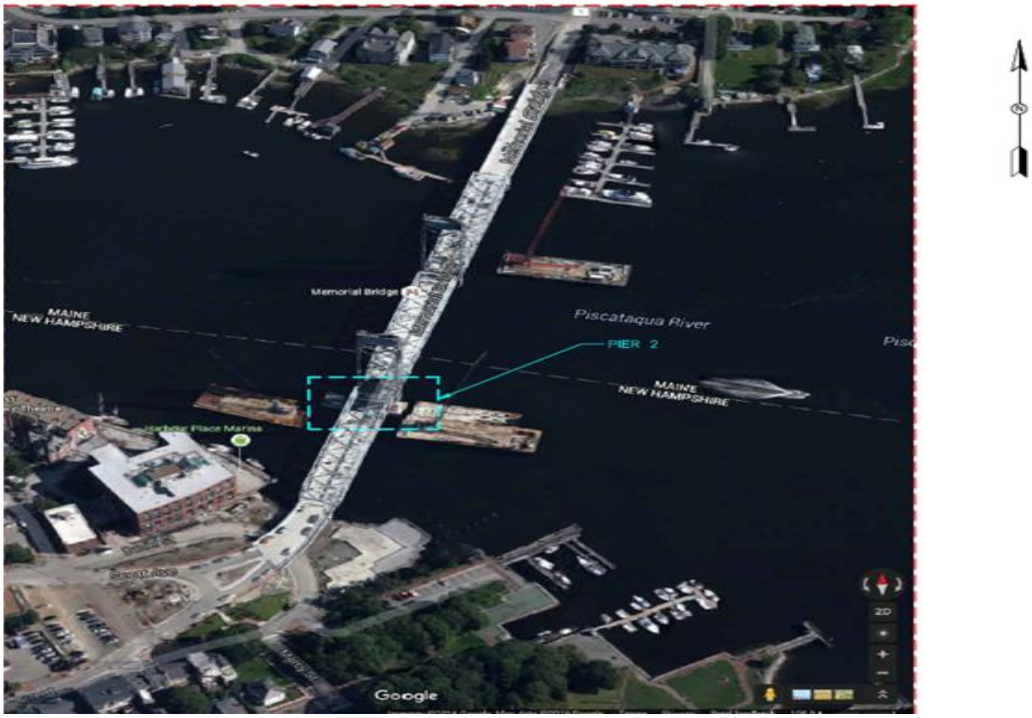

Figure 5: The Location of Memorial Bridge and the TTDS

3.1.1 The Tidal Turbine Deployment System (TTDS)

The Tidal Turbine Deployment System is a part of a system provide renewable energy to power the functions of a bridge. The TTDS for the Memorial Bridge is attached to the second pier from the Portsmouth, NH side as shown in Figure 5. The TTDS includes the Vertical Guide Post (VGP) anchored to the pier cap and Turbine Deployment Platform (TDP). The VGP consists of two 22-foot-long vertical members (Round HSS 16 x 0.5), two 24-foot-long horizontal members (Round HSS 10 x 0.5), and eight support legs (Square HSS 8 x 8 x 1/2), forming an A-frame shape. The A-frame legs are welded to eight plates which frame members are anchored to the pier cap (Figure 6). The dimension of VGP is shown in Figure 43 (Appendix B).

The main structural components of the TDP is a platform comprised of W 12 x 26 frame members and two 49-foot-long pontoons with a diameter of 21 inches. It includes the turbine, railings, etc. The dimensions of TDP is shown in Figure 44 (Appendix B). The TDP will float on the water surface and freely move up and down guided by using the VGP. The platform has an opening area named as a Moon Pool (shown in Figure 6) which allow the turbine to freely rotate. In this study, a computer model of the TTDS was modeled and static analysis was performed using GT-Strudl® [13].

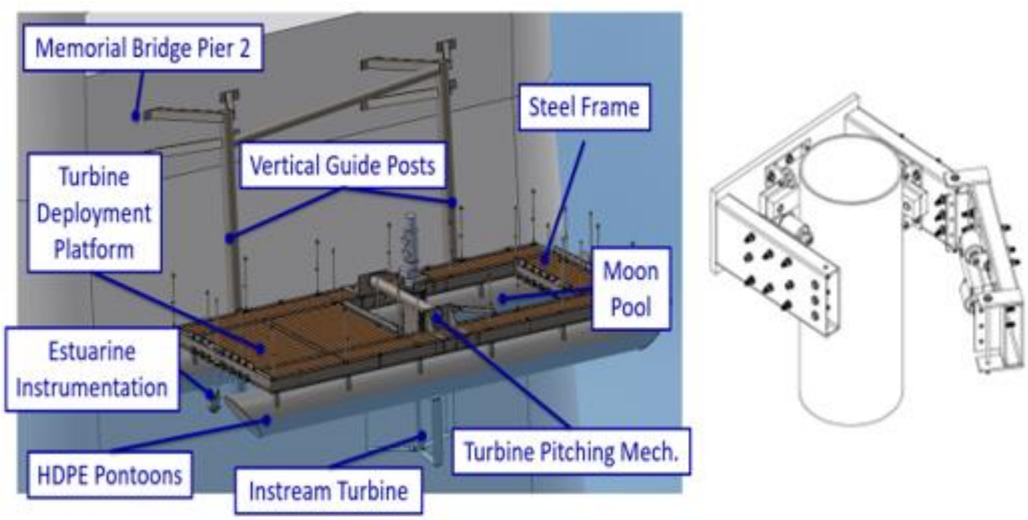

Figure 6: Tidal Turbine Deployment System and The Pile Guide [17]

3.1.2 Tidal Turbine Installation Consideration

The Memorial Bridge pier caps are supported by piles. The pier caps are made of reinforced concrete and used to protect the piles (shown in Figure 7). In order to maintain structural integrity and condition of the pier cap, the force demand allowable for the anchor bolt is based on a safety factor of four with respect to the structural capacity of the anchor bolt. In designing the pier cap anchorage for the TTDS, there were three actions that can be used to control the anchorage force demands, (1) stop turbine operation (2) remove turbine for water and (3) remove the platform from the bridge pier.

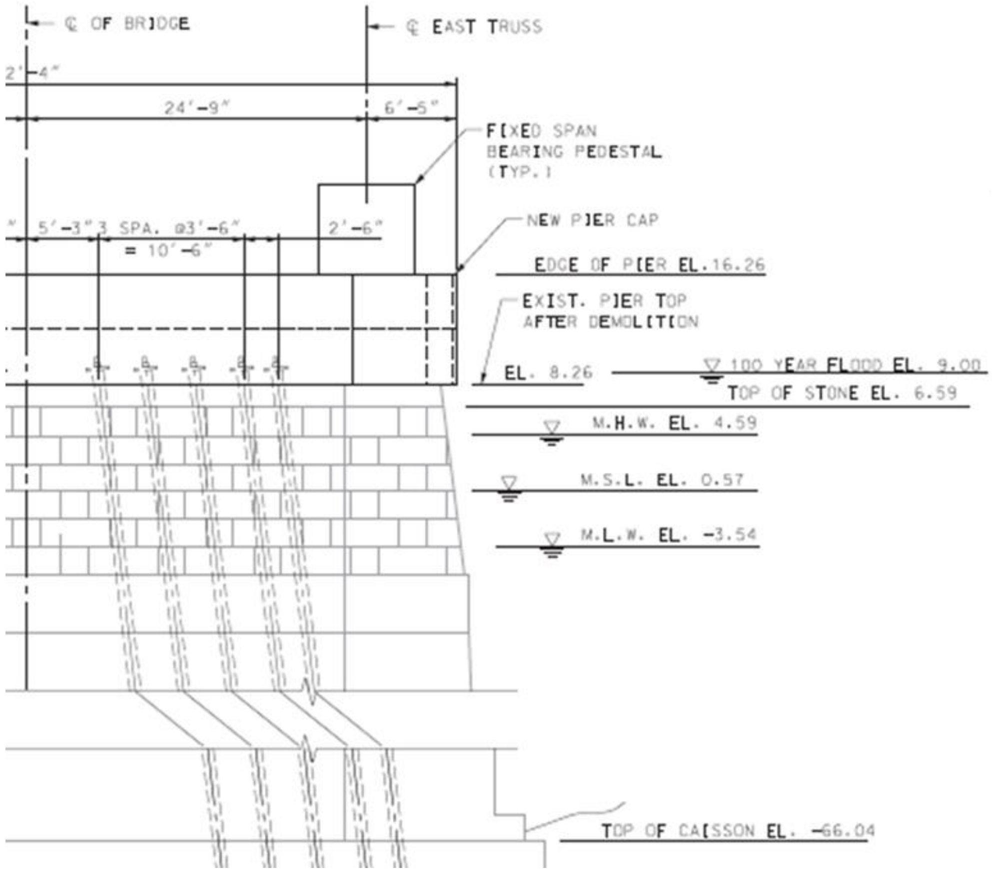

Figure 7: Excerpt from HNTB "PIER 2 - RETROFIT PLAN AND ELEVATIONS" [17]

The anchorage system is comprised of four one-inch diameter stainless-steel thread epoxy anchors (Appendix A: Figure 37). The first two actions, (1) and (2), are related to the turbine status and position (discussed in Section 6.1). The third reaction would require removal of the platform which involves releasing the pile guides and towing to the platform to an alternative site. The pile guide (Figure 6) is comprised of rectangular plates and rollers inside the plates. The design of the TTDS is based upon ‘worst-case conditions’ which includes the maximum expected wave load, the wind load, and the drag loads, applied under the worst structural configuration, i.e. when the tidal height is the lowest and the moment arm is the longest.

Prior to performing a PAoED for the PBD, a standard structural design was completed using available design codes, environmental information and structural modeling. The next part of Chapter 3 details the structural loads used in the initial design of the TTDS, including live, dead, wind, drag and wave loads. Several assumptions were needed in order to develop the environmental loading demands. The assumptions include the wave height determined as 2.5 feet, the wavelength chosen as 30.3 feet for parallel wave and 75.9 feet for perpendicular wave, the shallow draft of the platform used, etc. This led to a variability in these loads and the high level of uncertainty in the structural performance specifically related to the environmental demands, including wave and wind loading.

3.2 TTDS Structural Modeling

A Tidal Turbine Deployment System at the Memorial Bridge, as shown in Figure 6, includes two major components, the Vertical Guide Posts and the Turbine Deployment Platform. The TTDS will be subjected to highly variable tidal demand and a dynamic structural configuration as the turbine will be rotating to convert tidal energy to electric energy. The TDP must move vertically with the tide to ensure that the turbine is always properly submerged. The A-frame of the VGP is attached to rectangular plates and anchored to the pier cap. The support condition used in the model for the A-frame was a fixed support. All the elements of the TTDS are full moment connections except for the connection between pile guide and the VGP. The pile guide is rigidly connected to the TDP, but it allows the TDP to freely move up or down along the VGP. The connection between pile guide and VGP is modeled such that no vertical forces which can be transferred to the VGP and there is no moment about vertical axis of the VGP.

A sensitive analysis was performed using GT-Strudl®. Linear spring elements were used to represent the buoyancy force provided by the pontoons, see Figure 6 and Figure 8. The spring constant was calculated assuming the displacement of the platform was 1.0 inch, producing the spring constants shown in **Error! Reference source not found.**.

Table 1: Spring Coefficient

Location	Dipsl. (in)	Load (lbs)	K_spring (K/ft)
Inner	1	2547	30.56
Corner	1	1273	15.28

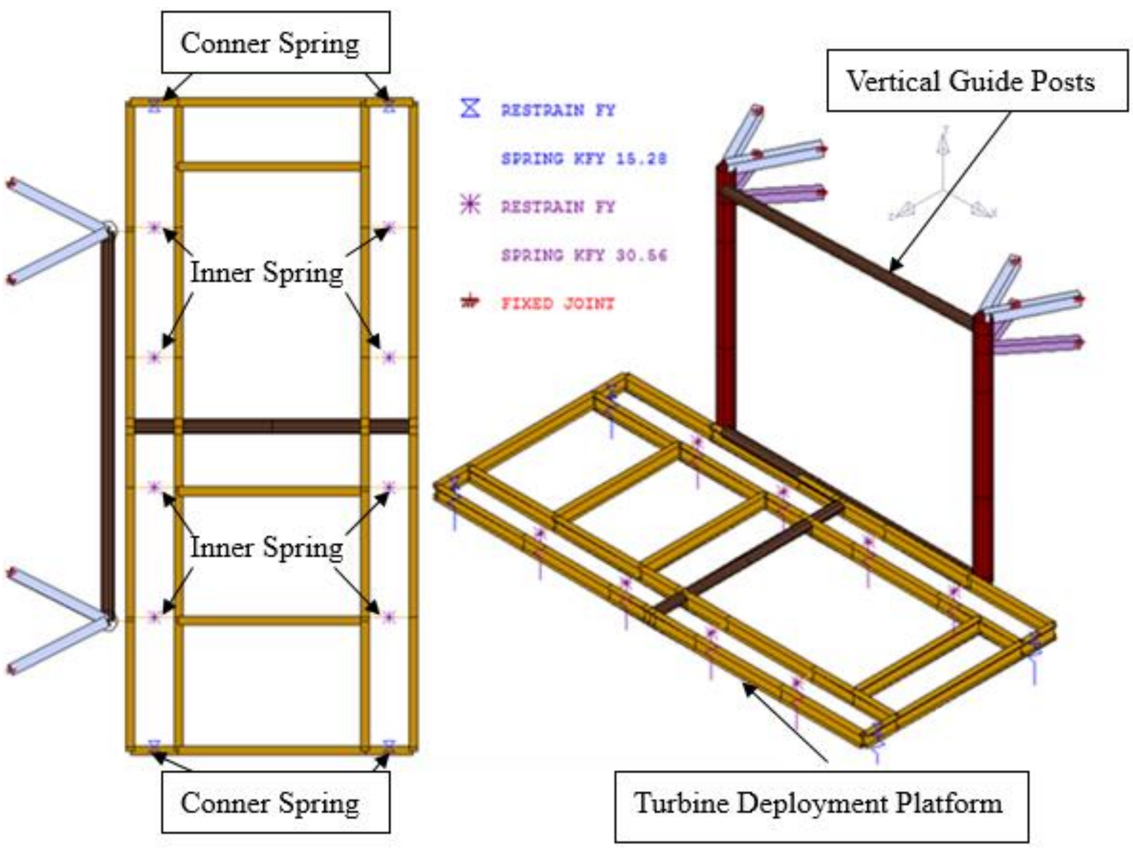

Figure 8: GT-Strudl® Model of TTDS

The GT-Strudl® [13] Model of TTDS shown in Figure 8 was created for the initial design purpose. It was considered as the model used for the 'worst case", because it offered the largest moment arm. However, after analyzing the data collected by the Acoustic Doppler Current Profiler (ADCP), the maximum current speed, 5.91 feet/s, had a relative depth of the tide which was 0.81 feet higher than the MSL. The ADCP is a hydro-acoustic current meter used to measures the speed and direction of ocean currents using the principle of "Doppler shift" [15]. Therefore, the model must be customized accordingly. In order to customize the model (shown in Figure 9) appropriately for the rest of the analysis, the distance from bottom of the VGP to the TDP was updated. This distance was calculated by combining the distance from the bottom of the VGP to the Mean Sea Level (MSL), 6.35 feet (Appendix B: Figure 43) and the relative depth of the tide which was 0.81 feet higher than the MSL.

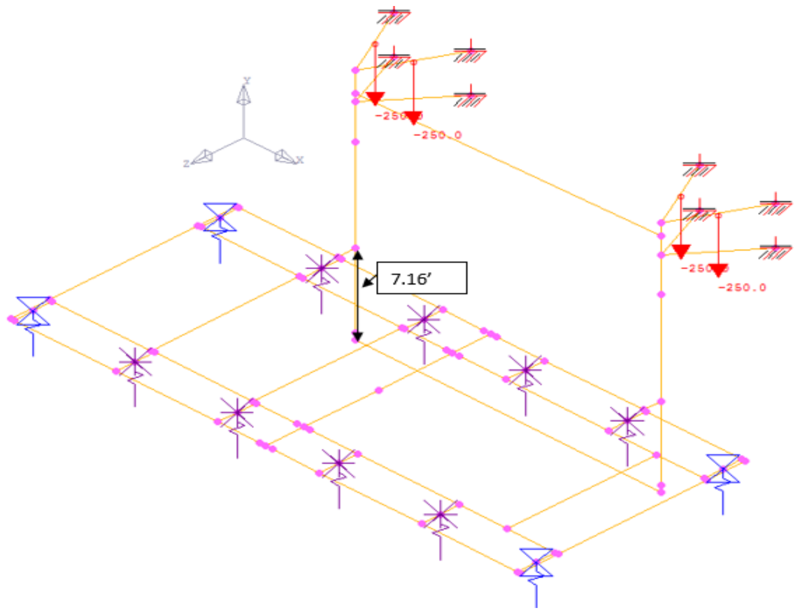

Figure 9: Updates of the GT-Strudl® Model of TTDS

3.3 Considered Design Loads

The loading guidelines shown in ASCE 7-10 states that structures, components, and foundations shall be designed so that their design strength equals or exceeds the effects of the factored loads [16]. In this thesis, the load factor which is equal to one was applied to all the load combinations that were used within the GT-Strudl® [13]. The load combination, PL, which includes the dead load, the live load, the drag loads, the friction load, and the parallel wave load. The drag loads include wind drag and current drag. Likewise, load combination, PP, has a similar combination except that the wave load that is perpendicular to the pier cap. A parallel wave load has a direction of the wave force parallel to the pier cap. A perpendicular wave load has a direction of the wave force perpendicular to the pier cap. Design loads that were considered in this study are shown in Table 2.

Table 2: Considered Design Load

Load Summary			
Loads	Values	Unit	Ref
Dead Load	Self-weight	*lbs*	ASCE 7-10
Live Load	250	*lbs*	ASCE 7-10
Current Drag on Pontoon	275.28	*lbs*	Equation 5
Current Drag on Turbine	4056.3	*lbs*	Equation 5
Turbine Torque	3105.2	*lbs-ft*	Equation 6
Wave Load on Turbine	12198	*lbs*	Ref 11
Perpendicular Wave Load on TDP	7721.5	*lbs*	Ref 12
Parallel Wave Load on TDP	3520.5	*lbs*	Ref 13
Wind Load on TDP	23.64	*lbs*	Equation 5

3.4 Location of Sensors on the A-Frame

Section 3.1 describes the tidal turbine deployment system. Maintaining structural integrity and condition of the pier cap is the major structural consideration, which means the demand of anchorage force must not exceed the allowable anchorage force which is 18 kips. It was decided that sensors (strain gages) needed to be installed on the A-frames of the VGP. The sensors can track changes in the strain which help engineers verify the design and protect the pier cap. The strain is calculated by using the following equation:

$$\varepsilon = \frac{\sigma}{E} \tag{4}$$

Where ε is the strain (in/in), σ is the stress (kips/in^2), and the E is the modulus of elasticity (kips/in^2). As the A-frame members are made of steel, the value of E is 29000 ksi. The combined stress is estimate by using the following equation:

$$\sigma_{total} = \sigma_{axial} + \sigma_{Y-bending} + \sigma_{Z-bending} \tag{5}$$

where the axial stress is using the $P_{axial}/A_{cross-section}$

bending stress is using the $M_{bending}/S$

M the bending moment estimated by from the GT-Strudl® model, and

S is the section modulus.

However, as sensors will be installed along the symmetric line of the cross-section of the member, the $\sigma_{Y-bending}$ equals zero. Then, the σ_{total} is calculated by using the σ_{axial} and $\sigma_{Z-bending}$. The properties of the A-frame members (Figure 6 and Figure 43) are shown in Table 3.

Table 3: Cross-section property of A-frame member

Member	**A (in²)**	**S (in³)**
Square HSS 10 x 8 x 1/2	15.3	42.7
Square HSS 8 x 8 x 1/2	13.5	31.2

The location of sensors is determined by the maximum strain approach. Both load combinations are considered for the strain calculation. In Table 4, the Load (PP) means the load combination which includes the maximum perpendicular wave load, the self-weight of the Tidal Turbine Deployment System, the maximum wind load, the maximum drag load, the torque of the turbine, and the considered live load. Similarly, the Load (PL) has a similar load combination except that the wave load is the parallel wave load instead of the perpendicular wave load. Meanwhile, in Table 4, the end close to plate means the end of a A-frame member close to the attached plate. The end close to the post is described as another end of a A-frame close to the Guide Post.

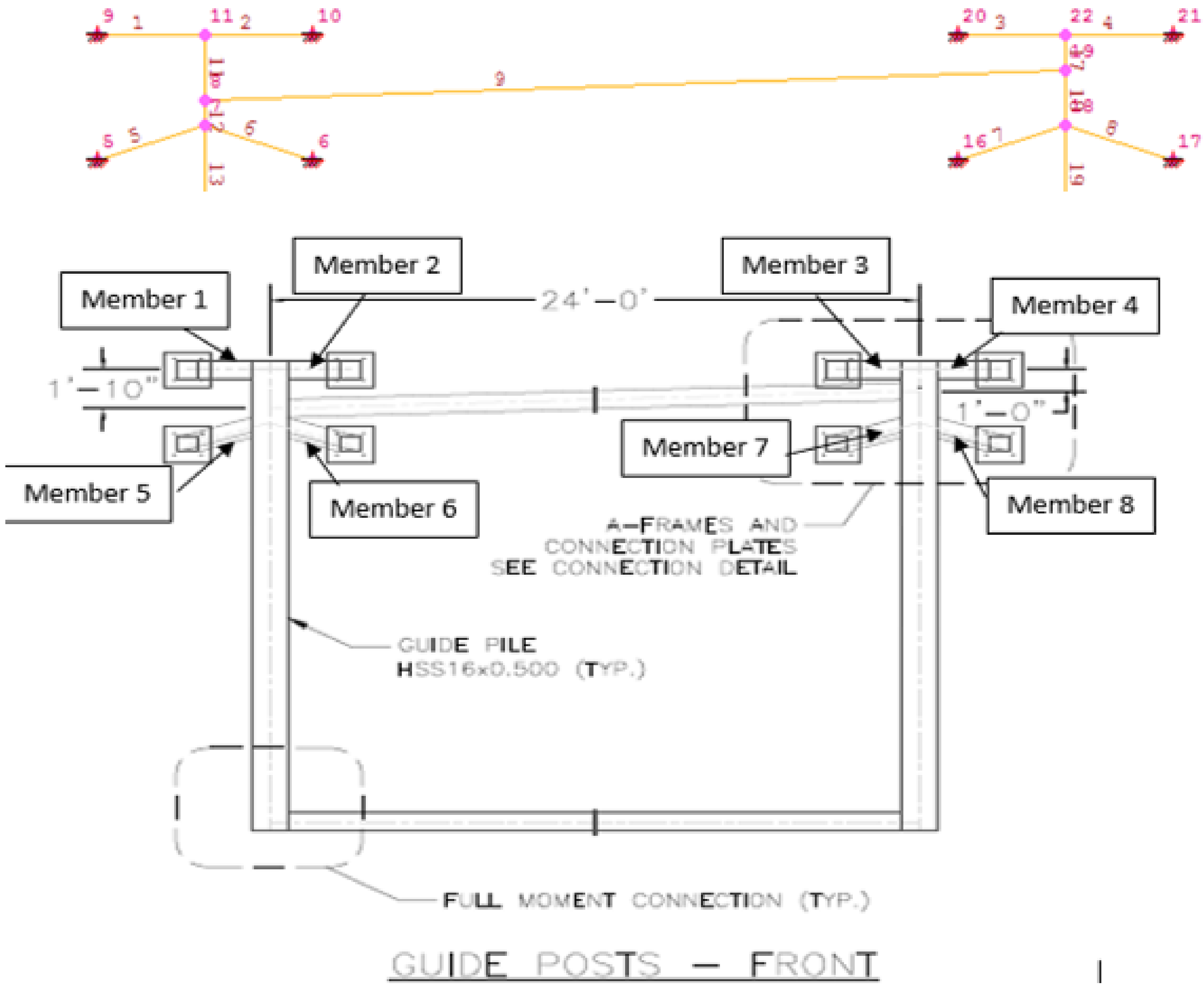

Figure 10: Member IDs and Support IDs

According to the Table 4, Member 1 and Member 5 have the highest strain on the top and the bottom of the member under these two load combinations. The Member 4 and the Member 8 also have higher strains than the other four members. However, as the analysis was based on one direction of the drag load, the wave load, and the wind load, the location of the sensors could not be determined without considering both directions of the tide, the income tide and outgoing tide. In order to estimate the strains on each member and finalize the locations of sensors, the assumption is made that the current speed, wind speed, and wave load are same in both tide directions. The loads are assumed to have same value but in a different tide direction whereas the strain is in symmetric. For example, the strains in Member 1 (Table 4) were computed based on the outgoing tide. When direction of the tide switches to the income tide, Member 4 will have the same strain values as strain in Member 1 computed based on the outgoing tide. Consequently, Members 1, 4, 5, and 8 were selected.

Table 4: Sensor locations and the maximum strain of each member

Member	Load PP(top)	Location	Load PP(bot)	Location	Load PL (top)	Location	Load PL(Bot)	Location
1	0.00022520	The end close to Post	0.00013404	The end close to Post	0.00030938	The end close to Post	0.00020442	The end close to Post
2	0.00012297	The end close to Post	0.00007602	The end close to Post	0.00010061	The end close to Plate	0.00005289	The end close to Plate
3	0.00015685	The end close to Post	0.00009302	The end close to Post	0.00009074	The end close to Post	0.00007232	The end close to Post
4	0.00007874	The end close to Post	0.00004238	The end close to Post	0.00023458	The end close to Post	0.00013584	The end close to Post
5	0.00026223	The end close to Plate	0.00029593	The end close to Post	0.00029751	The end close to Plate	0.00029668	The end close to Post
6	0.00017049	The end close to Plate	0.00022140	The end close to Post	0.00010206	The end close to Post	0.00004809	The end close to Plate
7	0.00019130	The end close to Plate	0.00005721	The end close to Post	0.00007789	The end close to Post	0.00001186	The end close to Post
8	0.00011638	The end close to Post	0.00014785	The end close to Post	0.00027390	The end close to Plate	0.00024853	The end close to Post

Base on the Table 4, two sensors were installed on the top and the bottom of Member 1. Table 4 shows that the maximum strain occurs at the end of the member (close to the post). However, the sensors are going to be installed 1.0 foot away from the post due to the installing issue.

Similarly, two sensors are going to be installed on the top and the bottom of Member 5. Table 4 shows that the maximum strains occur at the two ends of the Member 5 (close to the post and the support). After comparing the results, the bottom strains for both load combinations are relatively higher in the end that is close to the post than the strains on the top of the member. Therefore, the sensors are going to be installed 1.0 foot away from the post.

As previously mentioned, the Member 4 and 8 were determined by considering the symmetric environmental loads for both directions of the tide. Therefore, the sensors on Members 4 and 8 are going to be installed in the same way as Members 1 and 5.

The locations of the maximum strains found on Member 5 are different and the values of all the strains are larger. Two additional sensors were determined to be needed. One sensor was placed at the top of Member 5 and another one was installed at the top of Member 8. Both sensors were placed at the end of each member, close to the support.

Chapter 4: Load Developing for the Tidal Turbine Deployment Structure at the Living Bridge

Using the structural model created in Chapter 3, load demands were developed with input from faculty and students from the ocean engineering program at UNH. These demands include the dead load of the turbine, wind load, wave load (Figure 20), and the drag loads. In addition, the equations for the computation of these loads were estimated by the ocean engineering program. The load categories included live and dead loads, which were developed using standard structural design protocols and codes (section 4.1), drag and friction loads (section 4.2), wave loads, which is the main focus of the probabilistic assessment (section 4.3 and 4.4) and wind load, which are also included in the probabilistic assessment (section 4.2 and 4.4).

4.1 Live Load and Dead Load on the TTDS

4.1.1 Live Load

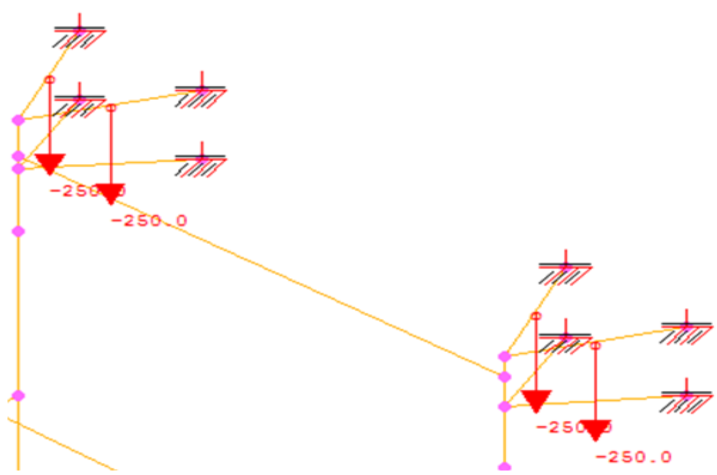

Figure 11: Designed live load on the model

In ASCE 7-10, live load is defined as a load produced by the use and occupancy of the structure [16]. However, the TTDS is a creative design which is not specified in ASCE 7-10 or AASHTO.

ASCE 7-10 also defines that the live load shall be determined in conformity to a method approved by the authority having competence if the occupancies or uses not designated in Chapter 4 [16]. Therefore, live load for the TTDS is considered as 250 lbs for design purpose, it includes the inspector's self-weight and the weight of all other equipment. The live load is applied on the middle of the members of the A-frames of the VGP shown in the Figure 11.

4.1.2 Dead Load

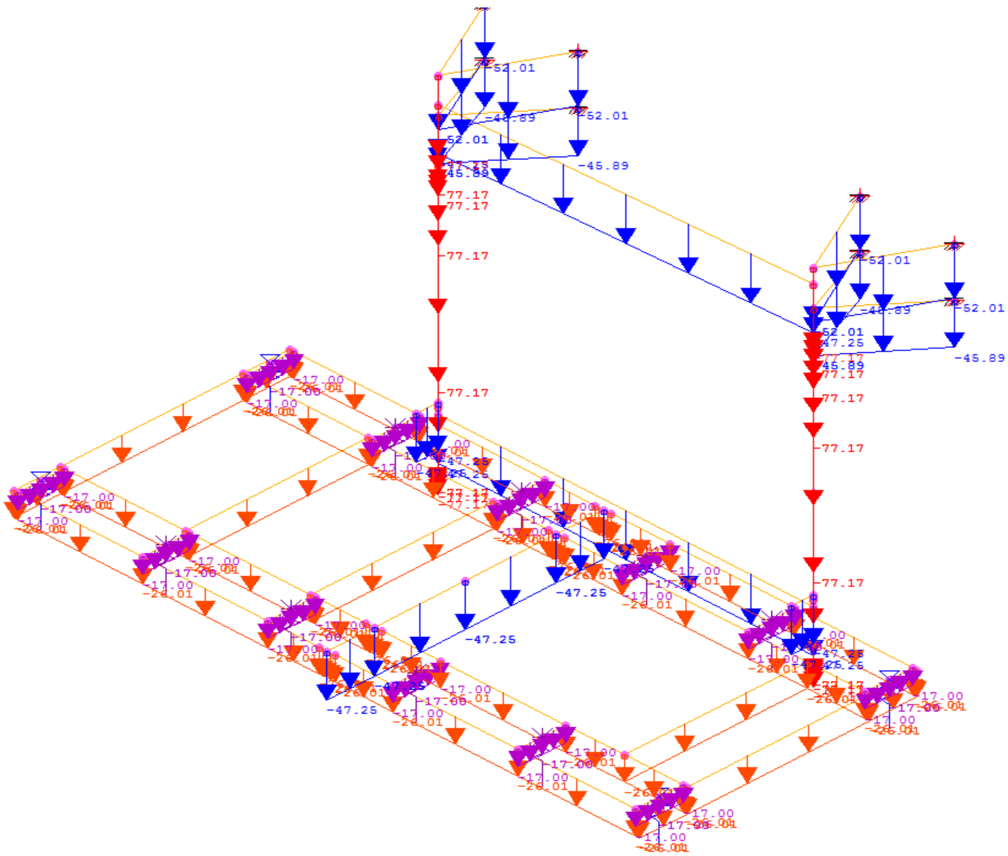

Figure 12: Designed self-weight of the TTDS on the TTDS

ASCE 7-10 has defined that dead loads consist of the weight of the materials of the structure [16]. For the TTDS model, it includes the self-weight of the VGP and the TDP, and self-weight of Turbine. The Figure 12 shows the self-weight of the VGP and TDP. The Figure 13 shows the equivalent dead load of the turbine.

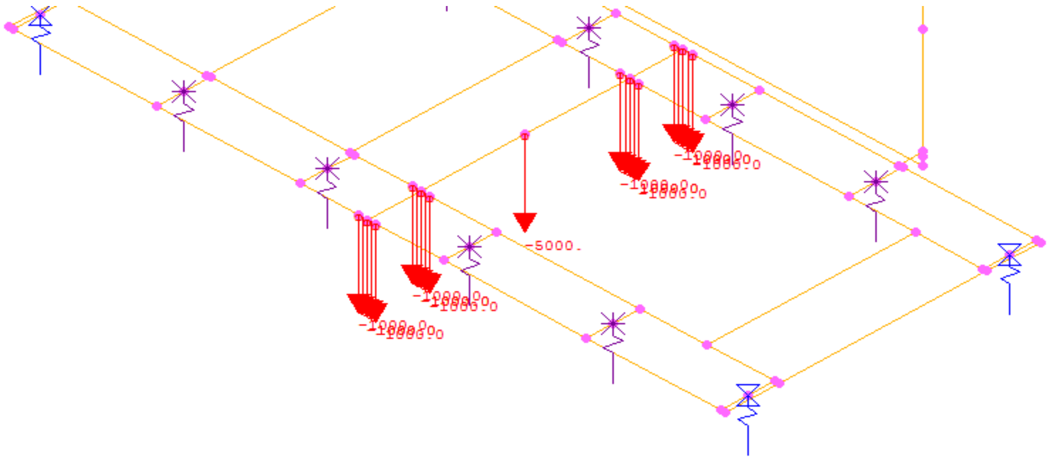

Figure 13: Equivalent self-weight of Turbine

4.2 Drag Load and Friction Load

The drag loads include tidal current drag loads and wind drag load. The tidal drag loads also have drag on the platform and the drag on the turbine. The highest current speed, 5.91 ft/s, was used to calculate tidal current drag loads measured by the ADCP, ADCP deployment performed near the deployment location in 2013-14(Figure 14).

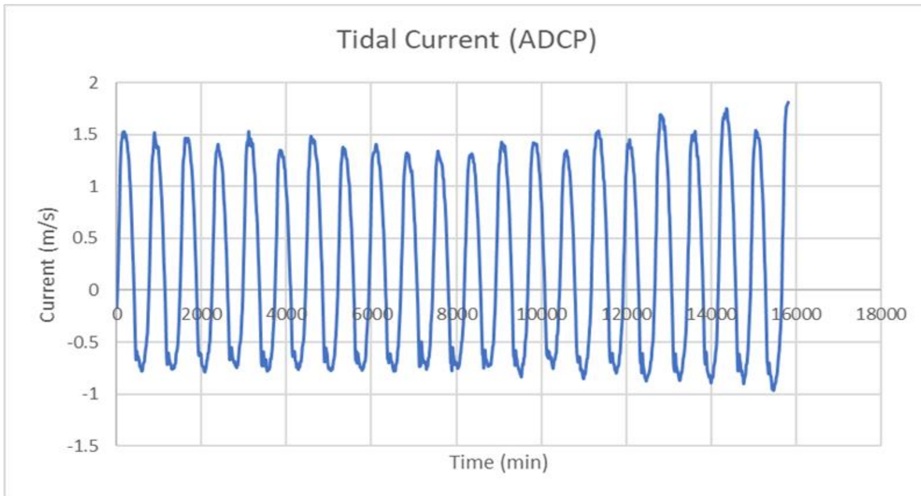

Figure 14: Tidal Current vs Time (ADCP)

The design wind speed is 45 mph which is the '100-year event' (non-extreme events) wind speed. The basic equation [17] which used to calculate the drag force is

$$D = C_T \frac{1}{2} A \rho V^2 \qquad (6)$$

D: the drag force

ρ: the density of salt-water

V: the velocity

A: cross section area

C_T: the coefficient of thrust (drag)

The density of the salt-water is 64.2 kips/ft^3. The cross-section area of the turbine is used as its swept area which is about 96.9 ft^2. The turbine size is determined by the Living Bridge Project group according to the collected ADCP data, bridge energy demands, and present turbine designs and performance specifications. The crossflow turbine for this site can have a 9.8 feet diameter and a rotor depth of no longer than 9.8 feet or a rotor swept area no larger than 96.9 ft^2 [17]. The coefficients of turbine drag approximately equal to 1.2 which is checked and computed through numerical modeling as well as physical testing of hydrokinetic cross flow turbines. Consequently, the drag force on the turbine equals to 4056 lbs (shown in Figure 15).

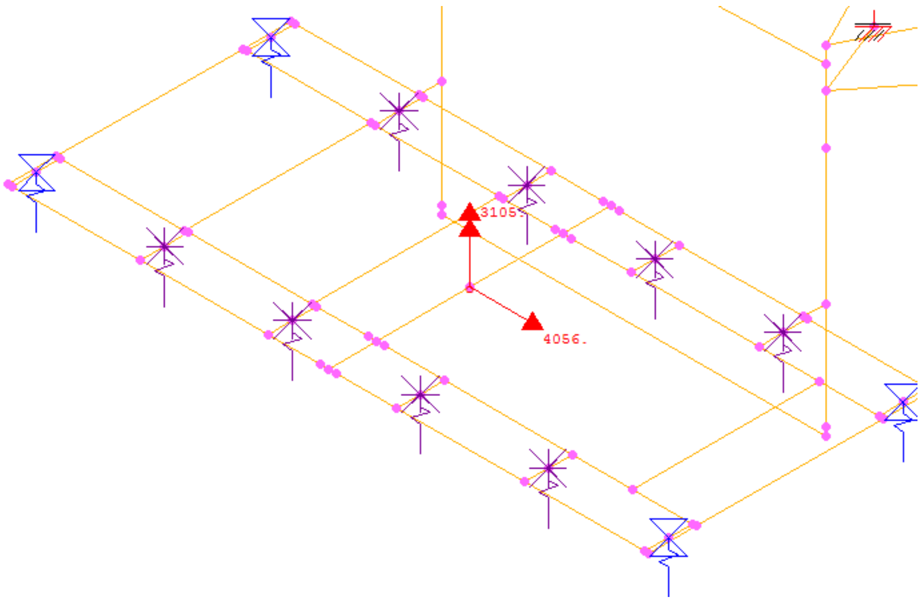

Figure 15: Designed Turbine Drag and Torque

In Figure 15, it shows the torque of the turbine which equals to 3105 lbs-ft while turbine is operating. Turbine torque is calculated based on the equation [17]:

$$T = P * \omega \qquad (7)$$

where P is the amount of the power which is produced by the rotating turbine with rotational speed ω. The amount of power (P) producing by the turbine at the maximum tidal current, 5.91 ft/s, is determined by the following equation [17]:

$$P = \frac{1}{2}\rho C_p A U^3 \qquad (8)$$

where, in a similar way, density of the salt water ρ, front facing area A, and the speed U, are as same as the values that were used in the equation 1. The value of C_p, the coefficient of power of the turbine, determine by living project group equals to 0.42.

The angular velocity, ω, is determined by using the following equation [17]:

$$\omega = \frac{\lambda U}{R} \qquad (9)$$

R: the rotor radius

λ: tip speed ratio

The tip speed ratio is 2.25 at maximum C_p. Overall, the final value of the torque is 3105.23 lbs-ft by using equation 2, 3, and 4.

Likewise, the drag loads on the pontoons are determined by using equation 5. The differences between turbine drag and pontoon drag are the cross-section area and the drag coefficient. For design purpose, an assumption can be made that two pontoons of 3.5 feet diameter are fully submerged under water. As a result, the cross-sectional area of one pontoons is 9.62 ft^2. With the L/D ratio of pontoon as 14 and the Reynolds number as 1,500,000, the drag coefficient of pontoon is determined as 0.82 in the flow direction [17]. Therefore, the drag load on each pontoon is computed as 275.28 lbs (shown in Figure 16).

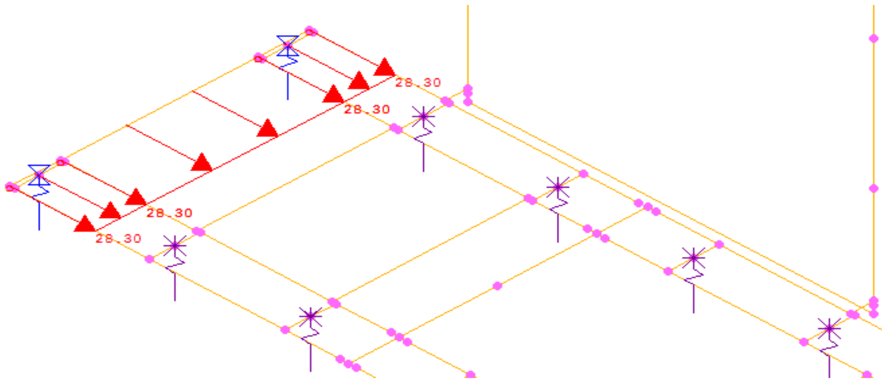

Figure 16: Wind load used for design

The wind load is computed by using the same method (equation 6). As discussed previously in this section, the design wind speed is chosen as 45 mph. However, for design purposes, the cross-section area, A, was roughly calculated. It is 5 feet x 18 feet rectangular which includes everything such as the post, the pontoons, the railings, etc. above sea level. With the rectangular shape of the cross-section, the wind drag coefficient of TDP is estimated as 1. Therefore, the wind load applied on the 18 feet long member is 28.3 plf (shown in Figure 17).

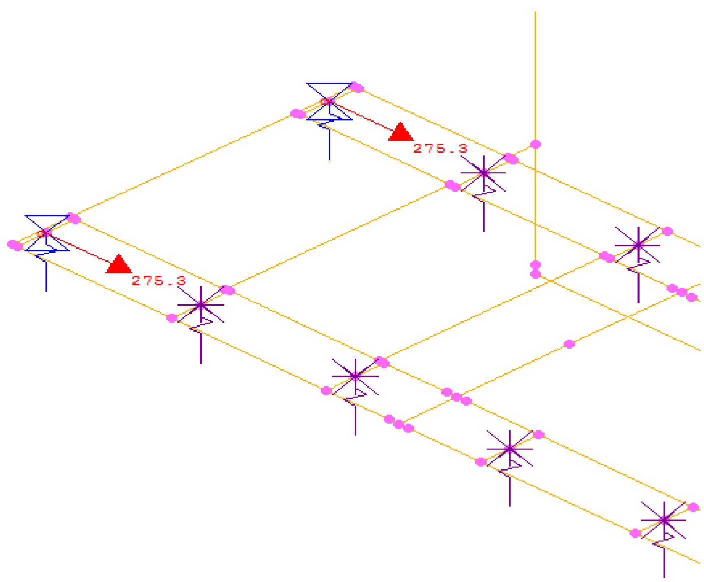

Figure 17: Pontoon Drag Force used for design purpose

The friction load is modeled as a vertical load applied on points where the pile guide connects the VGP. The friction load is the friction effect of the pile guides which connect the VGP and the TDP. The pile guides allow the TDP freely to move up or down along the VGP. Due to the uncertainties which cause the difficulties to estimate the friction load, the Living Bridge Project group decide to use 10% of the self-weight of the turbine.

4.4.3 Wave Load

The wave loads indicate the wave impact on the TTDS system. The wave loads include parallel wave load on the platform as well as the turbine and perpendicular wave load on the platform and the turbine. Parallel wave load is parallel to the pier cap. Perpendicular wave load is perpendicular to the pier cap. The wave load on the turbine is calculated with the equation (9) [18]:

$$F = \frac{\pi}{8}\rho H D^2 \tanh\left(\frac{2\pi d}{L}\right) C_m \cos(\omega t - \theta) \qquad (10)$$

Where ρ is the density of the salt-water, D is the swept diameter of the turbine rotor discussed in drag load, d is the water depth (60 feet) estimated by using the ADCP data, L is the designed wavelength (equation 11), H is the designed wave height (equation 12), ω is the angular velocity, t is time, θ is the wave phase angle. However, in order to get the 'worst wave load', $C_m \cos(\omega t - \theta)$ is set as maximum value which equals 1. C_m is the inertial coefficient which has a value range from 1.3 to 2.0. For design purpose, 2.0 is selected for the inertial coefficient.

The wavelength was calculated by using [17]

$$L = \frac{g T_{1/3}^2}{2\pi} \qquad (11)$$

Where $T_{1/3}$, the significant wave period at the site of Memorial Bridge, is 1.9 s (estimated by the ocean engineering group in the living bridge project). Similarly, H (H_1) is determined by using [17]

$$H_1 = 1.67H_{1/3} \tag{12}$$

Where $H_{1/3}$, the significant wave height, is estimated as 1.5 feet. Overall, the wave force on the turbine for both directions (parallel and perpendicular) is 12.2 kips.

The wave load on the platform was determined by using A Design Guide [19] which suggests a method that relies on experimentally determined added mass coefficients and Froude-Kriloff theory for determining the wave loading of a structure on its mooring [20]. The wave load is estimated by using Figure 18 and Figure 19. The first step of the method to determine the wave force is estimate the wave force (lb/ft^3) from Figure 18. Then, using the Figure 19 determine the body length adjustment factor.

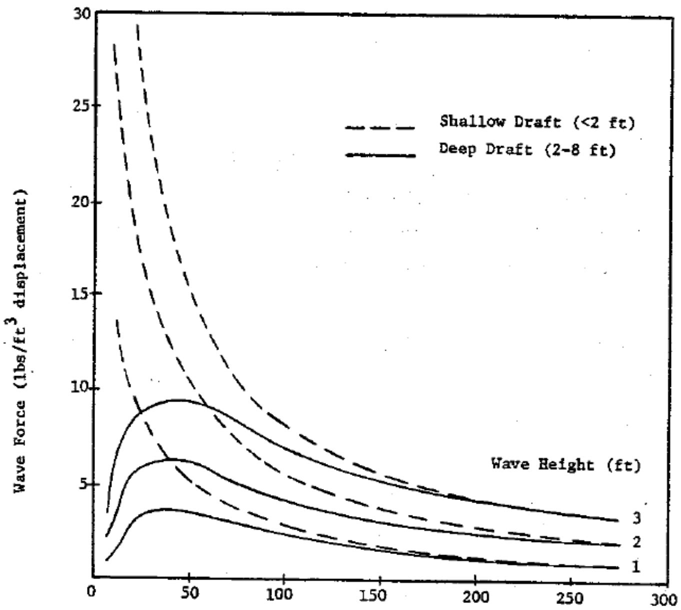

Figure 18: Horizontal Force on a Floating Object [19]

Then, the wave forces (for both directions) on the platform is calculated by using [17]

$$F = D * W * B \tag{13}$$

Where D is the displacement of the TDP, W is the wave force determined by using Figure 18, B is the body length adjustment factor estimated by using Figure 19.

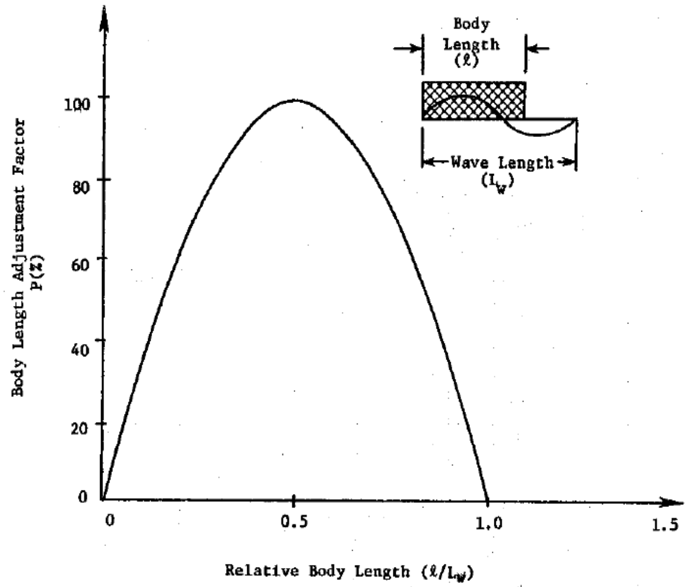

Figure 19: Wave force adjustment for relative body length [19]

By using the equation 13, Figure 18 and Figure 19, the relations between wave load (lbs) for both direction, wavelength, and wave height is shown in Figure 20.

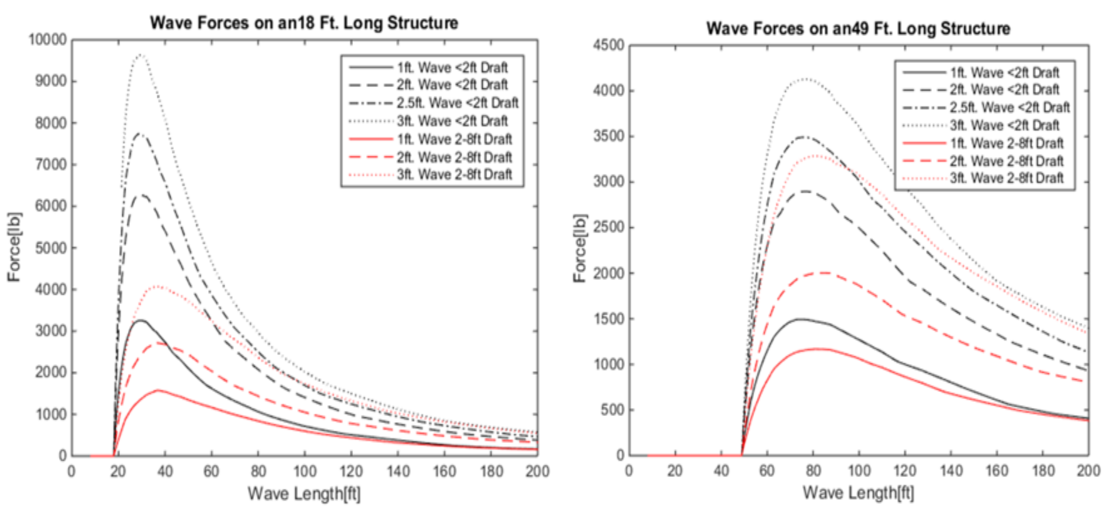

Figure 20: Re-plotted Wave Forces by Equation 12, "On an 18' Long Structure" means Perpendicular Wave, "On a 49' Long Structure" means Parallel Wave

According to Figure 20, the shallow draft offers a larger wave load. For design purposes, the draft for estimating wave load is determined as shallow draft which can give the 'worst-case' of wave demands. As discussed above, the designed wave height is 2.5 feet.

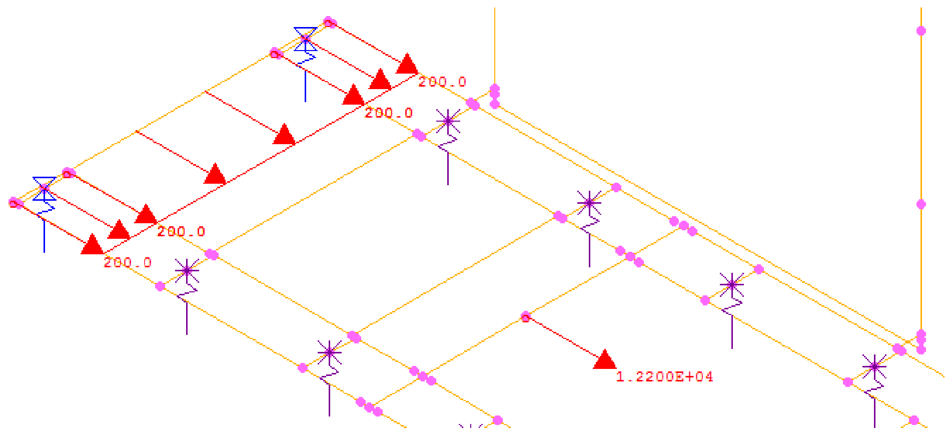

Figure 21: Designed Parallel Wave Force

The 'worst' parallel wave load is 200 lb/ft (shown in Figure 21) since wavelength is 75.9 feet. The 'worst' perpendicular wave load is 193 lb/ft (shown in Figure 22) when wavelength equal to 30.3 feet.

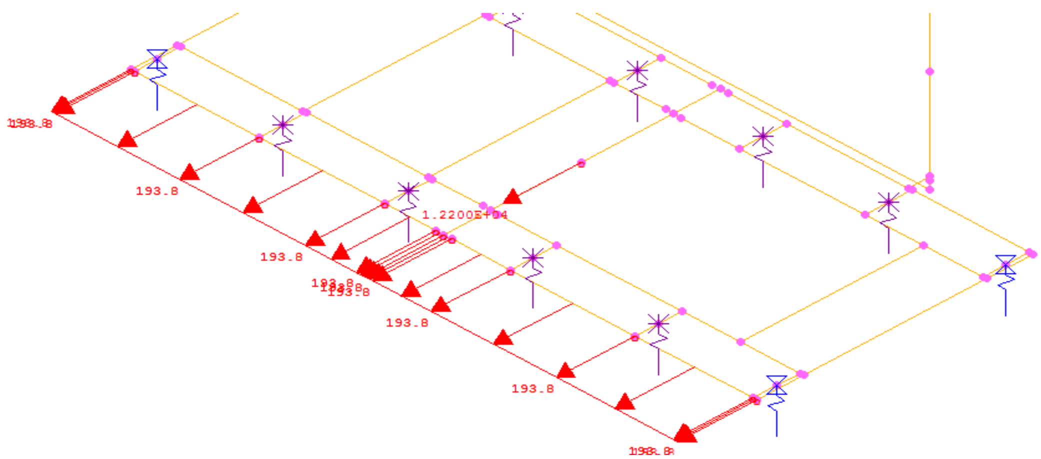

Figure 22: Designed Perpendicular Wave Force

4.4 Load Development

Chapter 3 discuses that the chosen loads are the 'worst' load cases, but the wave load, wind load, and drag load are greatly uncertain in reality. Furthermore, this study uses performance-based design which is a probabilistic approach. Extreme events should be considered, and the more data is required for an accurate probability estimation.

4.4.1 Wave Load On The TDP

Wave load on the TDP is selected as the 'worst' case for design purposes. However, as shown in Figure 20, the wave load on the platform is an uncertain factor considering its various wave height, wavelength, and the condition draft (shallow draft and deep draft). In order to estimate the probability of the anchorage force with constant wave height and variable wind speed, or constant wind speed and variable wave height, the wave force is estimated with the wave height set from 0.1 feet to 3.0 feet. The range of the wavelength of the perpendicular wave force was estimated from Figure 20. The range starts from 30.3 feet, the peak of the wave force curve, to 100 feet the tail of the curve. Similarly, the range of the wavelength of the parallel wave starts from 75.9 feet to 130 feet. The wave load needs to be inferred from the data, however, the data is absent so that wave load is unlikely to be computed. The wave load was estimated by interpolating on the Figure 20. The interpolation is shown in Figure 39-Figure 42 (Appendix A). For example, Table 5 shows the estimation (the parallel wave loads are set at 75.9 feet; the perpendicular wave loads are set at 30.3 feet.).

Table 5: Sample of Developed Wave Load On the TDP

Shallow Draft (TDP)		
Wavelength (ft)	30.3	75.9
Wave Height (ft)	PL Wave Force (lb)	PP Wave Force (lb)
0.1	328.6	150
0.2	657.2	300
0.3	985.8	450
0.4	1314.4	600
0.5	1643	750
0.6	1971.6	900
0.7	2300.2	1050
0.8	2628.8	1200
0.9	2957.4	1350
1	3286	1500
1.1	3586	1641.7
1.2	3886	1783.4
1.3	4186	1925.1
1.4	4486	2066.8
1.5	4786	2208.5
1.6	5086	2350.2
1.7	5386	2491.9
1.8	5686	2633.6
1.9	5986	2775.3
2	6286	2917
2.1	6621.7	3038.6
2.2	6957.4	3160.2
2.3	7293.1	3281.8
2.4	7628.8	3403.4
2.5	7964.5	3525
2.6	8300.2	3646.6
2.7	8635.9	3768.2
2.8	8971.6	3889.8
2.9	9307.3	4011.4
3	9643	4133

The design wave load on the TDP is based on the shallow draft, but the shallow draft has a limit state with the submerged depth being smaller than two feet. However, as the rotor of the turbine is submerged 10 feet, it is transformed into a deep draft with limit state being greater than 2 feet while the turbine is working. The wave load on the TDP is going to be estimated according to the shallow draft after lifting the turbine out of water. It also means that there is no wave load and drag load on the turbine once it is rotated out of water.

The wave load is determined based on the deep draft graph, for the turbine operating condition. As discussed previously, deep draft includes two turbine conditions. When the turbine is operating, the force on the turbine is calculated based on the equations discussed in Section 4.2. At the same time, when the turbine is turned off, the cross-sectional area decreases immensely. The area A, is going to be taken as 10 % of the swept area (shown in Figure 23).

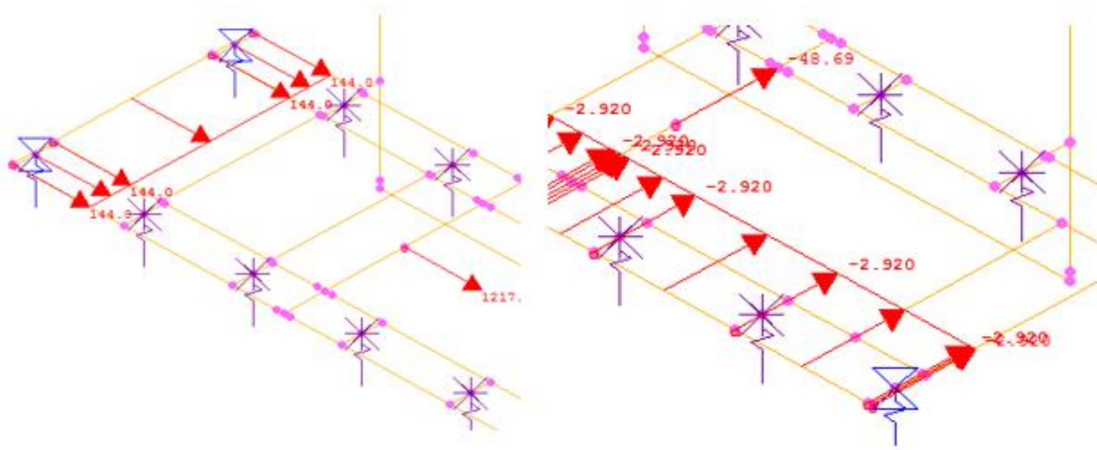

Figure 23: Reduced Wave Load on the Turbine

4.4.2 Wave Load On the VGP and On the Turbine

As the wave load on the VGP has low impact for the anchorage by comparing with the other loads, the wave load on the VGP was not used during designing the structure of the TTDS. However, the wave load on the VGP does have impact in reality. In order to have an accurate estimation of the wave load impact on the anchorages, wave loads on the VGP are developed and applied to the model in this study.

Wave load on the VGP is calculated by using the "Morison Equation". "Morison Equation" is the equation which is used to design oil platform and other offshore structures [21]. The "Morison Equation" is expressed as:

$$f = \frac{1}{2} C_d \rho A u^2 + C_m \rho V \dot{u} \qquad (14)$$

where C_d is drag coefficient,

ρ is the salt-water density,

A is the cross-section area perpendicular to the flow,

u is horizontal velocity,

C_m is the inertial coefficient (same value as discussed above),

V is volume of the underwater body, and

$\dot{u}$ is horizontal acceleration

The first step of utilizing the Morison equation is expressing the horizontal velocity (equation 15) and the acceleration (equation 16) by using Airy theory [22]:

$$u = \frac{\pi H}{T} \frac{\cosh[\left(\frac{2\pi}{L}\right)(d+z)]}{\sinh 2\pi d/L} \cos\theta \qquad (15)$$

and

$$\dot{u} = \frac{-2\pi^2 H}{T^2} \frac{\cosh[\left(\frac{2\pi}{L}\right)(d+z)]}{\sinh 2\pi d/L} \sin\theta \qquad (16)$$

where H is the wave height, L is the wavelength, T is wave period, d is the water depth, θ is the wave phase angle, and z is the distance from still water level. Figure 24 briefly shows these characters.

The equation of the wave force is utilized and proved as [22]:

$$f = \left[1 - \exp\left(-\frac{2\pi B}{L}\right)\right] \frac{\pi}{8} C_m \gamma D^2 H \qquad (14)$$

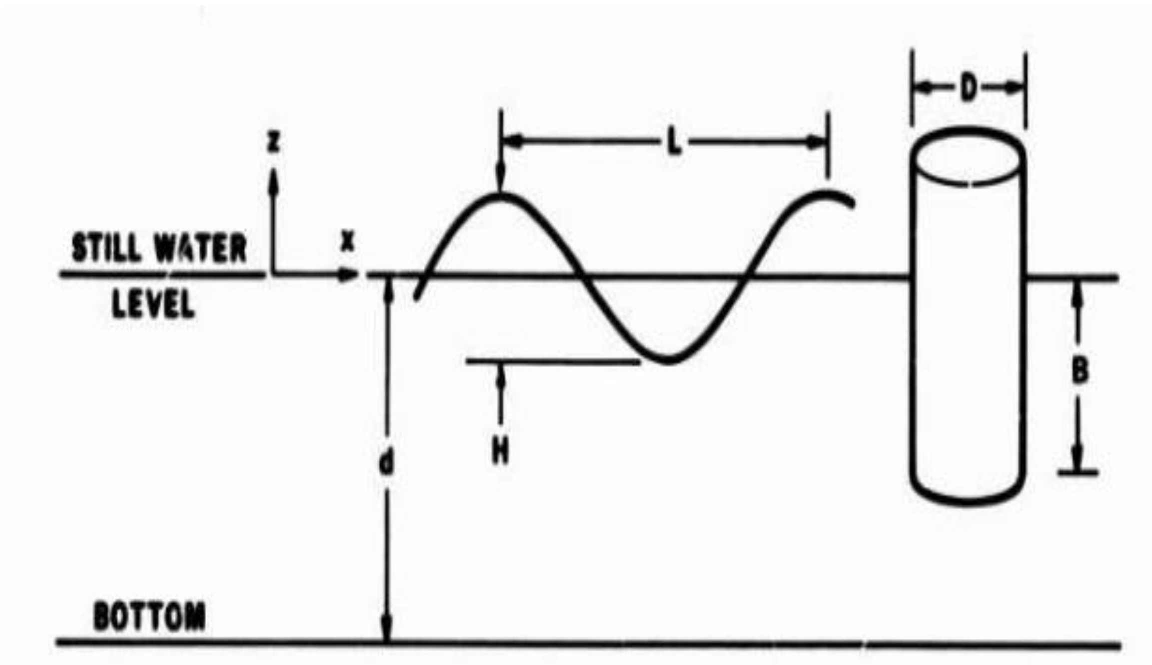

Figure 24: Coordinate System for Developing Morison Equation [22]

However, in order to use equation (14) to calculate the wave force on the VGP, the d/L ratio must be greater than 0.5, meaning that the condition is for "deep water". For the TTDS at the Memorial Bridge the depth, "d" as defined in Figure 24, varies from ~62 feet to ~78 feet depending on the tidal height [17]. Therefore, the wavelength range included in this study is between 75.9 feet and 130 feet. Under certain low tides conditions, the provision for "deep water" is not met but this information is included in this study given in the small magnitude of the loads and limited impact on the final result.

Table 6: Sample of Developed Wave Load On the VGP

Shallow Draft (VGP)		
Wavelength (ft)	30.3	75.9
Wave Height (ft)	PL Wave Force (lb)	PP Wave Force (lb)
0.1	6.9	4.0
0.2	13.8	8.0
0.3	20.7	12.0
0.4	27.6	16.0
0.5	34.5	19.9
0.6	41.4	23.9
0.7	48.3	27.9
0.8	55.2	31.9
0.9	62.1	35.9
1	69.0	39.9
1.1	75.9	43.9
1.2	82.8	47.9
1.3	89.7	51.9
1.4	96.6	55.9
1.5	103.5	59.8
1.6	110.4	63.8
1.7	117.3	67.8
1.8	124.2	71.8
1.9	131.1	75.8
2	138.0	79.8
2.1	144.9	83.8
2.2	151.8	87.8
2.3	158.7	91.8
2.4	165.6	95.8
2.5	172.5	99.7
2.6	179.4	103.7
2.7	186.3	107.7
2.8	193.2	111.7
2.9	200.1	115.7
3	207.0	119.7

Similarly, the wave force on the VGP is based on the same wavelength and wave height which are used in the estimation of wave load on the TDP. Table 6 shows the VGP wave load computed at parallel wavelength (75.9 feet) and perpendicular wavelength (30.3 feet). Figure 25 shows the wave load applied on the VGP.

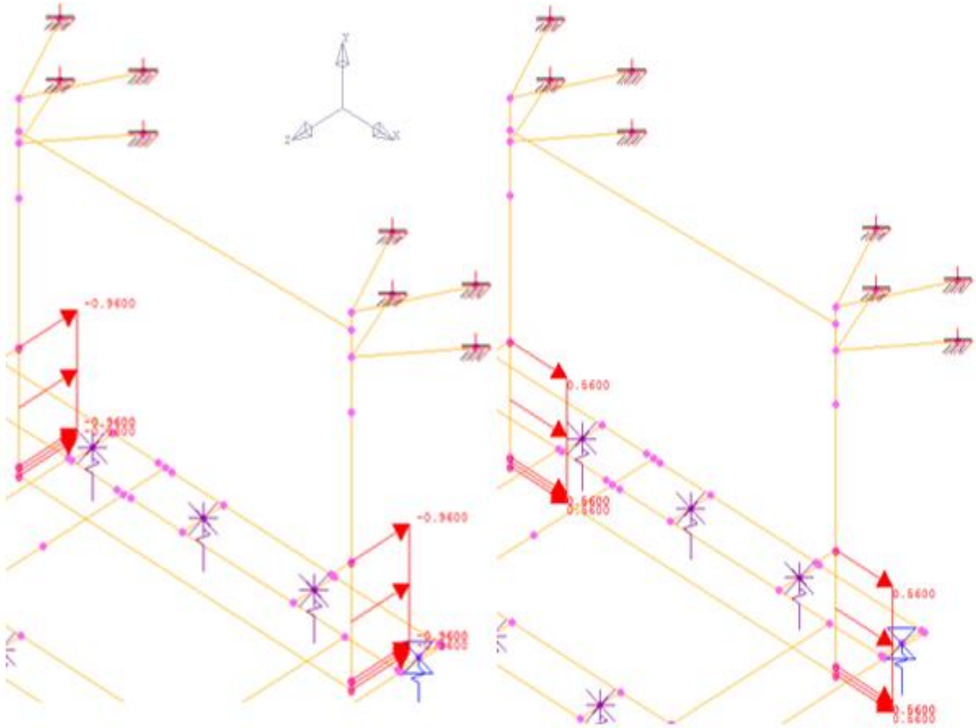

Figure 25: The Location of the VGP Wave Forces for Both Wave Directions

4.4.3 Wave load On Turbine

Since the wave load on the VGP and the platform are developed by the wave height and wave length in a particular range, the wave load on the turbine need to be re-calculated with the same range of wave height and the range of wave length used for calculating wave load on the TDP. Table 7 shows the turbine wave force re-computed.

Table 7: Developed Wave Loads acting on the Turbine

	Wave Load on The Turbine												
WaveLength (ft)	30.3	37.1	40	50	60	70	75.9	80	90	100	110	120	130
Wave Height (ft)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)
0.1	486.9	486.9	486.9	486.9	486.9	486.9	486.9	486.9	486.7	486.4	485.9	485.1	484.0
0.2	973.9	973.9	973.9	973.9	973.9	973.9	973.8	973.7	973.4	972.9	971.8	970.3	968.0
0.3	1460.8	1460.8	1460.8	1460.8	1460.8	1460.8	1460.7	1460.6	1460.2	1459.3	1457.8	1455.4	1452.0
0.4	1947.8	1947.8	1947.8	1947.8	1947.8	1947.7	1947.6	1947.5	1946.9	1945.7	1943.7	1940.5	1936.0
0.5	2434.7	2434.7	2434.7	2434.7	2434.7	2434.6	2434.5	2434.3	2433.6	2432.2	2429.6	2425.7	2420.0
0.6	2921.7	2921.7	2921.7	2921.7	2921.7	2921.6	2921.4	2921.2	2920.3	2918.6	2915.5	2910.8	2904.0
0.7	3408.6	3408.6	3408.6	3408.6	3408.6	3408.5	3408.3	3408.1	3407.1	3405.0	3401.5	3395.9	3388.1
0.8	3895.6	3895.6	3895.6	3895.6	3895.6	3895.4	3895.2	3895.0	3893.8	3891.4	3887.4	3881.1	3872.1
0.9	4382.5	4382.5	4382.5	4382.5	4382.5	4382.3	4382.1	4381.8	4380.5	4377.9	4373.3	4366.2	4356.1
1	4869.5	4869.5	4869.5	4869.5	4869.4	4869.3	4869.0	4868.7	4867.2	4864.3	4859.2	4851.3	4840.1
1.1	5356.4	5356.4	5356.4	5356.4	5356.4	5356.2	5355.9	5355.6	5354.0	5350.7	5345.1	5336.5	5324.1
1.2	5843.4	5843.4	5843.4	5843.4	5843.3	5843.1	5842.8	5842.4	5840.7	5837.2	5831.1	5821.6	5808.1
1.3	6330.3	6330.3	6330.3	6330.3	6330.3	6330.1	6329.7	6329.3	6327.4	6323.6	6317.0	6306.7	6292.1
1.4	6817.3	6817.3	6817.3	6817.3	6817.2	6817.0	6816.6	6816.2	6814.1	6810.0	6802.9	6791.9	6776.1
1.5	7304.2	7304.2	7304.2	7304.2	7304.2	7303.9	7303.5	7303.0	7300.9	7296.5	7288.8	7277.0	7260.1
1.6	7791.2	7791.2	7791.2	7791.2	7791.1	7790.8	7790.4	7789.9	7787.6	7782.9	7774.7	7762.1	7744.1
1.7	8278.1	8278.1	8278.1	8278.1	8278.1	8277.8	8277.3	8276.8	8274.3	8269.3	8260.7	8247.3	8228.1
1.8	8765.1	8765.1	8765.1	8765.1	8765.0	8764.7	8764.2	8763.6	8761.0	8755.7	8746.6	8732.4	8712.1
1.9	9252.0	9252.0	9252.0	9252.0	9251.9	9251.6	9251.1	9250.5	9247.8	9242.2	9232.5	9217.5	9196.1
2	9739.0	9739.0	9739.0	9739.0	9738.9	9738.5	9738.0	9737.4	9734.5	9728.6	9718.4	9702.7	9680.2
2.1	10225.9	10225.9	10225.9	10225.9	10225.8	10225.5	10224.9	10224.3	10221.2	10215.0	10204.4	10187.8	10164.2
2.2	10712.9	10712.9	10712.9	10712.8	10712.8	10712.4	10711.8	10711.1	10707.9	10701.5	10690.3	10672.9	10648.2
2.3	11199.8	11199.8	11199.8	11199.8	11199.7	11199.3	11198.7	11198.0	11194.7	11187.9	11176.2	11158.0	11132.2
2.4	11686.7	11686.7	11686.7	11686.7	11686.7	11686.3	11685.6	11684.9	11681.4	11674.3	11662.1	11643.2	11616.2
2.5	12173.7	12173.7	12173.7	12173.7	12173.6	12173.2	12172.5	12171.7	12168.1	12160.8	12148.0	12128.3	12100.2
2.6	12660.6	12660.6	12660.6	12660.6	12660.6	12660.1	12659.4	12658.6	12654.8	12647.2	12634.0	12613.4	12584.2
2.7	13147.6	13147.6	13147.6	13147.6	13147.5	13147.0	13146.3	13145.5	13141.5	13133.6	13119.9	13098.6	13068.2
2.8	13634.5	13634.5	13634.5	13634.5	13634.4	13634.0	13633.2	13632.3	13628.3	13620.1	13605.8	13583.7	13552.2
2.9	14121.5	14121.5	14121.5	14121.5	14121.4	14120.9	14120.1	14119.2	14115.0	14106.5	14091.7	14068.8	14036.2
3	14608.4	14608.4	14608.4	14608.4	14608.3	14607.8	14607.0	14606.1	14601.7	14592.9	14577.6	14554.0	14520.2

4.4.4 Wind Load Development

The basic wind speed was selected based on the non-extreme events, but, in reality, wind speed can be much higher than the design wind speed. In addition, Progress and Challenges in

Incorporating Climate Change Information into Transportation Research and Design [23] states that :

> *The transportation sector consistently points to the following set of potential climate change impacts as being most relevant to transportation infrastructure: (1) increases in intense precipitation events, (2) increases in Arctic temperatures (leading to permafrost melting), (3) rising sea levels, (4) increases in very hot days and heat waves, and (5) increases in hurricane intensity.*

For the purpose of developing wind load for the extreme events, the windspeed must be determined first. The wind speeds of extreme events are selected by using the “Wind Speed Website” of the Applied Technology Council Website. After entering the Latitude and the Longitude of the location of the TTDS, the website shows the specific extreme windspeeds at the location of the TTDS, such as 77 mph (10 years events), 87 mph (25 years events), 93 mph (50 years events), and 99 mph (100 years events) [24]. In the case of evaluating the impact on the anchorages with increasing windspeed, the chosen windspeeds and the related wind force on the VGP and TDP are shown in Table 8.

Table 8: Developed Wind Forces on the TDP and the VGP

Wind Speed (mph)	10	20	30	40	50	60	70	80	90	100
Wind Load (plf) (TDP)	1.31	5.25	11.82	21.02	32.84	47.29	64.36	84.06	106.39	131.35
Reynolds number	1338939	2677879	4016818	5355758	6694697	8033637	9372576	10711515.8	12050455.3	13389394.7
C_d of VGP	0.47	0.62	0.8	0.81	0.815	0.82	0.83	0.84	0.84	0.84
Wind Load (plf) (VGP)	0.526	2.773	8.05	14.49	22.78	33.01	45.47	60.11	76.08	93.92

To calculate the wind force, the equation (6) is applied. For wind force on the TDP, the same drag coefficient value, C_d, and same cross-section area, A, are used. However, as the posts behave as a cylinder, the drag coefficient need be determined at variable windspeed (shown in Figure 26 and Table 8). Wind loads on the new TTDS model is shown in Figure 26.

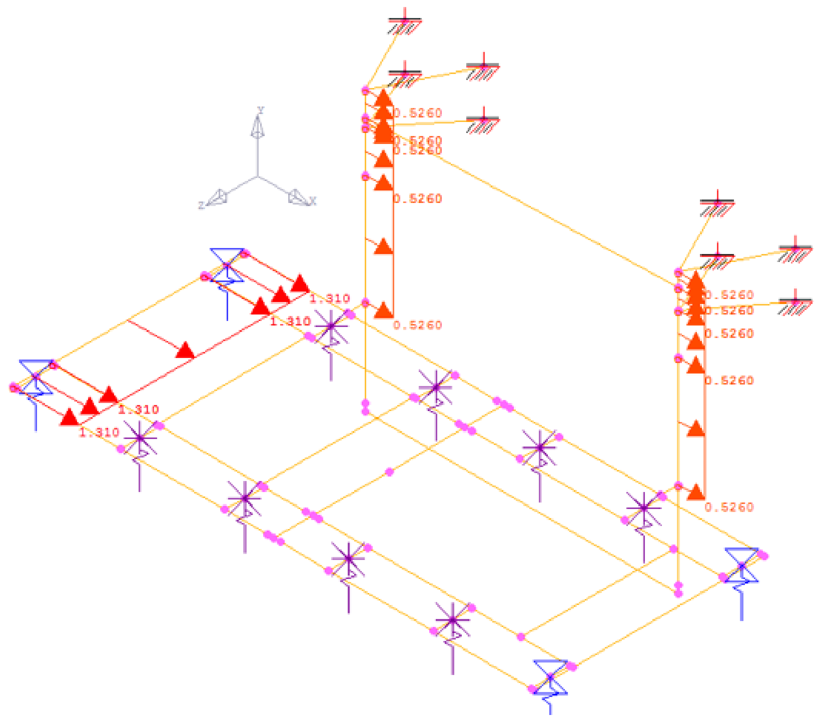

Figure 26: An Example of Developed Wind Loads on VGP and TDP

Chapter 5 Application of Probability Assessment of Environmental Demands to the TTDP

One of the critical components in the design of the VGP anchorage and the TTDS overall at the Memorial Bridge was the allowable capacity of the anchorage to the pier cap. The epoxy anchors were drilled in the existing reinforced concrete pier. As the project aims to promote the integration of renewable energy technology into bridge structural design, the installation of the renewable energy support structure, must not cause structural damages or require additional structural maintenance activities. Therefore, the capacity of the TTDS anchorage must not be exceeded under the variable environmental or operational loading. In order to analyze the wind impact and wave impact on the TTDS, two methodologies were applied in this research. One was setting wind speed as a constant parameter with variable wave height. Another method was setting wave height as a constant parameter with variable wind speed.

A major objective of this study is to verify the design and determine the responses which are used to protect the pier cap with respect to the allowable anchorage force, via the probabilistic assessment of environmental demands. Therefore, the structural response impacts of wave load and wind load, which have the most uncertainties, were calculated using structural models created in GT-Strudl®.

5.1 Anchorage Force Calculation

In order to calculate the anchorage forces, the resultant forces of the supports need be determined first. The resultant forces on the support are estimated by running the GT-Strudl® model. The support condition of the VGP is a fixed end in the model. According to the Figure 37 and Figure 43, the A-frame members of the VGP are attached to the pier cap with eight plates which are through the anchorages. The end of member of the A-frame is welded at the center of the plate. The anchorage force is calculated by using the force couple which is a static method. Table 9 shows the resultant force of one of the load cases (sample calculation in Appendix A).

Table 9: Sample Reaction Force for Parallel Wave @ wavelength=75.9', wave height = 0.1', wind speed = 10 mph

Reaction PL wind 10 mph, wave height 0.1 ft						
Support	X	Y	Z	Mx	My	Mz
	Kip	Kip	Kip	Kip-in	Kip-in	Kip-in
5	4.5	-0.7	8.9	65.5	3.6	-23.8
6	3.5	-2.2	-6.6	30.2	12.5	27.4
9	-3.3	-2.4	-5.9	77.1	-12.2	-30.8
10	-3.2	-1.5	5.6	51.1	-12.3	33.3
16	2.3	-0.3	4.3	36.7	11.5	-4.6
17	8.1	-2.4	-15.9	-0.9	9.2	7.9
20	-0.6	-1.8	-0.2	60.4	-13.8	-19.6
21	-5.2	-0.8	9.7	29.5	-10.4	22.5

Table 10 through Table 11 show the anchorage forces computed at each support (supports' IDs show in Figure 10). Positive numbers indicate tensile forces. Negative numbers indicate compression. The unit of forces is kip. Plate details show in Figure 36.

Table 10: The anchorage forces on support 5, 6, 9 and 10

Support 5					Support 6				
Bolt	Shear X	Shear Y	Axial	shear	Bolt	Shear X	Shear Y	Axial	shear
1	1.5	0.4	4.7	1.6	1	0.4	0.1	0.0	0.4
2	1.5	0.4	4.4	1.6	2	0.4	0.1	-1.1	0.4
3	0.7	-0.8	0.0	1.0	3	1.3	-1.2	-2.2	1.8
4	0.7	-0.8	-0.3	1.0	4	1.3	-1.2	-3.2	1.8
Support 9					Support 10				
Bolt	Shear X	Shear Y	Axial	shear	Bolt	Shear X	Shear Y	Axial	shear
1	-0.3	0.1	0.8	0.3	1	-1.4	-1.2	2.7	1.8
2	-0.3	0.1	1.8	0.3	2	-1.4	-1.2	3.7	1.8
3	-1.3	-1.3	-4.7	1.9	3	-0.2	0.4	-0.9	0.5
4	-1.3	-1.3	-3.7	1.9	4	-0.2	0.4	0.1	0.5

Table 11: The anchorage forces on support 16, 17, 20 and 21

Support 16					Support 17				
Bolt	Shear X	Shear Y	Axial	shear	Bolt	Shear X	Shear Y	Axial	shear
1	0.7	0.0	2.9	0.7	1	1.9	-0.8	-3.6	2.0
2	0.7	0.0	1.9	0.7	2	1.9	-0.8	-4.4	2.0
3	0.5	-0.2	0.2	0.5	3	2.1	-0.4	-3.5	2.2
4	0.5	-0.2	-0.7	0.5	4	2.1	-0.4	-4.3	2.2
Support 20					Support 21				
Bolt	Shear X	Shear Y	Axial	shear	Bolt	Shear X	Shear Y	Axial	shear
1	0.3	-0.9	1.9	1.0	1	-1.7	-0.7	3.1	1.8
2	0.3	-0.9	3.0	1.0	2	-1.7	-0.7	3.9	1.8
3	-0.6	0.0	-3.2	0.6	3	-0.9	0.4	0.9	1.0
4	-0.6	0.0	-2.0	0.6	4	-0.9	0.4	1.8	1.0

From Table 10 and Table 11, the maximum anchorage force is 4.7 kips at the wavelength 75.9 feet, wave height 0.1 feet, and wind speed 10 mph. As mentioned above, positive values are the tensile forces. The anchorage is bolted into the pier cap, therefore, the compression force (the negative force) is not considered. The compression forces transmit themselves directly to the plates and then to the pier cap. However, the tension forces are pull-out forces. They are the main forces which are compared with the allowable anchorage force. The maximum anchorage forces of all the load cases with wavelength 75.9 feet are summarized in the Table 12. Appendix C includes more summarized tables with wavelengths of different values.

Table 12: Summarized Maximum Anchorage Forces at Wavelength = 75.9', Parallel Wave, Deep Draft

PL

Deep

Wind Speed (MPH)	10	20	30	40	50	60	70	80	90	100
Wave Height (ft)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)
0.1	4.712	4.778	4.900	5.063	5.273	5.531	5.838	6.195	6.594	7.041
0.2	5.128	5.194	5.316	5.480	5.690	5.948	6.255	6.612	7.011	7.457
0.3	5.545	5.611	5.733	5.897	6.107	6.364	6.672	7.028	7.428	7.874
0.4	5.962	6.028	6.150	6.313	6.524	6.781	7.089	7.445	7.845	8.291
0.5	6.379	6.445	6.567	6.730	6.940	7.198	7.505	7.862	8.261	8.708
0.6	6.795	6.861	6.983	7.147	7.357	7.615	7.922	8.279	8.678	9.124
0.7	7.212	7.278	7.400	7.564	7.774	8.031	8.339	8.695	9.095	9.541
0.8	7.629	7.695	7.817	7.980	8.191	8.448	8.756	9.112	9.512	9.958
0.9	8.046	8.112	8.234	8.397	8.607	8.865	9.172	9.529	9.928	10.375
1	8.462	8.528	8.650	8.814	9.024	9.281	9.589	9.946	10.345	10.791
1.1	8.859	8.925	9.047	9.210	9.420	9.678	9.985	10.342	10.741	11.188
1.2	9.255	9.321	9.443	9.607	9.817	10.074	10.382	10.738	11.138	11.584
1.3	9.652	9.718	9.840	10.003	10.213	10.471	10.778	11.135	11.534	11.981
1.4	10.048	10.114	10.236	10.400	10.610	10.867	11.175	11.531	11.931	12.377
1.5	10.445	10.511	10.633	10.796	11.006	11.264	11.571	11.928	12.327	12.774
1.6	10.841	10.907	11.029	11.192	11.403	11.660	11.968	12.324	12.724	13.170
1.7	11.238	11.303	11.426	11.589	11.799	12.057	12.364	12.721	13.120	13.567
1.8	11.634	11.700	11.822	11.985	12.196	12.453	12.761	13.117	13.517	13.963
1.9	12.030	12.096	12.218	12.382	12.592	12.850	13.157	13.514	13.913	14.359
2	12.427	12.493	12.615	12.778	12.989	13.246	13.553	13.910	14.310	14.756
2.1	12.852	12.917	13.040	13.203	13.413	13.671	13.978	14.335	14.734	15.181
2.2	13.276	13.342	13.464	13.628	13.838	14.096	14.403	14.760	15.159	15.605
2.3	13.701	13.767	13.889	14.052	14.262	14.520	14.827	15.184	15.584	16.030
2.4	14.126	14.192	14.314	14.477	14.687	14.945	15.252	15.609	16.008	16.455
2.5	14.550	14.616	14.738	14.902	15.112	15.369	15.677	16.034	16.433	16.879
2.6	14.975	15.041	15.163	15.326	15.536	15.794	16.101	16.458	16.857	17.304
2.7	15.400	15.466	15.588	15.751	15.961	16.219	16.526	16.883	17.282	17.729
2.8	15.824	15.890	16.012	16.176	16.386	16.643	16.951	17.308	17.707	18.153
2.9	16.249	16.315	16.437	16.601	16.811	17.068	17.376	17.732	18.132	18.578
3	16.674	16.740	16.862	17.025	17.235	17.493	17.800	18.157	18.556	19.003

5.2 Probabilistic Analysis

When computing the probability of exceedance of the allowable anchorage force, the first step is to estimate the normal cumulative distribution curves of the anchorage force with constant wave height and variable wind speed or constant wind speed and variable wave height. However, a verification is required to show that the normal cumulative distribution curves can be used in further analyses. The methodology for the verification is the K-S test (Kolmogorov-Smirnov Test). The K-S test is a non-parametric test of the equality of continuous, one-dimensional probability distributions that can be used to compare a sample with a reference probability distribution (one-sample K–S test), or to compare two samples (two-sample K–S test) [25]. The K-S test is based on maximum difference between the empirical cumulative distribution function (ECDF) curve and the normal cumulative distribution function curve. The ECDF can be expressed by giving N ordered data points Y1, Y2, ..., YN [26]. Its equation is defined as

$$E_N = \frac{n(i)}{N} \qquad (15)$$

where n(i) is the number of points less than Yi and the Yi are ordered from smallest to largest value.

The previous chapters have mentioned that two main uncertainties are wave load and wind load. The following probability calculation of the anchorage forces are based on different wave height, wind speed, and wavelength. By using the same anchorage forces summarized in Table 12, Table 13 shows the calculation and K-S test of CDF and ECDF for wind speed approach. By comparing the values of CDF and ECDF, these two group of values are same. Then, the CDF can be properly used in the further analysis. The limit of probability of exceedance is set as 5%. This is determined by the Living Bridge team.

Table 13: Cumulative Distribution Probability Calculation and K-S test on Wind Speed Approach at Wavelength =75.9', Deep Draft

Wind Speed (MPH)	10	10	20	20	30	30	40	40	50	50	60	60	70	70	80	80	90	90	100	100
Wave Height (ft)	CDP	ECDP	CDP	ECDP	CDP	ECDP	CDP	ECDP	CDP	ECDP	CDP	ECDP	CDP	ECDP	CDP	ECDP	CDP	ECDP	CDP	ECDP
0.1	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049
0.2	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062
0.3	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078
0.4	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096
0.5	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117
0.6	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141	0.141
0.7	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169	0.169
0.8	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
0.9	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234
1	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271
1.1	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308	0.308
1.2	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348	0.348
1.3	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389	0.389
1.4	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432	0.432
1.5	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476
1.6	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520
1.7	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563	0.563
1.8	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606	0.606
1.9	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648
2	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688	0.688
2.1	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728	0.728
2.2	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766	0.766
2.3	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800
2.4	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832
2.5	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860
2.6	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884	0.884
2.7	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906	0.906
2.8	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.924
2.9	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939
3	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952	0.952

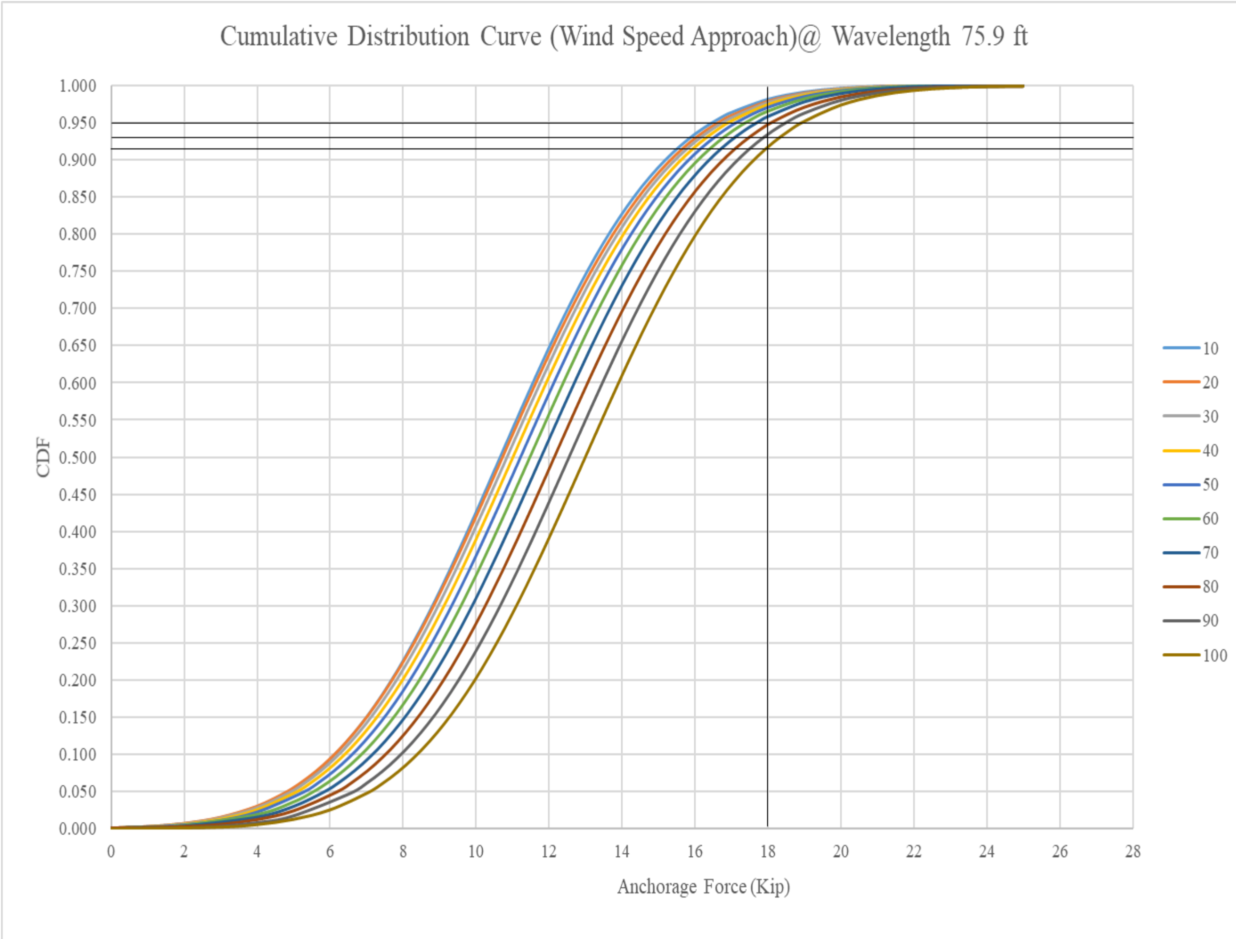

Figure 27: Cumulative Distribution Curve for Variable Wind Speeds @ Wavelength = 75.9'

Figure 27 which will be used to estimate the probability of exceedance, wind speed approach, describes the fragility curve of different wind speed.

Table 14 shows the calculation and K-S test of CDF and ECDF for wave height approach. Likewise, the CDP can be properly used in the further analysis. Figure 28 illuminates the fragility curve of different wave height at constant wavelength 75.9 feet.

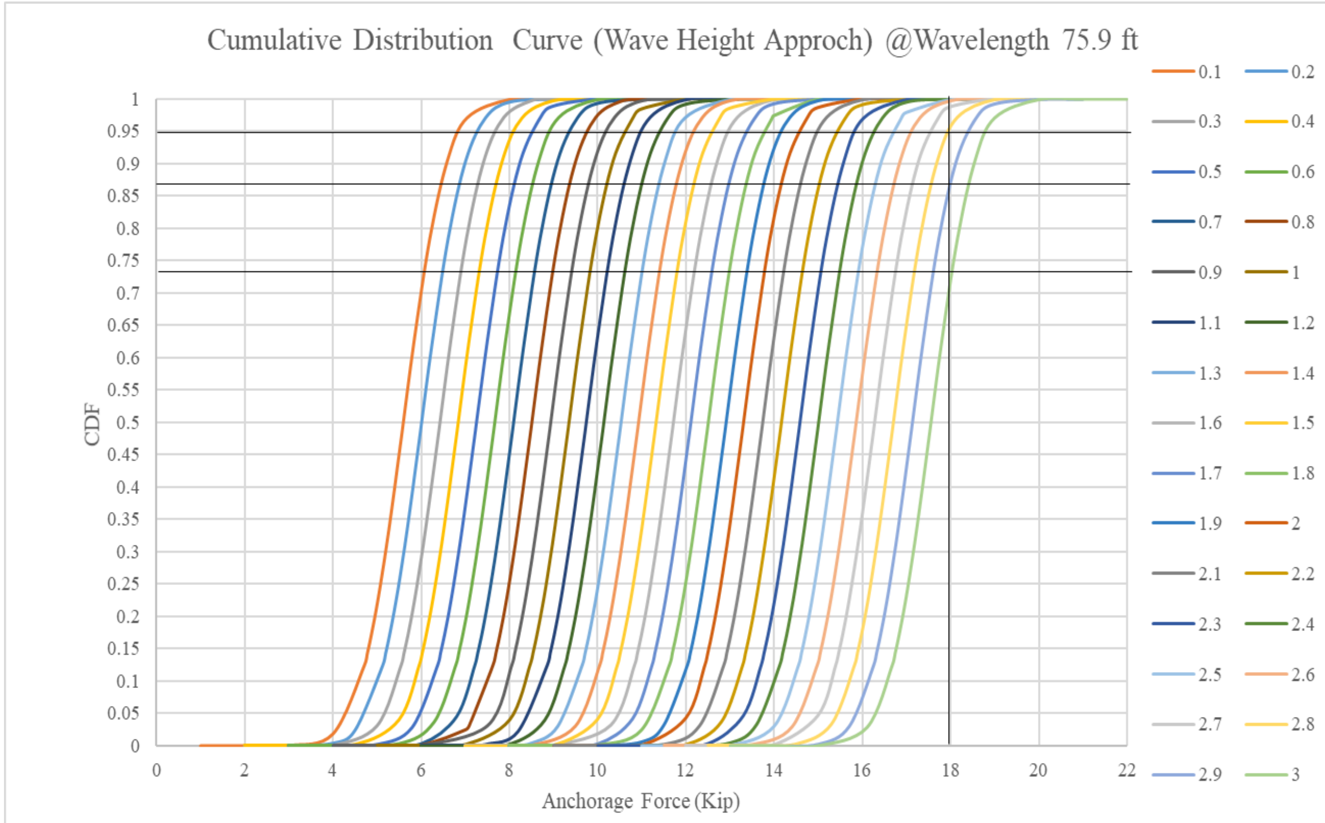

Figure 28: Cumulative Distribution Curve for Variable Wave Heights @ Wavelength = 75.9'

Table 14: Cumulative Distribution Probability Calculation and K-S test on Wave Height Approach at Wavelength =75.9', Deep Draft

Wind Speed (MPH)		10	20	30	40	50	60	70	80	90	100
Wave Height (ft)											
0.1	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.1	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.2	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.2	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.3	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.3	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.4	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.4	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.5	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.5	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.6	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.6	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.7	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.7	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.8	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.8	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.9	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
0.9	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.1	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.1	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.2	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.2	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.3	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.3	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.4	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.4	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.5	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.5	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.6	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.6	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.7	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.7	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.8	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.8	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.9	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
1.9	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.1	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.1	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.2	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.2	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.3	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.3	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.4	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.4	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.5	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.5	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.6	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.6	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.7	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.7	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.8	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.8	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.9	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
2.9	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
3	CDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964
3	ECDP	0.137	0.156	0.195	0.255	0.346	0.470	0.620	0.773	0.893	0.964

5.3 Strain Estimation and Response Determination

In order to obtain an immediate response when the anchorage force is over the allowable force, sensors (strain gages) are needed to monitor the strain changes on A-frames, which is discussed in chapter 3. By using the same methodology, the strains of each member are based on the equation 3 and 4 and member forces from GT-Strudl® [13]. Furthermore, the same load cases used in the anchorage force calculation are also used for strain estimation. The bottom strains of member one for the same load case used in the probability analysis are estimated in Table 15. Member section is used to evaluate the strain changes in a member.

Table 15: Strain Calculation at the Bottom of Member One @ Wavelength = 75.9', Section = 0 (The beginning of the member), Deep Draft

Wind Speed (MPH)			10	20	30	40	50	60	70	80	90	100
Member	**Section**	**Wave Hight (ft)**	**Strain bot**	**Strain bot**	**Strain bot**	**Strain bot**	**Strain bot**	**Strain bot**	**Strain bot**	**Strain bot**	**Strain bot**	**Strain bot**
1	0	0.1	8.167E-05	8.225E-05	8.33E-05	8.472E-05	8.655E-05	8.879E-05	9.146E-05	9.456E-05	9.803E-05	0.0001019
1	0	0.2	8.554E-05	8.612E-05	8.72E-05	8.86E-05	9.043E-05	9.267E-05	9.534E-05	9.843E-05	0.0001019	0.0001058
1	0	0.3	8.942E-05	9E-05	9.11E-05	9.247E-05	9.43E-05	9.654E-05	9.921E-05	0.0001023	0.0001058	0.0001097
1	0	0.4	9.329E-05	9.387E-05	9.49E-05	9.635E-05	9.818E-05	0.0001004	0.0001031	0.0001062	0.0001097	0.0001135
1	0	0.5	9.717E-05	9.775E-05	9.88E-05	0.0001002	0.0001021	0.0001043	0.000107	0.0001101	0.0001135	0.0001174
1	0	0.6	0.000101	0.0001016	0.000103	0.0001041	0.0001059	0.0001082	0.0001108	0.0001139	0.0001174	0.0001213
1	0	0.7	0.0001049	0.0001055	0.000107	0.000108	0.0001098	0.000112	0.0001147	0.0001178	0.0001213	0.0001252
1	0	0.8	0.0001088	0.0001094	0.00011	0.0001119	0.0001137	0.0001159	0.0001186	0.0001217	0.0001252	0.000129
1	0	0.9	0.0001127	0.0001133	0.000114	0.0001157	0.0001176	0.0001198	0.0001225	0.0001256	0.000129	0.0001329
1	0	1	0.0001165	0.0001171	0.000118	0.0001196	0.0001214	0.0001237	0.0001263	0.0001294	0.0001329	0.0001368
1	0	1.1	0.0001202	0.0001208	0.000122	0.0001233	0.0001251	0.0001274	0.00013	0.0001331	0.0001366	0.0001405
1	0	1.2	0.0001239	0.0001245	0.000126	0.000127	0.0001288	0.000131	0.0001337	0.0001368	0.0001403	0.0001442
1	0	1.3	0.0001276	0.0001282	0.000129	0.0001307	0.0001325	0.0001347	0.0001374	0.0001405	0.000144	0.0001478
1	0	1.4	0.0001313	0.0001319	0.000133	0.0001344	0.0001362	0.0001384	0.0001411	0.0001442	0.0001477	0.0001515
1	0	1.5	0.000135	0.0001356	0.000137	0.000138	0.0001399	0.0001421	0.0001448	0.0001479	0.0001513	0.0001552
1	0	1.6	0.0001387	0.0001392	0.00014	0.0001417	0.0001436	0.0001458	0.0001485	0.0001516	0.000155	0.0001589
1	0	1.7	0.0001424	0.0001429	0.000144	0.0001454	0.0001472	0.0001495	0.0001522	0.0001552	0.0001587	0.0001626
1	0	1.8	0.000146	0.0001466	0.000148	0.0001491	0.0001509	0.0001532	0.0001558	0.0001589	0.0001624	0.0001663
1	0	1.9	0.0001497	0.0001503	0.000151	0.0001528	0.0001546	0.0001569	0.0001595	0.0001626	0.0001661	0.00017
1	0	2	0.0001534	0.000154	0.000155	0.0001565	0.0001583	0.0001605	0.0001632	0.0001663	0.0001698	0.0001737
1	0	2.1	0.0001574	0.0001579	0.000159	0.0001604	0.0001623	0.0001645	0.0001672	0.0001703	0.0001737	0.0001776
1	0	2.2	0.0001613	0.0001619	0.000163	0.0001644	0.0001662	0.0001684	0.0001711	0.0001742	0.0001777	0.0001816
1	0	2.3	0.0001653	0.0001658	0.000167	0.0001683	0.0001702	0.0001724	0.0001751	0.0001782	0.0001816	0.0001855
1	0	2.4	0.0001692	0.0001698	0.000171	0.0001723	0.0001741	0.0001763	0.000179	0.0001821	0.0001856	0.0001895
1	0	2.5	0.0001732	0.0001737	0.000175	0.0001762	0.0001781	0.0001803	0.000183	0.0001861	0.0001895	0.0001934
1	0	2.6	0.0001771	0.0001777	0.000179	0.0001802	0.000182	0.0001842	0.0001869	0.00019	0.0001935	0.0001974
1	0	2.7	0.0001811	0.0001816	0.000183	0.0001841	0.0001859	0.0001882	0.0001909	0.000194	0.0001974	0.0002013
1	0	2.8	0.000185	0.0001856	0.000187	0.0001881	0.0001899	0.0001921	0.0001948	0.0001979	0.0002014	0.0002053
1	0	2.9	0.000189	0.0001895	0.000191	0.000192	0.0001938	0.0001961	0.0001988	0.0002019	0.0002053	0.0002092
1	0	3	0.0001929	0.0001935	0.000195	0.000196	0.0001978	0.0002	0.0002027	0.0002058	0.0002093	0.0002132

The Table 15 only shows part of the strain changes in member 1. The analysis of strain includes three sections for both the top and the bottom of a member.

The responses are estimated using the strain changes and the probability of exceedance. Two responses can be used in the future work. The first response is to shut down turbine. The second is to lift turbine out of water. With the probability of exceedance being greater than 5%, the response need to be made to either shut down turbine or lift out of water. For example, according to **Error! Reference source not found.**, the probability is lower than 5% when the wind speed is 80 mph. Therefore, the turbine does not need to be shut down or lift out immediately. If the strain is close to the strain predicted which interacts with the allowable force, the inspector or engineer need to make a decision whether to shut down turbine or lift it out. In addition, in Figure 28, the probability is much higher than 5% when the wave height is 2.9 feet, or 3.0 feet, in that case the action must be immediately taken to avoid damaging the pier cap.

Chapter 6 Results and Recommendation

Thousands of different load cases were developed, applied to the TTDS, and discussed in this thesis. The load cases took into account that there were many different load conditions due to the variability of the wind speeds, the wave heights, the wavelengths, directions of waves, and the floating drafts (deep draft and shallow draft). Each load case generated structural conditions that were used to determine the turbine's position and operating condition: lifting the tidal turbine out of water or just shutting the turbine down. Each load case was analyzed using GT-Strudl® [13] models. The results of each analytical run were used to develop a more accurate idea of the effects on the anchorage due to the different load cases. Some of the effects are the influence of the tidal turbine during operation, the impact of different wave variations' impacts, and the influence of the wind. With this information more applicable recommendations can be given to the safe operation conditions of the tidal turbine.

6.1 Effect of the Turbine Under Operation

In order to determine the effects of turbine upon the anchorages while it is generating power, three models are customized for the analysis of each load case, such as deep draft with fully operating turbine, deep daft with non-working turbine, and a shallow draft model in which the turbine is lifted out of the water. The only difference among the three models lies in the loads acting on the turbine, whereas some of the other load aspects remain the same. For instance, with a deep daft model, when the turbine is fully operating, the applied loads in Section 4.4.3 (Table 7) on the turbine are remain same. If the turbine is shut down, the applied wave load and drag load are reduced by 90% (discussed in Chapter 4-Section 4.4.1), and the torque is reduced to zero. There are no loads on the turbine when the turbine is lifted out of water. After comparing the maximum forces on the anchorage system due to the three models, an observation was made that the turbine has a significant impact on the anchorage. Figure 29, Figure 30, and Figure 31 show the changing anchorage forces at different wave heights and wind speeds when the wave forces are parallel to the pier cap and the wave length is 75.9 feet.

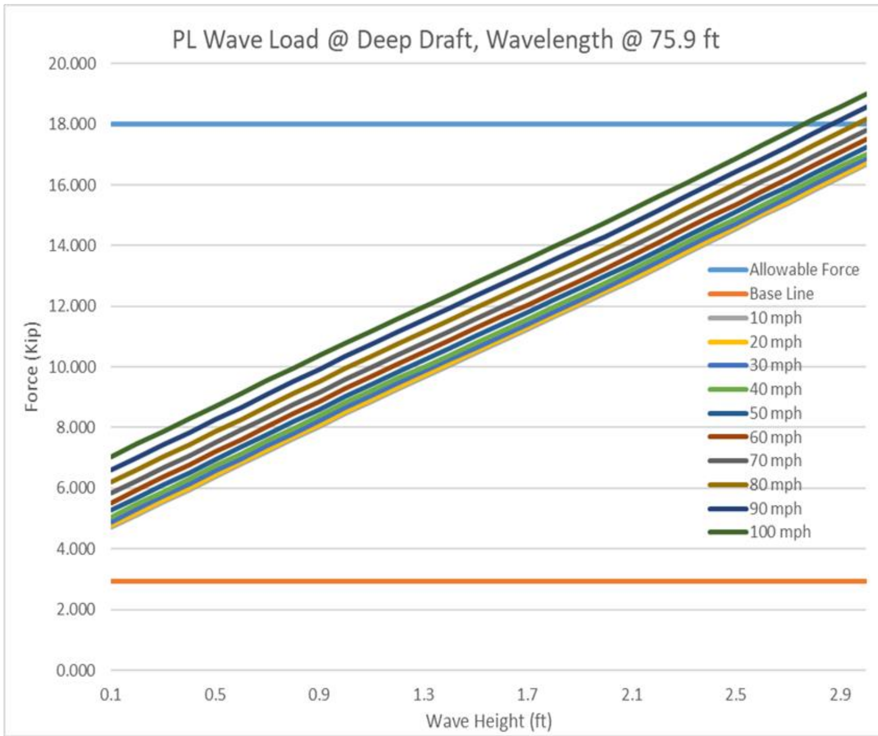

Figure 29: Anchorage Force vs Wave Height @ Wavelength = 75.9 feet, Parallel Wave Force, Deep Draft

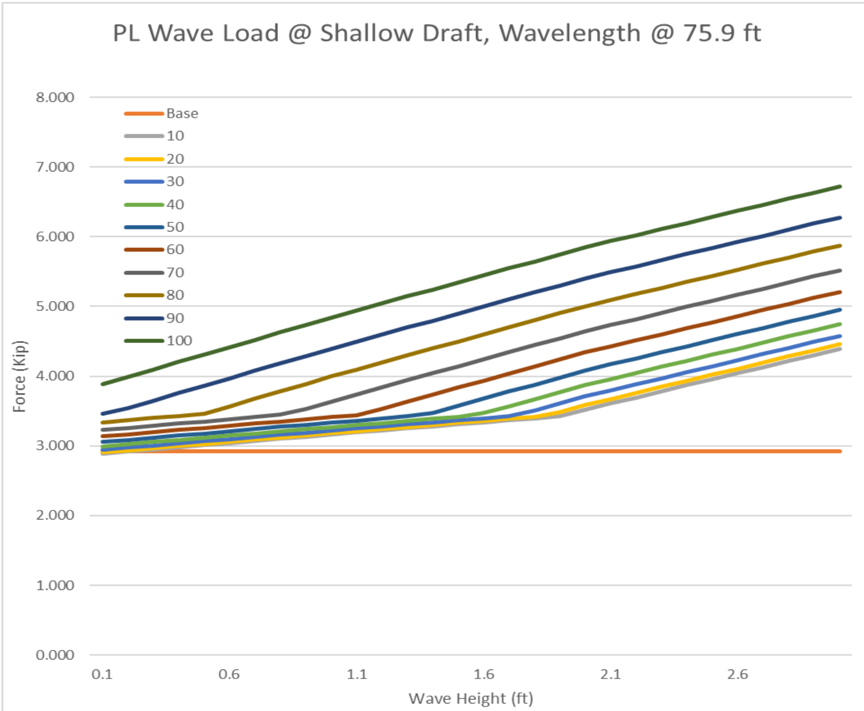

Figure 30: Anchorage Force vs Wave Height @ Wavelength = 75.9 feet, Parallel Wave Force, Shallow Draft

In these figures, the base means the basic anchorage force related to the basic loads which includes all the loads except wind loads, drag loads and torque on the tidal turbine, and wave loads. Other lines represent how the anchorage forces change with variable wave loads when the wind load is constant. Each line has a different constant wind speed. These figures describe how the impact of the tidal turbine changes from operational position to non-operational position (fully lifted out the water). The effect of the turbine on the pier cap anchorage is much larger than other loads by comparing Figure 29 and Figure 31. For example, when the wave height is 0.1 feet, the anchorage forces in Figure 29 are around 50 % higher than the force in Figure 30. In addition, the forces in Figure 29 are around three times higher than the force in Figure 30 since the wave height is higher than 1.0 feet. On the other hand, shutting down the turbine and lifting the turbine out of the water give slightly different results after comparing Figure 30 and Figure 31. Shutting down the turbine gives a slightly higher value. Comparing these models when the TTDS are having the perpendicular wave loads, the turbine has a similar impact as discussed above.

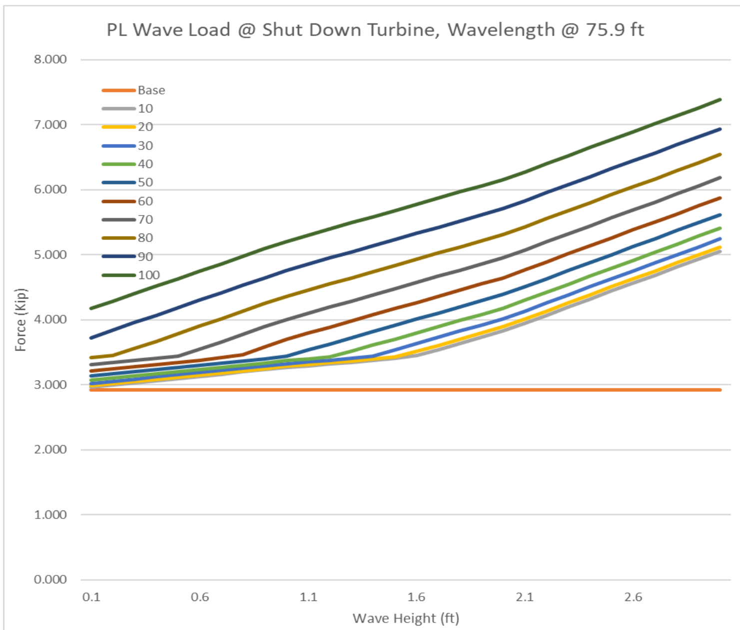

Figure 31: Anchorage Force vs Wave Height @ Wavelength = 75.9 feet, Parallel Wave Force, Shut Down Turbine

6.2 Wave Effect

6.2.1 Parallel Wave Verses Perpendicular Wave

Wave loads are identified as parallel wave loads and perpendicular wave loads. In the previous chapters, the anchorage forces based on parallel wave load has been shown in Table 12 and Figure 29 to Figure 31 at wavelength 75.9 ft. Figure 32, Figure 33, and Figure 34 shows the change anchorage forces as the wave heights and wind speeds are varied for a perpendiculars to the pier cap wave force and a wave length of 30.3 ft.

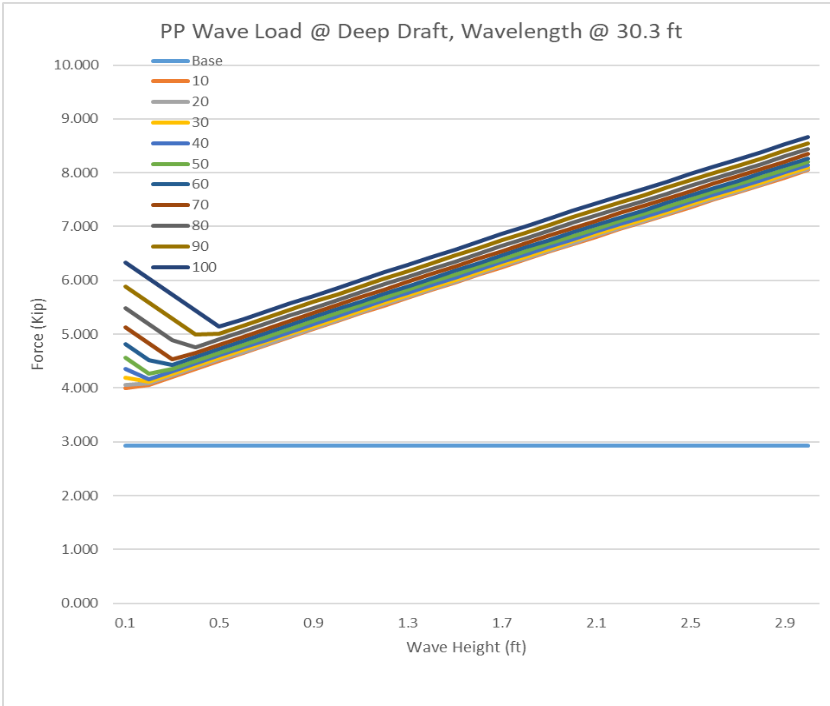

Figure 32: Anchorage Force vs Wave Height @ Wavelength = 30.3feet, Perpendicular Wave Force, Deep Draft

It shows that the perpendicular wave force undoubtedly has much less impact on the pier cap anchorage than does the parallel wave force after comparing Figure 29 to Figure 31 and Figure 32 to Figure 34. The maximum anchorage forces shown in Figure 32 to Figure 34 is less than 50% of the allowable anchorage force. The setting of wavelength is based on the wave curves shown in (Figure 20). For instance, the parallel wave load reaches a maximum when the wavelength is equal to 75.9 feet. The wave load appears to decrease as the wavelength increases. Therefore, one can draw the conclusion that the design of TTDS is satisfied for perpendicular wave load combination. The decision (stop operating turbine) has to be made when the parallel wave load is applied on the TTDS.

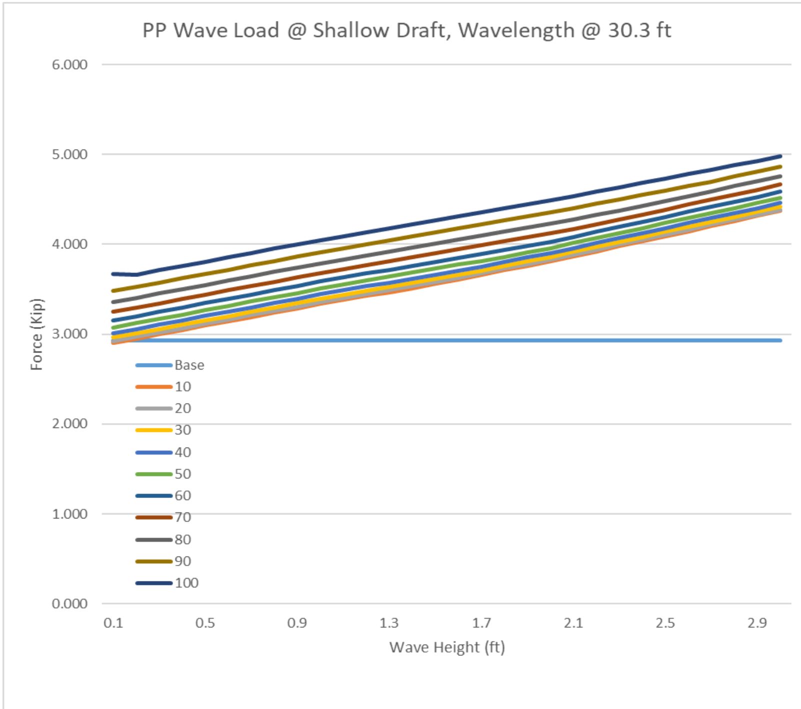

Figure 33: Anchorage Force vs Wave Height @ Wavelength = 30.3feet, Perpendicular Wave Force, Shallow Draft

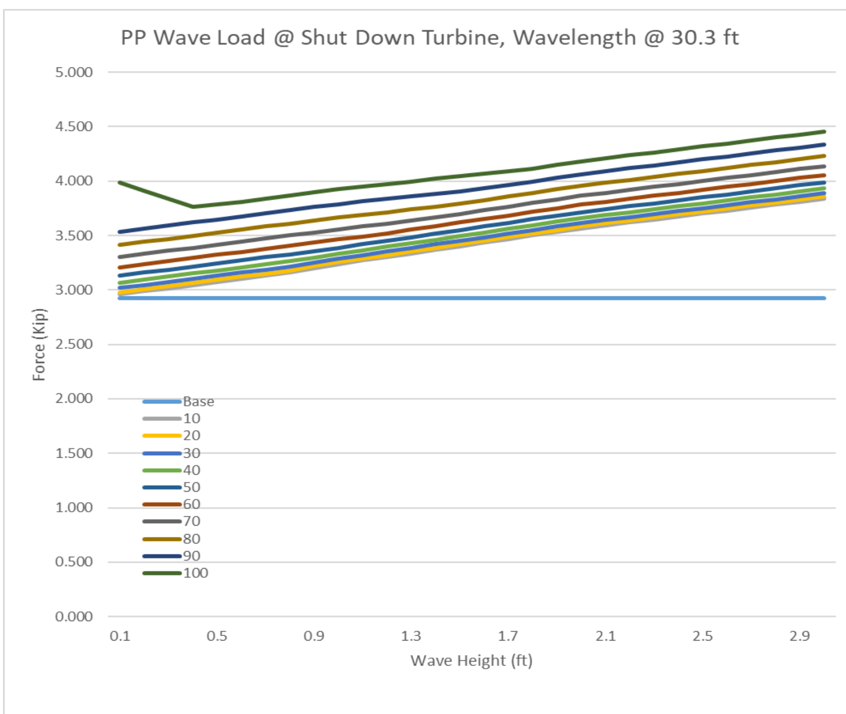

Figure 34: Anchorage Force vs Wave Height @ Wavelength = 30.3feet, Perpendicular Wave Force, Shut Down Turbine

6.2.2 Annual Probability of Exceedance (POE) of the Allowable Anchor Force

One can utilize the probability of exceedance by using 100% minus the estimated standard cumulative distribution function (CDF). This method was used to calculate the POE of the target anchorage force, 18 kips. As discussed above, this methodology can be only used for the parallel wave load cases when the turbine is fully operational. According the Figure 27 and Figure 28, the probability of exceedance of the target anchorage force at variable wind speeds is lower than probability of exceedance of the target anchorage force at variable wave heights. Figure 27, it shows that the probabilities of exceedance are 4.9 %, 6.5%, and 8% for 80 mph, 90 mph, and 100 mph, respectively. However, Figure 28 how the probabilities of exceedance are 4.8 %, 11%, and 24% for 2.8 feet, 2.9 feet, and 3.0 feet, respectively.

The probabilities of exceedance of wind speed were calculated by using the equation 16 [10]:

$$P(at\ least\ on\ event\ in\ time\ t) = 1 - e^{-\lambda t} \qquad (16)$$

where, $\lambda = 1/T$,

λ is the annual frequency of exceedance, and

T is the return period.

if λt is small (less than approximately 0.1), the probability of exceedance can also be approximately equal to λt. In this study, this method was applied to use estimate the probability of exceedance of wind speed. The t was determined as one. The estimation is shown in Table 16.

The overall POE of all case is computed as the POE of the target anchorage forces by multiplying POE of target wind speed or target wave height. For instance, when the wind speed is the 80 mph, the POE of this wind speed is equal to 0.1. In addition, the POE of the target anchorage force is 0.049 when the wind speed is 80 mph. Then, the overall POE is equal to 0.49% (Table 16).

Table 16: Overall POE Calculations with Varied Wind Speed

Wind Speed (mph)	Return Peirod	POE of Wind	POE of Anchor/wind	Overall POE
80	10.0	10.0%	4.9%	0.49%
90	50.0	2.0%	6.5%	0.13%
100	100.0	1.0%	8.0%	0.08%

6.3 Wind Effect

As mentioned in the wind load development section, the number of hurricanes increases due to the climate change [23]. Loads due to the wind velocity is one of the main considerations in this study. However, wind has relatively smaller impact on the pier cap anchorage force than do the wave loads. Through the comparison of the Figure 29 and the Figure 35, the anchorage forces increase slightly when the wind speed increases, but the forces increase significantly when the wave height increases.

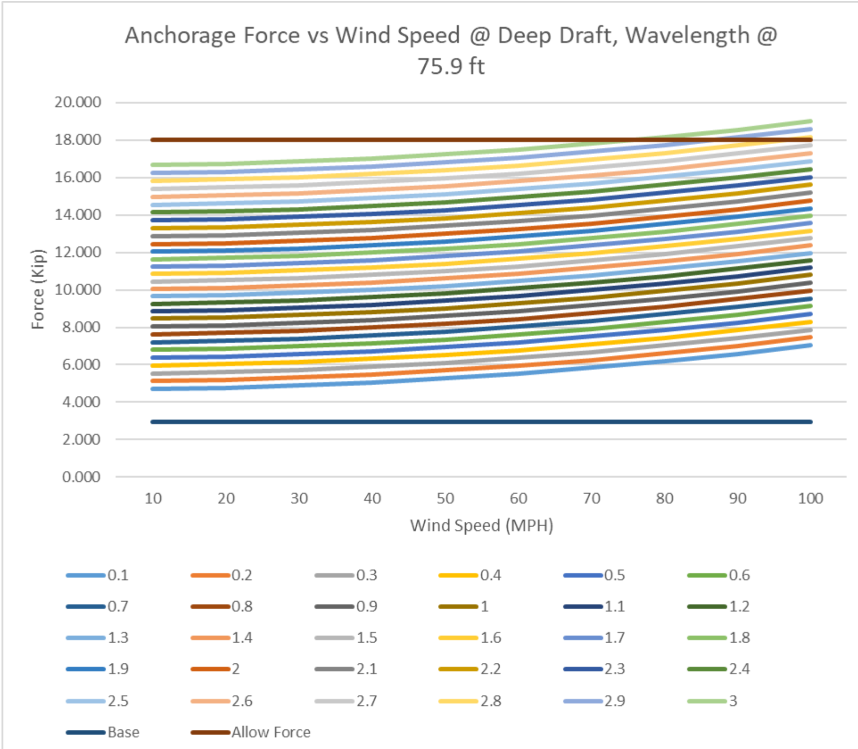

Figure 35: Anchorage Force vs Wind Speed @ Deep Draft, Wavelength @ 75.9 feet with varying wave height

6.4 Recommendation

According to the Section 6.1, the responses associated with turning off the turbine or lifting the turbine out of the water, can be considered as one response. Regarding the Section 6.1, there is no noticeable difference between the two responses due to their similar model-based results. Turning off the turbine can be done in a control room, while lifting the turbine out of the water is much harder to accomplish. Lifting the turbine has to be done from the platform. Performing this operation while on the platform during extreme events can be dangerous as well. Therefore, the recommended response is turning off the turbine and leave it in the water.

Base on the POE analysis, turning off the turbine is recommended when the wave range is between 75.9 feet and 130 feet or when the wind speed is higher than 100 mph (a 100-year event). While the wind speed is greater than 90 mph, the response shall be taken when the wavelength range is between 75.9 feet and 130 feet (Table 17).

Table 17: Turbine Response-Wind vs Wave

Wavelength (ft)	75.9	80	90	100	110	120	130
Wind Speed (mph)	Turn off Turbine (Y/N)?						
10	N	N	N	N	N	N	N
20	N	N	N	N	N	N	N
30	N	N	N	N	N	N	N
40	N	N	N	N	N	N	N
50	N	N	N	N	N	N	N
60	N	N	N	N	N	N	N
70	N	N	N	N	N	N	N
80	Y	Y	Y	Y	N	N	N
90	Y	Y	Y	Y	Y	Y	N
100	Y	Y	Y	Y	Y	Y	Y

Likewise, the response shall be taken at the similar wavelength ranges when the wave height is greater than 2.8 feet, 2.9 feet, or 3.0 feet (Table 18).

The most effective remedial action to a major event for the safe operation of the TTDS is to turn the turbine off. As shown in Table 17 and Table 18, this action is clearly stated under varied wind speeds and varied wave height and wavelengths. By computing the overall POE, the structural design of the TTDS is adequate under the highest expected wave and wind load, outside of an extreme weather event.

Table 18: Turbine Response-Wind vs Wave

Wavelength (ft)	75.9	80	90	100	110	120	130
Wave Height (ft)	Turn off Turbine (Y/N)?						
0.1	N	N	N	N	N	N	N
0.2	N	N	N	N	N	N	N
0.3	N	N	N	N	N	N	N
0.4	N	N	N	N	N	N	N
0.5	N	N	N	N	N	N	N
0.6	N	N	N	N	N	N	N
0.7	N	N	N	N	N	N	N
0.8	N	N	N	N	N	N	N
0.9	N	N	N	N	N	N	N
1	N	N	N	N	N	N	N
1.1	N	N	N	N	N	N	N
1.2	N	N	N	N	N	N	N
1.3	N	N	N	N	N	N	N
1.4	N	N	N	N	N	N	N
1.5	N	N	N	N	N	N	N
1.6	N	N	N	N	N	N	N
1.7	N	N	N	N	N	N	N
1.8	N	N	N	N	N	N	N
1.9	N	N	N	N	N	N	N
2	N	N	N	N	N	N	N
2.1	N	N	N	N	N	N	N
2.2	N	N	N	N	N	N	N
2.3	N	N	N	N	N	N	N
2.4	N	N	N	N	N	N	N
2.5	N	N	N	N	N	N	N
2.6	N	N	N	N	N	N	N
2.7	N	N	N	N	N	N	N
2.8	Y	Y	Y	Y	N	N	N
2.9	Y	Y	Y	Y	Y	Y	N
3	Y	Y	Y	Y	Y	Y	Y

Chapter 7 Conclusion and Future Work

7.1 Conclusion

The TTDS is a new design, unlike the normal structure design, such as office buildings, hospital, apartments, has specific design code, load factors, and guides of loads' selections. The TTDS does not have enough sources and design guides, it also has tremendous uncertainties such as wave loads, drags, live loads, etc. The probabilistic approach of PBD can help quantify these uncertainties. PBD is developed because of losses of the major events, such as, earthquake, hurricanes, and flood. Similarly, these events also have an unpredictable nature. Therefore, multiple methods of PBD were developed in the past decades. This study aims to use the Probabilistic approach of PBD to verify the design and evaluate the impact of wind and wave load, and explore the exceedance in a variety of the load setup.

Unlike other design loads for the TTDS, loads of wind and wave of different values are required to run the Probabilistic methodology. In our study, wavelengths of 16 different values, from 30.3 feet to 130 feet, and wave heights of 30 different values are chosen. In a similar matter, wind speeds of 10 distinctive values, from 10 mph to 100 mph, are selected. Moreover, the wind speeds include non-extreme events and extreme events (from ATC), whereas turbine's impact is also considered. Consequently, thousands of load cases are generated, which are run by GT-Strudl®.

After comparing the impact of parallel wave loads and the impact perpendicular wave loads, it is observed that the anchorage force exceeds the allowable force when the parallel wave load acts on the TTDS. Through the analysis of the results from GT-Strudl® and computation of the probability of the exceedance of the allowable anchorage forces, the structure of TTDS is considered satisfactory because the overall POE based on POE of extreme wind speed and POE of an anchorage is under 5%. However, it might not be satisfactory during extreme wind events when wind speed is higher than 80 mph. It might also not be satisfactory when the wave height is higher than 2.8 feet. Furthermore, the wave load appears to decrease as the wavelength increases. Therefore, one can draw the conclusion that the design of TTDS is satisfied for perpendicular wave load combination. The decision (stop operating turbine) has to be made when the parallel wave load is applied on the TTDS. In those cases, an action to protect the pier cap is required. The action is determined according to the results of the impact of the turbine. Similarly, strain calculation is based on the results that are given by GT-Strudl®. Strain calculation is used to do future simulation which will be associated to the sensors (strain gages) and programmed in a proper matter.

In summary, this study proves the TTDP design based on analyzing wave impact, wind impact, turbine impact, and the probability of exceedance of the anchorage forces. Meanwhile, the TTDS can handle all the predict extreme events except the wind speeds, higher than 80 mph, and wave heights, greater than 2.8 feet with wavelength range of the parallel wave load from 75.9 feet to 130 feet.

7.2 Future Work

While this work, provided a basis for turbine operational protocols during high wind and wave condition, has several limitations. The limitations come from the estimation of drag load, wave load, and wind load. They also affect the accuracy of the final results. Take wind load for instance, the only issue is the lack of available data.

- Collecting ADCP data and developing drag loads
  - The initial current velocity is 5.91 ft/s, but the newest ADCP data shows the current velocity is 8.20 ft/s.
  - Re-adjusting the water depth based on the ADCP data and modifying the position of the tidal turbine platform.
  - Due to the changing current speed and tide height, creating a dynamic model can offer a more reasonable result.
- Collecting wave height and wavelength information and developing the wave loads
  - The wave load for the TDP was developed by interpolating Figure 19 in this study, but the wave information will be collected in the future. New wave load need be calculated by using the collected information.
  - The method used in this study was based on static analysis, and the applied loads were the equivalent static load. However, the wave load is a dynamic. For the future work, creating dynamic models for wave loads will give more accurate and reasonable results.
- Estimating the relationship between wind speed and wave height and wavelength
  - The wave loads and wind loads are developed independently in this study, however, in reality, waves can be formed when the wind blows on the water surface. Then, for future work, to estimate this relationship is necessary to:
    - Estimate how wind speed affects the wave height
    - Estimate how the wavelength changes when the wind speed increase
- Creating a simulation used to provide alerts for action
  - Turn the Turbine off

- Predicting strains on each A-frame member based on the developed environmental demands
- Collecting data by strain gages with the changing environmental loads
- Comparing the predicted strains with the collected strains, and then, making decision.

With additional information collected from the sensor installed in October 2017 on the VGP, the structural response can be refined, and the procedure applied for strain evaluations of wind load and wave load can be response-based and not model-based. The POE computation of wind speed, wave height, and wave length will be more reliable if the sensor data are available for the normal events and extreme events. Given the delayed timing of the sensor installation, this data was not available for this work to compare the model-based results. Therefore, the recommendation of data inclusion are strains on the A-frames, wave height, wavelength, and wind speed.

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Appendices

Appendix A

Sample Calculations

Anchorage Force Computation:

The given resultant forces show in table 8. The X, Y, and Z are in a global coordinate system. The dimensions and the shop drawing are shown in table 17 and figure 36.

$$Anchorage\ 1 = \frac{F_z}{4} + \frac{M_x}{4 * y_{monment\ arm}} + \frac{M_y}{4 * x_{monment\ arm}}$$

$$F_z = 8.93\ kips\ (table\ 8)$$

$$M_x = 65.33\ kips - in\ (table\ 8)$$

$$M_y = 3.49\ kips - in\ (table\ 8)$$

$$Anchorage\ 1 = 4.7\ kip\ (Tension)$$

Similarly,

$$Anchorage\ 2 = \frac{F_z}{4} + \frac{M_x}{4 * y_{monment\ arm}} - \frac{M_y}{4 * x_{monment\ arm}} = 4.4\ kips$$

$$Anchorage\ 3 = \frac{F_z}{4} - \frac{M_x}{4 * y_{monment\ arm}} + \frac{M_y}{4 * x_{monment\ arm}} = 0.05\ kips$$

$$Anchorage\ 4 = \frac{F_z}{4} - \frac{M_x}{4 * y_{monment\ arm}} - \frac{M_y}{4 * x_{monment\ arm}} = -0.2\ kips$$

The anchorage forces on the other supports can be computed with these four equations.

Table 19: Plate Dimensions

Plate Dimensions		
b	12	in
h	14	in
Moment arm x	6	in
Moment arm y	7	in

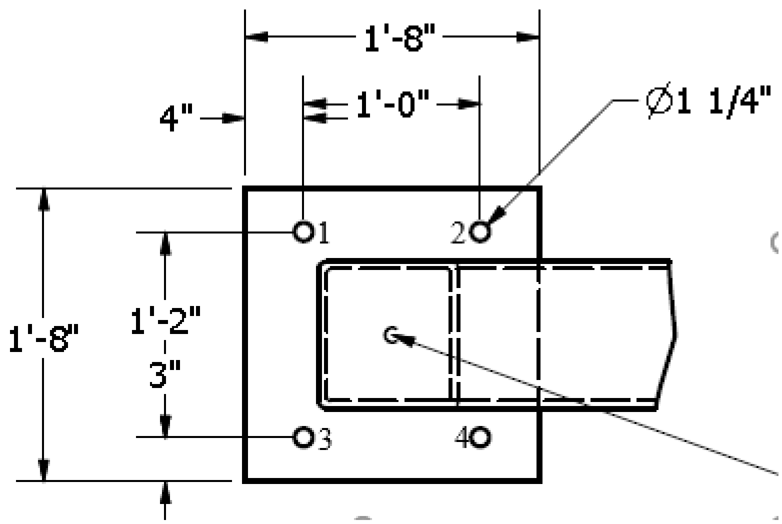

Figure 36: Plate Dimension and Details

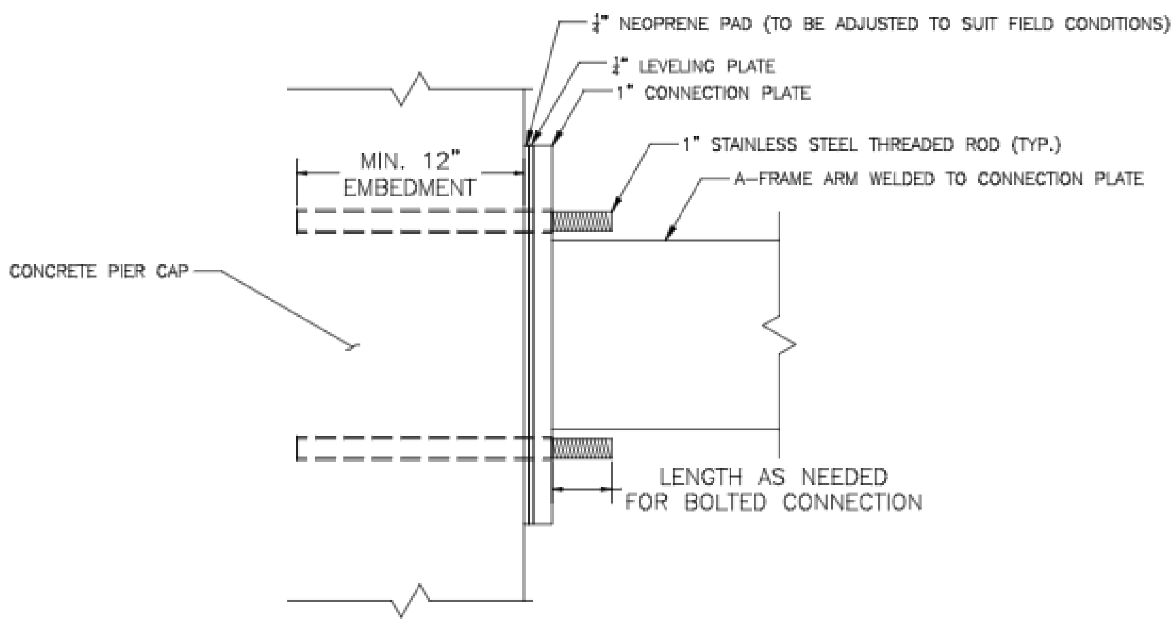

Figure 37: Anchorage Drawing

Interpolation

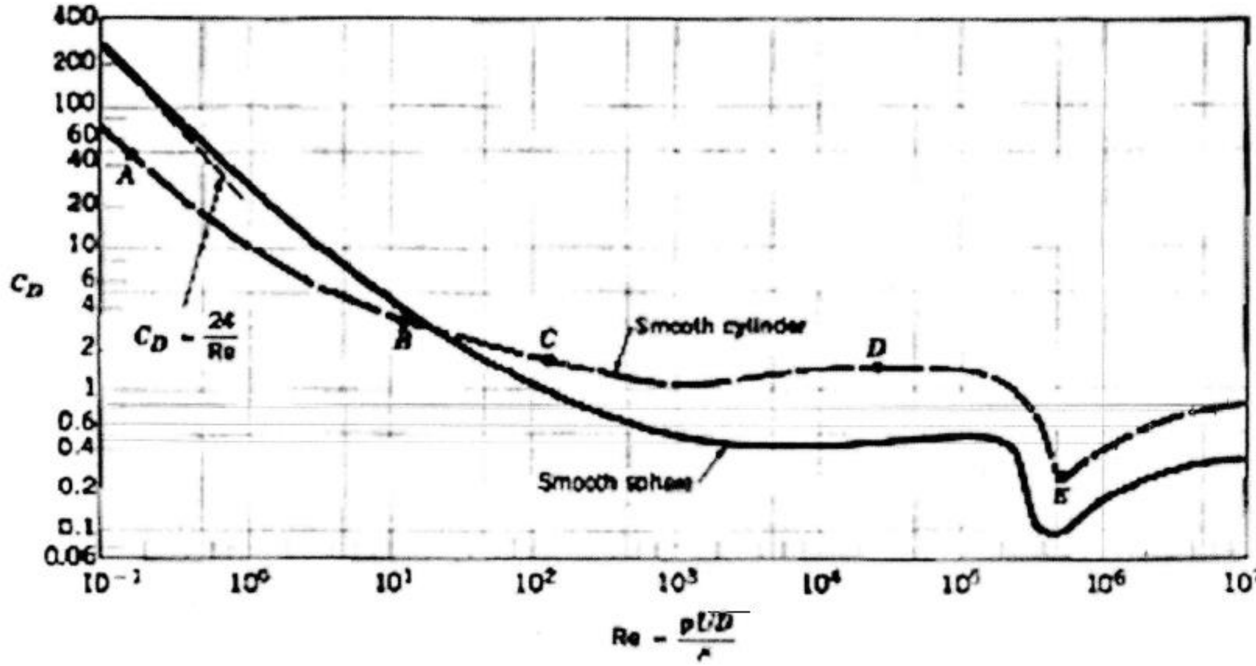

Figure 38: Drag Coefficient Interpolation [23]

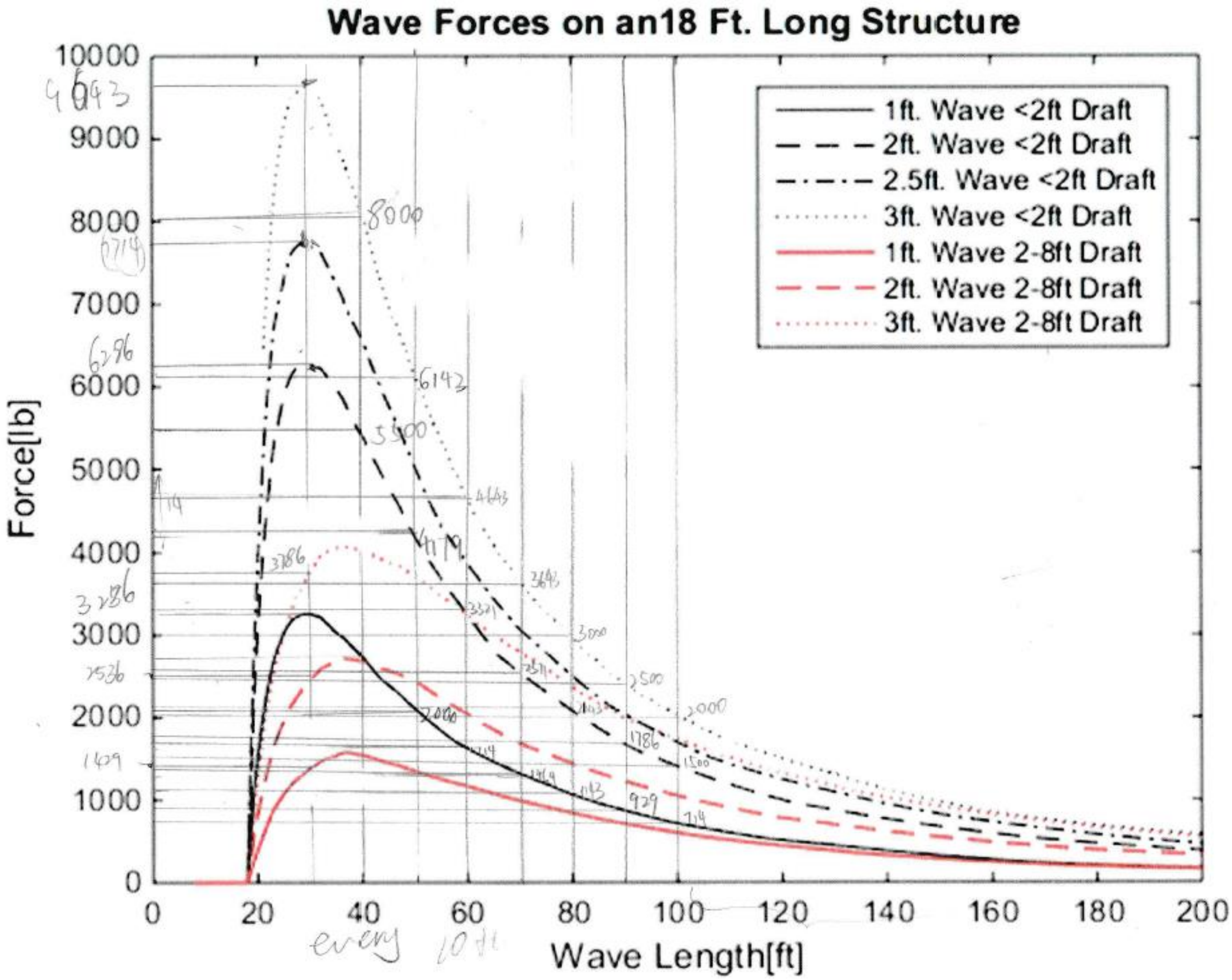

Figure 39: Perpendicular Wave Load Interpolation @ Shallow Draft

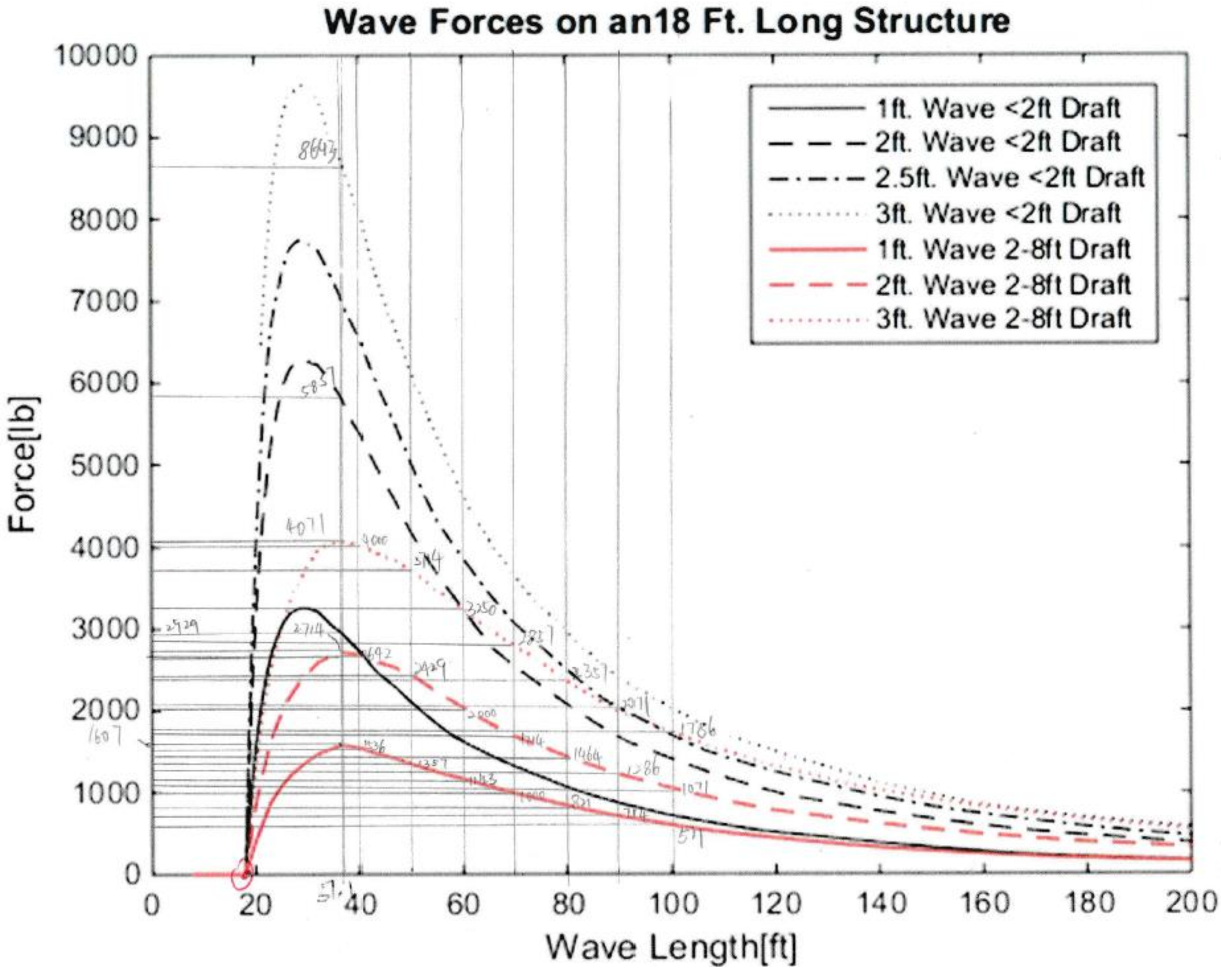

Figure 40: Perpendicular Wave Load Interpolation @ Deep Draft

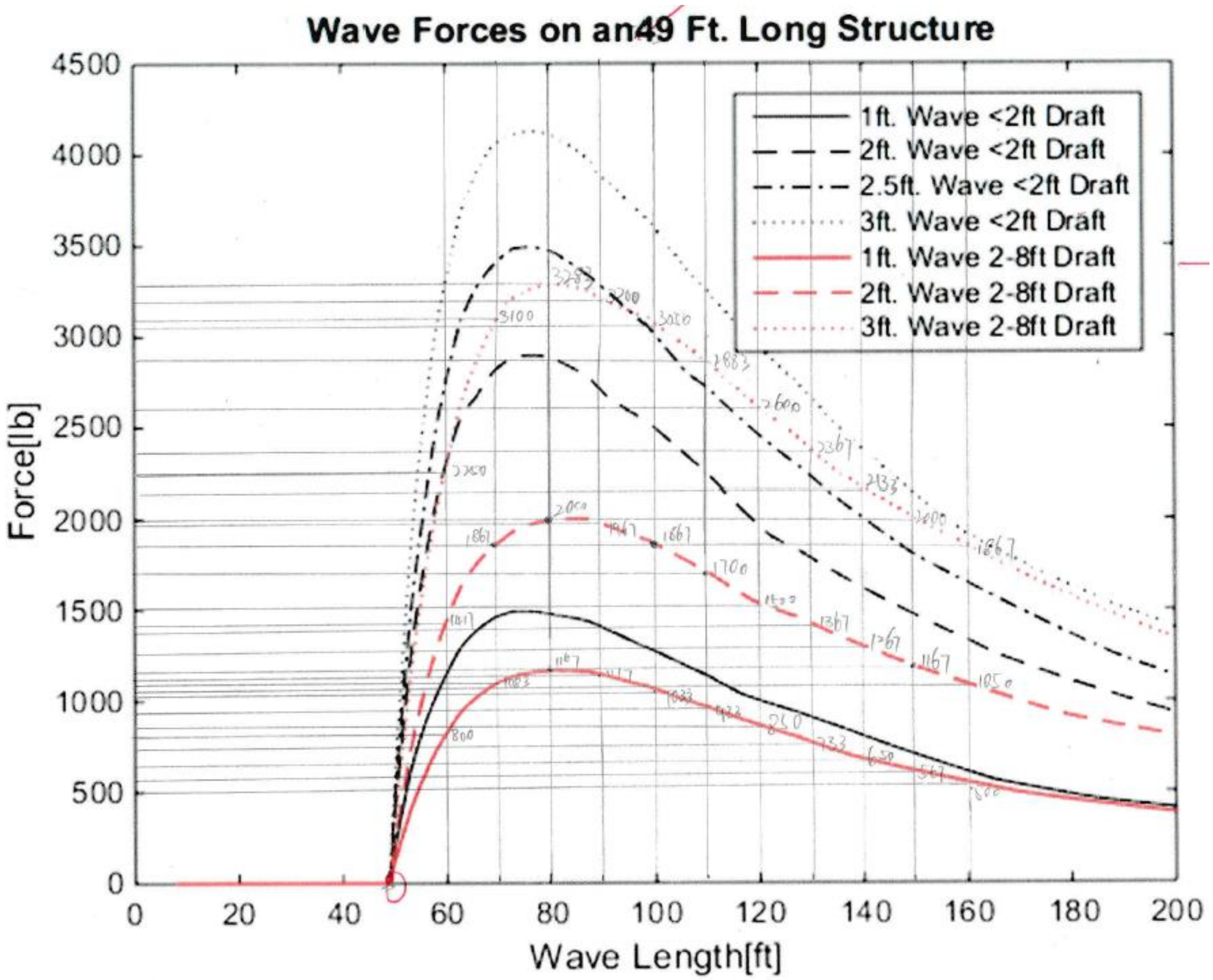

Figure 41: Parallel Wave Load Interpolation @ Deep Draft

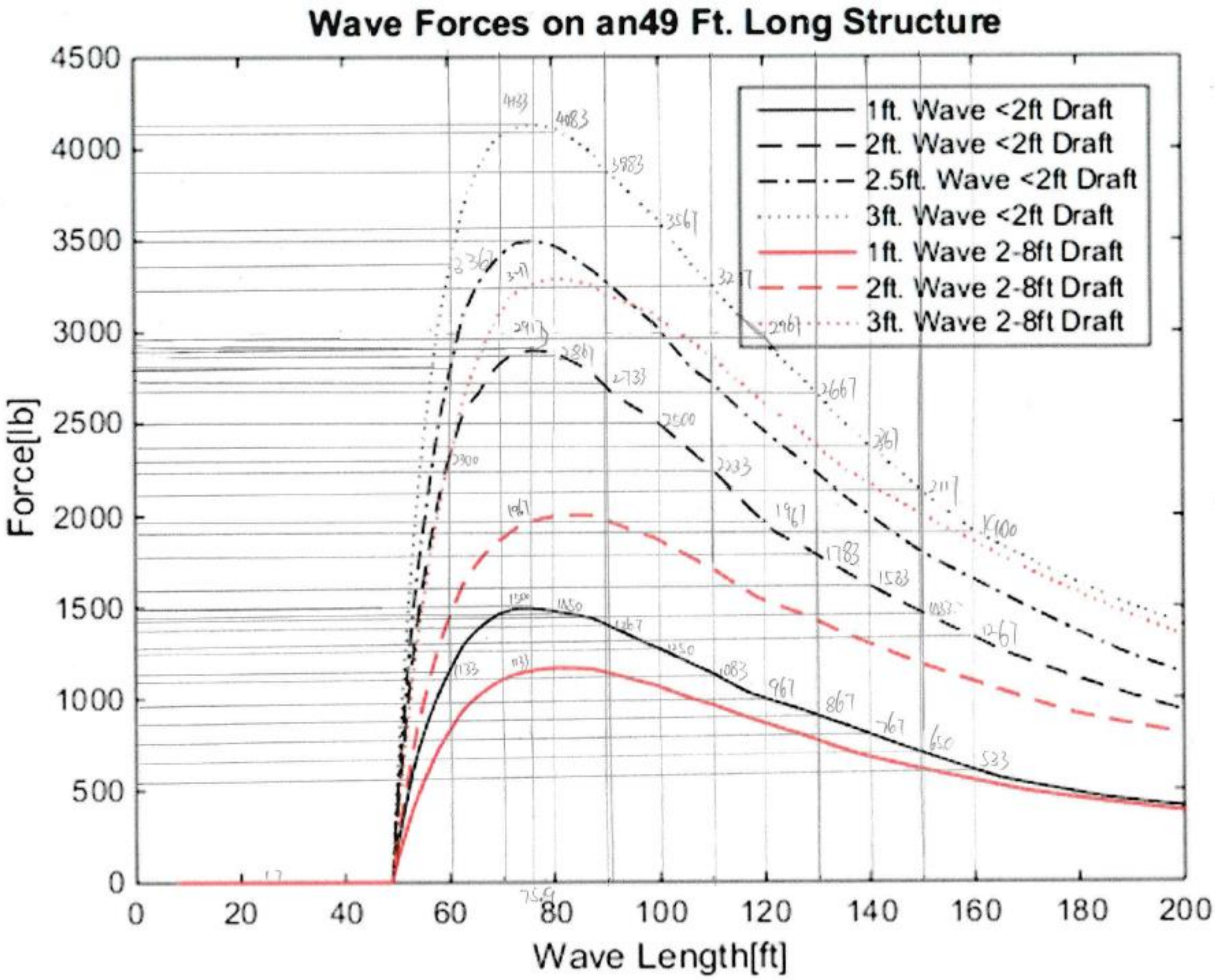

Figure 42: Parallel Wave Load Interpolation @ Shallow Draft

Applied Wave Loads

Table 20: Perpendicular Wave (Shallow Draft)

Perpendicular Wave (Shallow Draft)									
Wavelength (ft)	30.3	37.1	40	50	60	70	80	90	100
Wave Height (ft)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)
0.1	328.6	292.9	271.4	200	171.4	146.4	114.3	92.9	71.4
0.2	657.2	585.8	542.8	400	342.8	292.8	228.6	185.8	142.8
0.3	985.8	878.7	814.2	600	514.2	439.2	342.9	278.7	214.2
0.4	1314.4	1171.6	1085.6	800	685.6	585.6	457.2	371.6	285.6
0.5	1643	1464.5	1357	1000	857	732	571.5	464.5	357
0.6	1971.6	1757.4	1628.4	1200	1028.4	878.4	685.8	557.4	428.4
0.7	2300.2	2050.3	1899.8	1400	1199.8	1024.8	800.1	650.3	499.8
0.8	2628.8	2343.2	2171.2	1600	1371.2	1171.2	914.4	743.2	571.2
0.9	2957.4	2636.1	2442.6	1800	1542.6	1317.6	1028.7	836.1	642.6
1	3286	2929	2714	2000	1714	1464	1143	929	714
1.1	3586	3221.8	2992.6	2217.9	1874.7	1574.7	1243	1014.7	792.6
1.2	3886	3514.6	3271.2	2435.8	2035.4	1685.4	1343	1100.4	871.2
1.3	4186	3807.4	3549.8	2653.7	2196.1	1796.1	1443	1186.1	949.8
1.4	4486	4100.2	3828.4	2871.6	2356.8	1906.8	1543	1271.8	1028.4
1.5	4786	4393	4107	3089.5	2517.5	2017.5	1643	1357.5	1107
1.6	5086	4685.8	4385.6	3307.4	2678.2	2128.2	1743	1443.2	1185.6
1.7	5386	4978.6	4664.2	3525.3	2838.9	2238.9	1843	1528.9	1264.2
1.8	5686	5271.4	4942.8	3743.2	2999.6	2349.6	1943	1614.6	1342.8
1.9	5986	5564.2	5221.4	3961.1	3160.3	2460.3	2043	1700.3	1421.4
2	6286	5857	5500	4179	3321	2571	2143	1786	1500
2.1	6621.7	6135.6	5750	4375.4	3453.2	2678.2	2228.7	1857.4	1550
2.2	6957.4	6414.2	6000	4571.8	3585.4	2785.4	2314.4	1928.8	1600
2.3	7293.1	6692.8	6250	4768.2	3717.6	2892.6	2400.1	2000.2	1650
2.4	7628.8	6971.4	6500	4964.6	3849.8	2999.8	2485.8	2071.6	1700
2.5	7964.5	7250	6750	5161	3982	3107	2571.5	2143	1750
2.6	8300.2	7528.6	7000	5357.4	4114.2	3214.2	2657.2	2214.4	1800
2.7	8635.9	7807.2	7250	5553.8	4246.4	3321.4	2742.9	2285.8	1850
2.8	8971.6	8085.8	7500	5750.2	4378.6	3428.6	2828.6	2357.2	1900
2.9	9307.3	8364.4	7750	5946.6	4510.8	3535.8	2914.3	2428.6	1950
3	9643	8643	8000	6143	4643	3643	3000	2500	2000

Table 21: Perpendicular Wave (Deep Draft)

Perpendicular Wave (Deep Draft)									
Wavelength (ft)	30.3	37.1	40	50	60	70	80	90	100
Wave Height (ft)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)
0.1	142.9	160.7	153.6	135.7	114.3	100	82.1	71.4	57.1
0.2	285.8	321.4	307.2	271.4	228.6	200	164.2	142.8	114.2
0.3	428.7	482.1	460.8	407.1	342.9	300	246.3	214.2	171.3
0.4	571.6	642.8	614.4	542.8	457.2	400	328.4	285.6	228.4
0.5	714.5	803.5	768	678.5	571.5	500	410.5	357	285.5
0.6	857.4	964.2	921.6	814.2	685.8	600	492.6	428.4	342.6
0.7	1000.3	1124.9	1075.2	949.9	800.1	700	574.7	499.8	399.7
0.8	1143.2	1285.6	1228.8	1085.6	914.4	800	656.8	571.2	456.8
0.9	1286.1	1446.3	1382.4	1221.3	1028.7	900	738.9	642.6	513.9
1	1429	1607	1536	1357	1143	1000	821	714	571
1.1	1539.7	1717.7	1646.6	1464.2	1228.7	1071.4	885.3	771.2	621
1.2	1650.4	1828.4	1757.2	1571.4	1314.4	1142.8	949.6	828.4	671
1.3	1761.1	1939.1	1867.8	1678.6	1400.1	1214.2	1013.9	885.6	721
1.4	1871.8	2049.8	1978.4	1785.8	1485.8	1285.6	1078.2	942.8	771
1.5	1982.5	2160.5	2089	1893	1571.5	1357	1142.5	1000	821
1.6	2093.2	2271.2	2199.6	2000.2	1657.2	1428.4	1206.8	1057.2	871
1.7	2203.9	2381.9	2310.2	2107.4	1742.9	1499.8	1271.1	1114.4	921
1.8	2314.6	2492.6	2420.8	2214.6	1828.6	1571.2	1335.4	1171.6	971
1.9	2425.3	2603.3	2531.4	2321.8	1914.3	1642.6	1399.7	1228.8	1021
2	2536	2714	2642	2429	2000	1714	1464	1286	1071
2.1	2611	2849.7	2777.8	2557.5	2125	1828.3	1553.3	1359.1	1142.5
2.2	2686	2985.4	2913.6	2686	2250	1942.6	1642.6	1432.2	1214
2.3	2761	3121.1	3049.4	2814.5	2375	2056.9	1731.9	1505.3	1285.5
2.4	2836	3256.8	3185.2	2943	2500	2171.2	1821.2	1578.4	1357
2.5	2911	3392.5	3321	3071.5	2625	2285.5	1910.5	1651.5	1428.5
2.6	2986	3528.2	3456.8	3200	2750	2399.8	1999.8	1724.6	1500
2.7	3061	3663.9	3592.6	3328.5	2875	2514.1	2089.1	1797.7	1571.5
2.8	3136	3799.6	3728.4	3457	3000	2628.4	2178.4	1870.8	1643
2.9	3211	3935.3	3864.2	3585.5	3125	2742.7	2267.7	1943.9	1714.5
3	3286	4071	4000	3714	3250	2857	2357	2017	1786

Table 22: Parallel Wave (Shallow Draft)

Parallel Wave (Shallow Draft)									
Wavelength (ft)	75.9	80	90	100	110	120	130	140	150
Wave Height (ft)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)
0.1	150	145	136.7	125	108.3	96.7	86.7	76.7	65
0.2	300	290	273.4	250	216.6	193.4	173.4	153.4	130
0.3	450	435	410.1	375	324.9	290.1	260.1	230.1	195
0.4	600	580	546.8	500	433.2	386.8	346.8	306.8	260
0.5	750	725	683.5	625	541.5	483.5	433.5	383.5	325
0.6	900	870	820.2	750	649.8	580.2	520.2	460.2	390
0.7	1050	1015	956.9	875	758.1	676.9	606.9	536.9	455
0.8	1200	1160	1093.6	1000	866.4	773.6	693.6	613.6	520
0.9	1350	1305	1230.3	1125	974.7	870.3	780.3	690.3	585
1	1500	1450	1367	1250	1083	967	867	767	650
1.1	1641.7	1591.7	1503.6	1375	1198	1067	958.6	848.6	728.3
1.2	1783.4	1733.4	1640.2	1500	1313	1167	1050.2	930.2	806.6
1.3	1925.1	1875.1	1776.8	1625	1428	1267	1141.8	1011.8	884.9
1.4	2066.8	2016.8	1913.4	1750	1543	1367	1233.4	1093.4	963.2
1.5	2208.5	2158.5	2050	1875	1658	1467	1325	1175	1041.5
1.6	2350.2	2300.2	2186.6	2000	1773	1567	1416.6	1256.6	1119.8
1.7	2491.9	2441.9	2323.2	2125	1888	1667	1508.2	1338.2	1198.1
1.8	2633.6	2583.6	2459.8	2250	2003	1767	1599.8	1419.8	1276.4
1.9	2775.3	2725.3	2596.4	2375	2118	1867	1691.4	1501.4	1354.7
2	2917	2867	2733	2500	2233	1967	1783	1583	1433
2.1	3038.6	2988.6	2848	2606.7	2331.4	2067	1871.4	1661.4	1501.4
2.2	3160.2	3110.2	2963	2713.4	2429.8	2167	1959.8	1739.8	1569.8
2.3	3281.8	3231.8	3078	2820.1	2528.2	2267	2048.2	1818.2	1638.2
2.4	3403.4	3353.4	3193	2926.8	2626.6	2367	2136.6	1896.6	1706.6
2.5	3525	3475	3308	3033.5	2725	2467	2225	1975	1775
2.6	3646.6	3596.6	3423	3140.2	2823.4	2567	2313.4	2053.4	1843.4
2.7	3768.2	3718.2	3538	3246.9	2921.8	2667	2401.8	2131.8	1911.8
2.8	3889.8	3839.8	3653	3353.6	3020.2	2767	2490.2	2210.2	1980.2
2.9	4011.4	3961.4	3768	3460.3	3118.6	2867	2578.6	2288.6	2048.6
3	4133	4083	3883	3567	3217	2967	2667	2367	2117

Table 23: Parallel Wave (Deep Draft)

Parallel Wave (Deep Draft)									
Wavelength (ft)	75.9	80	90	100	110	120	130	140	150
Wave Height (ft)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)
0.1	113.3	116.7	111.7	103.3	93.3	85	73.3	65	56.7
0.2	226.6	233.4	223.4	206.6	186.6	170	146.6	130	113.4
0.3	339.9	350.1	335.1	309.9	279.9	255	219.9	195	170.1
0.4	453.2	466.8	446.8	413.2	373.2	340	293.2	260	226.8
0.5	566.5	583.5	558.5	516.5	466.5	425	366.5	325	283.5
0.6	679.8	700.2	670.2	619.8	559.8	510	439.8	390	340.2
0.7	793.1	816.9	781.9	723.1	653.1	595	513.1	455	396.9
0.8	906.4	933.6	893.6	826.4	746.4	680	586.4	520	453.6
0.9	1019.7	1050.3	1005.3	929.7	839.7	765	659.7	585	510.3
1	1133	1167	1117	1033	933	850	733	650	567
1.1	1216.4	1250.3	1202	1116.4	1009.7	915	796.4	711.7	627
1.2	1299.8	1333.6	1287	1199.8	1086.4	980	859.8	773.4	687
1.3	1383.2	1416.9	1372	1283.2	1163.1	1045	923.2	835.1	747
1.4	1466.6	1500.2	1457	1366.6	1239.8	1110	986.6	896.8	807
1.5	1550	1583.5	1542	1450	1316.5	1175	1050	958.5	867
1.6	1633.4	1666.8	1627	1533.4	1393.2	1240	1113.4	1020.2	927
1.7	1716.8	1750.1	1712	1616.8	1469.9	1305	1176.8	1081.9	987
1.8	1800.2	1833.4	1797	1700.2	1546.6	1370	1240.2	1143.6	1047
1.9	1883.6	1916.7	1882	1783.6	1623.3	1435	1303.6	1205.3	1107
2	1967	2000	1967	1867	1700	1500	1367	1267	1167
2.1	2092	2128.3	2090.3	1985.3	1818.3	1610	1467	1353.6	1250.3
2.2	2217	2256.6	2213.6	2103.6	1936.6	1720	1567	1440.2	1333.6
2.3	2342	2384.9	2336.9	2221.9	2054.9	1830	1667	1526.8	1416.9
2.4	2467	2513.2	2460.2	2340.2	2173.2	1940	1767	1613.4	1500.2
2.5	2592	2641.5	2583.5	2458.5	2291.5	2050	1867	1700	1583.5
2.6	2717	2769.8	2706.8	2576.8	2409.8	2160	1967	1786.6	1666.8
2.7	2842	2898.1	2830.1	2695.1	2528.1	2270	2067	1873.2	1750.1
2.8	2967	3026.4	2953.4	2813.4	2646.4	2380	2167	1959.8	1833.4
2.9	3092	3154.7	3076.7	2931.7	2764.7	2490	2267	2046.4	1916.7
3	3217	3283	3200	3050	2883	2600	2367	2133	2000

Table 24: Perpendicular Wave VGP

Perpendicular Wave VGP									
Wavelength (ft)	30.3	37.1	40.0	50.0	60.0	70.0	80.0	90.0	100.0
Wave Height (ft)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)
0.1	6.90	6.27	6.02	5.29	4.71	4.23	3.84	3.51	3.23
0.2	13.80	12.54	12.05	10.59	9.41	8.46	7.68	7.02	6.46
0.3	20.70	18.81	18.07	15.88	14.12	12.69	11.51	10.53	9.70
0.4	27.60	25.07	24.10	21.18	18.83	16.92	15.35	14.04	12.93
0.5	34.50	31.34	30.12	26.47	23.53	21.15	19.19	17.55	16.16
0.6	41.40	37.61	36.15	31.76	28.24	25.38	23.03	21.06	19.39
0.7	48.31	43.88	42.17	37.06	32.95	29.61	26.86	24.57	22.63
0.8	55.21	50.15	48.20	42.35	37.65	33.84	30.70	28.08	25.86
0.9	62.11	56.42	54.22	47.64	42.36	38.07	34.54	31.59	29.09
1	69.01	62.68	60.25	52.94	47.07	42.30	38.38	35.10	32.32
1.1	75.91	68.95	66.27	58.23	51.77	46.53	42.21	38.61	35.56
1.2	82.81	75.22	72.30	63.53	56.48	50.76	46.05	42.12	38.79
1.3	89.71	81.49	78.32	68.82	61.19	54.99	49.89	45.63	42.02
1.4	96.61	87.76	84.34	74.11	65.89	59.22	53.73	49.14	45.25
1.5	103.51	94.03	90.37	79.41	70.60	63.45	57.56	52.65	48.49
1.6	110.41	100.30	96.39	84.70	75.31	67.68	61.40	56.16	51.72
1.7	117.31	106.56	102.42	89.99	80.01	71.91	65.24	59.67	54.95
1.8	124.21	112.83	108.44	95.29	84.72	76.14	69.08	63.18	58.18
1.9	131.11	119.10	114.47	100.58	89.43	80.37	72.92	66.69	61.42
2	138.01	125.37	120.49	105.88	94.13	84.60	76.75	70.20	64.65
2.1	144.92	131.64	126.52	111.17	98.84	88.83	80.59	73.71	67.88
2.2	151.82	137.91	132.54	116.46	103.55	93.06	84.43	77.22	71.11
2.3	158.72	144.18	138.57	121.76	108.26	97.29	88.27	80.73	74.35
2.4	165.62	150.44	144.59	127.05	112.96	101.52	92.10	84.24	77.58
2.5	172.52	156.71	150.62	132.34	117.67	105.75	95.94	87.75	80.81
2.6	179.42	162.98	156.64	137.64	122.38	109.98	99.78	91.26	84.04
2.7	186.32	169.25	162.67	142.93	127.08	114.21	103.62	94.77	87.28
2.8	193.22	175.52	168.69	148.23	131.79	118.44	107.45	98.28	90.51
2.9	200.12	181.79	174.71	153.52	136.50	122.67	111.29	101.79	93.74
3	207.02	188.05	180.74	158.81	141.20	126.90	115.13	105.30	96.97

Table 25: Parallel Wave VGP

Parallel Wave VGP									
Wavelength (ft)	75.9	80.0	90.0	100.0	110.0	120.0	130.0	140.0	150.0
Wave Height (ft)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)
0.1	3.99	3.84	3.51	3.23	2.99	2.79	2.61	2.45	2.31
0.2	7.98	7.68	7.02	6.46	5.99	5.58	5.22	4.90	4.62
0.3	11.97	11.51	10.53	9.70	8.98	8.37	7.83	7.36	6.94
0.4	15.96	15.35	14.04	12.93	11.98	11.16	10.44	9.81	9.25
0.5	19.95	19.19	17.55	16.16	14.97	13.95	13.05	12.26	11.56
0.6	23.94	23.03	21.06	19.39	17.97	16.74	15.66	14.71	13.87
0.7	27.93	26.86	24.57	22.63	20.96	19.53	18.27	17.16	16.18
0.8	31.92	30.70	28.08	25.86	23.96	22.32	20.88	19.62	18.50
0.9	35.91	34.54	31.59	29.09	26.95	25.10	23.49	22.07	20.81
1	39.90	38.38	35.10	32.32	29.95	27.89	26.10	24.52	23.12
1.1	43.89	42.21	38.61	35.56	32.94	30.68	28.71	26.97	25.43
1.2	47.88	46.05	42.12	38.79	35.94	33.47	31.32	29.42	27.74
1.3	51.87	49.89	45.63	42.02	38.93	36.26	33.93	31.88	30.05
1.4	55.86	53.73	49.14	45.25	41.93	39.05	36.54	34.33	32.37
1.5	59.85	57.56	52.65	48.49	44.92	41.84	39.15	36.78	34.68
1.6	63.84	61.40	56.16	51.72	47.92	44.63	41.76	39.23	36.99
1.7	67.83	65.24	59.67	54.95	50.91	47.42	44.37	41.68	39.30
1.8	71.82	69.08	63.18	58.18	53.91	50.21	46.98	44.14	41.61
1.9	75.81	72.92	66.69	61.42	56.90	53.00	49.59	46.59	43.93
2	79.80	76.75	70.20	64.65	59.90	55.79	52.20	49.04	46.24
2.1	83.79	80.59	73.71	67.88	62.89	58.58	54.81	51.49	48.55
2.2	87.78	84.43	77.22	71.11	65.89	61.37	57.42	53.94	50.86
2.3	91.77	88.27	80.73	74.35	68.88	64.16	60.03	56.40	53.17
2.4	95.76	92.10	84.24	77.58	71.88	66.95	62.64	58.85	55.49
2.5	99.74	95.94	87.75	80.81	74.87	69.74	65.25	61.30	57.80
2.6	103.73	99.78	91.26	84.04	77.87	72.52	67.86	63.75	60.11
2.7	107.72	103.62	94.77	87.28	80.86	75.31	70.47	66.20	62.42
2.8	111.71	107.45	98.28	90.51	83.86	78.10	73.08	68.66	64.73
2.9	115.70	111.29	101.79	93.74	86.85	80.89	75.69	71.11	67.05
3	119.69	115.13	105.30	96.97	89.85	83.68	78.30	73.56	69.36

Table 26: Perpendicular Wave Turbine

Perpendicular Wave Turbine									
Wavelength (ft)	30.3	37.1	40.0	50.0	60.0	70.0	80.0	90.0	100.0
Wave Height (ft)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)
0.1	486.9	486.9	486.9	486.9	486.9	486.9	486.9	486.7	486.4
0.2	973.9	973.9	973.9	973.9	973.9	973.9	973.7	973.4	972.9
0.3	1460.8	1460.8	1460.8	1460.8	1460.8	1460.8	1460.6	1460.2	1459.3
0.4	1947.8	1947.8	1947.8	1947.8	1947.8	1947.7	1947.5	1946.9	1945.7
0.5	2434.7	2434.7	2434.7	2434.7	2434.7	2434.6	2434.3	2433.6	2432.2
0.6	2921.7	2921.7	2921.7	2921.7	2921.7	2921.6	2921.2	2920.3	2918.6
0.7	3408.6	3408.6	3408.6	3408.6	3408.6	3408.5	3408.1	3407.1	3405.0
0.8	3895.6	3895.6	3895.6	3895.6	3895.6	3895.4	3895.0	3893.8	3891.4
0.9	4382.5	4382.5	4382.5	4382.5	4382.5	4382.3	4381.8	4380.5	4377.9
1	4869.5	4869.5	4869.5	4869.5	4869.4	4869.3	4868.7	4867.2	4864.3
1.1	5356.4	5356.4	5356.4	5356.4	5356.4	5356.2	5355.6	5354.0	5350.7
1.2	5843.4	5843.4	5843.4	5843.4	5843.3	5843.1	5842.4	5840.7	5837.2
1.3	6330.3	6330.3	6330.3	6330.3	6330.3	6330.1	6329.3	6327.4	6323.6
1.4	6817.3	6817.3	6817.3	6817.3	6817.2	6817.0	6816.2	6814.1	6810.0
1.5	7304.2	7304.2	7304.2	7304.2	7304.2	7303.9	7303.0	7300.9	7296.5
1.6	7791.2	7791.2	7791.2	7791.2	7791.1	7790.8	7789.9	7787.6	7782.9
1.7	8278.1	8278.1	8278.1	8278.1	8278.1	8277.8	8276.8	8274.3	8269.3
1.8	8765.1	8765.1	8765.1	8765.1	8765.0	8764.7	8763.6	8761.0	8755.7
1.9	9252.0	9252.0	9252.0	9252.0	9251.9	9251.6	9250.5	9247.8	9242.2
2	9739.0	9739.0	9739.0	9739.0	9738.9	9738.5	9737.4	9734.5	9728.6
2.1	10225.9	10225.9	10225.9	10225.9	10225.8	10225.5	10224.3	10221.2	10215.0
2.2	10712.9	10712.9	10712.9	10712.8	10712.8	10712.4	10711.1	10707.9	10701.5
2.3	11199.8	11199.8	11199.8	11199.8	11199.7	11199.3	11198.0	11194.7	11187.9
2.4	11686.7	11686.7	11686.7	11686.7	11686.7	11686.3	11684.9	11681.4	11674.3
2.5	12173.7	12173.7	12173.7	12173.7	12173.6	12173.2	12171.7	12168.1	12160.8
2.6	12660.6	12660.6	12660.6	12660.6	12660.6	12660.1	12658.6	12654.8	12647.2
2.7	13147.6	13147.6	13147.6	13147.6	13147.5	13147.0	13145.5	13141.5	13133.6
2.8	13634.5	13634.5	13634.5	13634.5	13634.4	13634.0	13632.3	13628.3	13620.1
2.9	14121.5	14121.5	14121.5	14121.5	14121.4	14120.9	14119.2	14115.0	14106.5
3	14608.4	14608.4	14608.4	14608.4	14608.3	14607.8	14606.1	14601.7	14592.9

Table 27: Parallel Wave Turbine

Parallel Wave Turbine									
Wavelength (ft)	75.9	80.0	90.0	100.0	110.0	120.0	130.0	140.0	150.0
Wave Height (ft)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)	Force (lb)
0.1	486.9	486.9	486.7	486.4	485.9	485.1	484.0	482.5	480.6
0.2	973.8	973.7	973.4	972.9	971.8	970.3	968.0	965.0	961.2
0.3	1460.7	1460.6	1460.2	1459.3	1457.8	1455.4	1452.0	1447.5	1441.8
0.4	1947.6	1947.5	1946.9	1945.7	1943.7	1940.5	1936.0	1930.0	1922.4
0.5	2434.5	2434.3	2433.6	2432.2	2429.6	2425.7	2420.0	2412.5	2403.0
0.6	2921.4	2921.2	2920.3	2918.6	2915.5	2910.8	2904.0	2895.0	2883.6
0.7	3408.3	3408.1	3407.1	3405.0	3401.5	3395.9	3388.1	3377.5	3364.2
0.8	3895.2	3895.0	3893.8	3891.4	3887.4	3881.1	3872.1	3860.0	3844.8
0.9	4382.1	4381.8	4380.5	4377.9	4373.3	4366.2	4356.1	4342.6	4325.4
1	4869.0	4868.7	4867.2	4864.3	4859.2	4851.3	4840.1	4825.1	4806.0
1.1	5355.9	5355.6	5354.0	5350.7	5345.1	5336.5	5324.1	5307.6	5286.6
1.2	5842.8	5842.4	5840.7	5837.2	5831.1	5821.6	5808.1	5790.1	5767.2
1.3	6329.7	6329.3	6327.4	6323.6	6317.0	6306.7	6292.1	6272.6	6247.8
1.4	6816.6	6816.2	6814.1	6810.0	6802.9	6791.9	6776.1	6755.1	6728.4
1.5	7303.5	7303.0	7300.9	7296.5	7288.8	7277.0	7260.1	7237.6	7209.0
1.6	7790.4	7789.9	7787.6	7782.9	7774.7	7762.1	7744.1	7720.1	7689.6
1.7	8277.3	8276.8	8274.3	8269.3	8260.7	8247.3	8228.1	8202.6	8170.2
1.8	8764.2	8763.6	8761.0	8755.7	8746.6	8732.4	8712.1	8685.1	8650.8
1.9	9251.1	9250.5	9247.8	9242.2	9232.5	9217.5	9196.1	9167.6	9131.4
2	9738.0	9737.4	9734.5	9728.6	9718.4	9702.7	9680.2	9650.1	9612.0
2.1	10224.9	10224.3	10221.2	10215.0	10204.4	10187.8	10164.2	10132.6	10092.6
2.2	10711.8	10711.1	10707.9	10701.5	10690.3	10672.9	10648.2	10615.1	10573.2
2.3	11198.7	11198.0	11194.7	11187.9	11176.2	11158.0	11132.2	11097.6	11053.8
2.4	11685.6	11684.9	11681.4	11674.3	11662.1	11643.2	11616.2	11580.1	11534.4
2.5	12172.5	12171.7	12168.1	12160.8	12148.0	12128.3	12100.2	12062.6	12015.0
2.6	12659.4	12658.6	12654.8	12647.2	12634.0	12613.4	12584.2	12545.1	12495.6
2.7	13146.3	13145.5	13141.5	13133.6	13119.9	13098.6	13068.2	13027.7	12976.2
2.8	13633.2	13632.3	13628.3	13620.1	13605.8	13583.7	13552.2	13510.2	13456.8
2.9	14120.1	14119.2	14115.0	14106.5	14091.7	14068.8	14036.2	13992.7	13937.4
3	14607.0	14606.1	14601.7	14592.9	14577.6	14554.0	14520.2	14475.2	14418.0

Appendix B

Model Dimensions

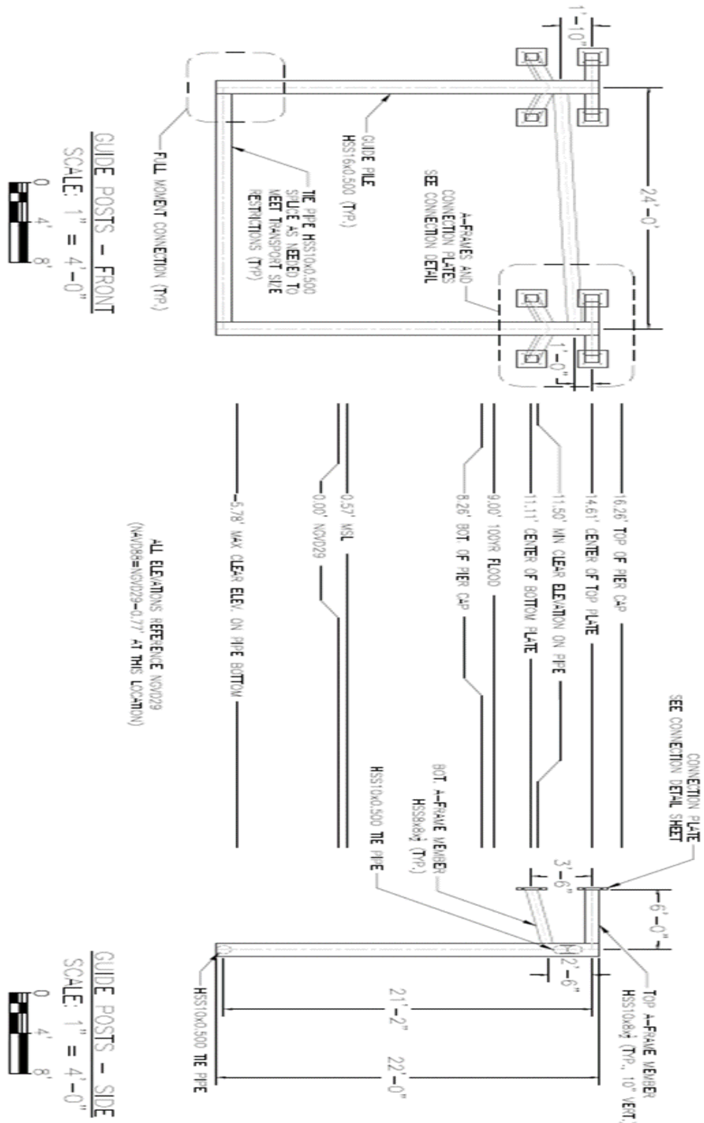

Figure 43: Shop Drawing of the VGP

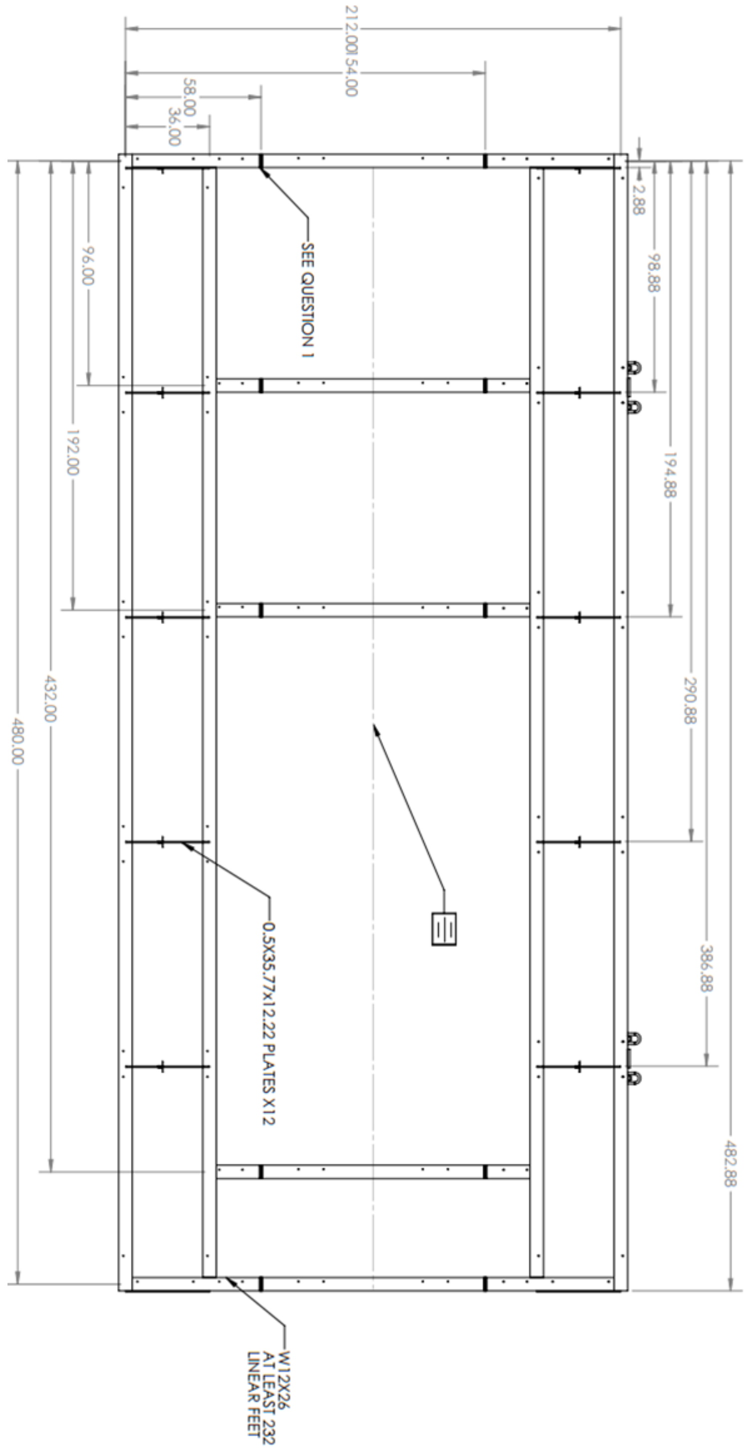

Figure 44: TDP Dimension

Appendix C:

CDF

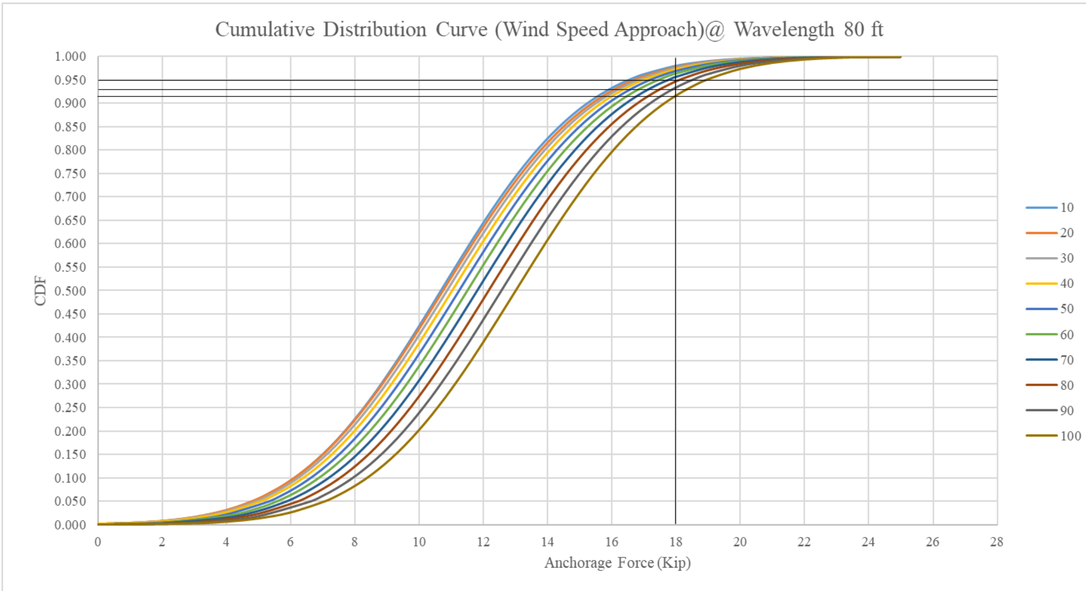

Figure 45: Cumulative Distribution Curve for Variable Wind Speeds @ Wavelength = 80'

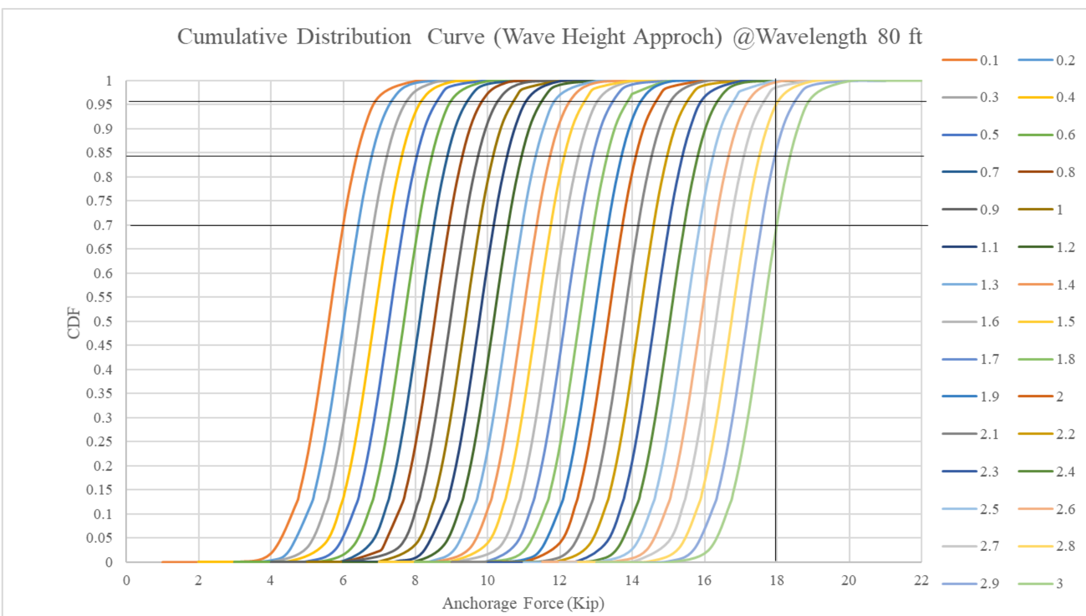

Figure 46: Cumulative Distribution Curve for Variable Wave Heights @ Wavelength = 80'

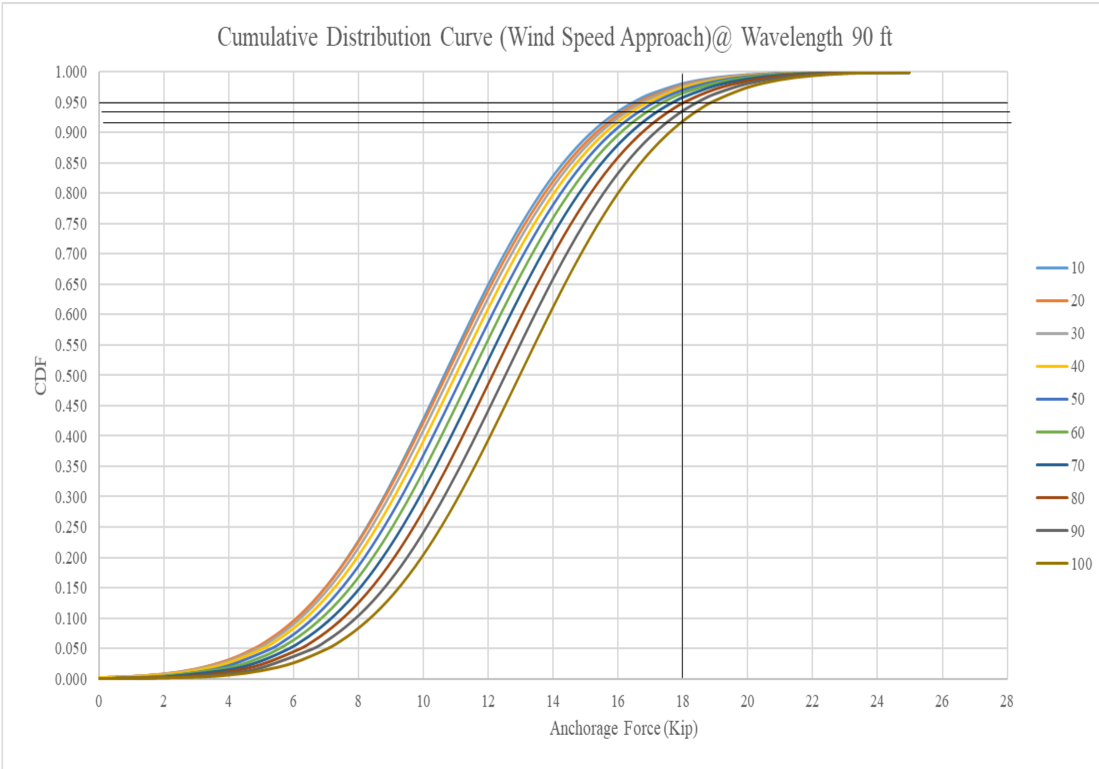

Figure 47: Cumulative Distribution Curve for Variable Wind Speeds @ Wavelength = 90'

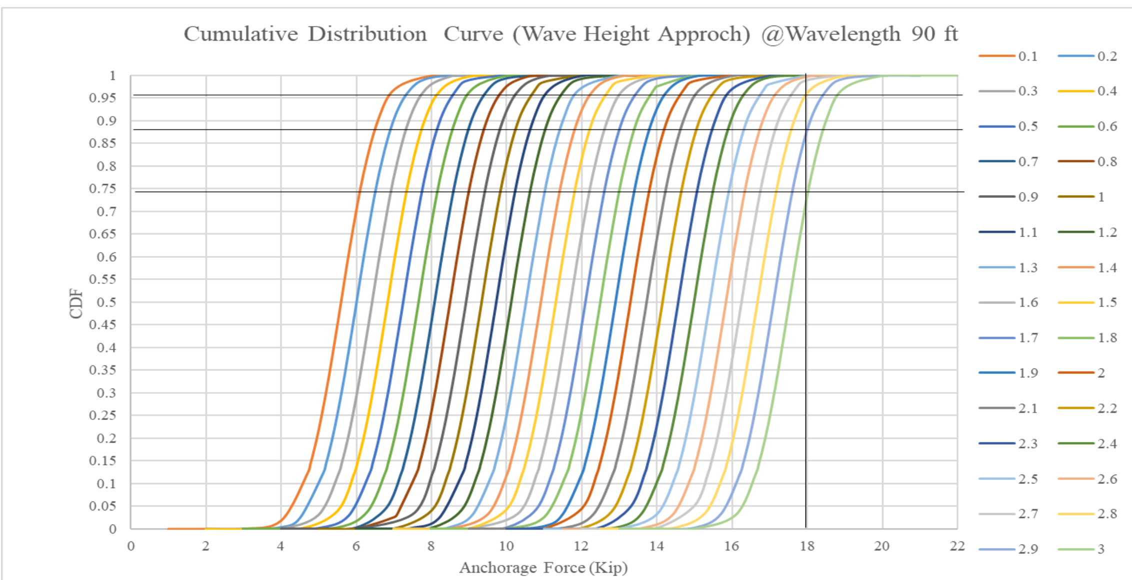

Figure 48:Cumulative Distribution Curve for Variable Wave Heights @ Wavelength = 90'

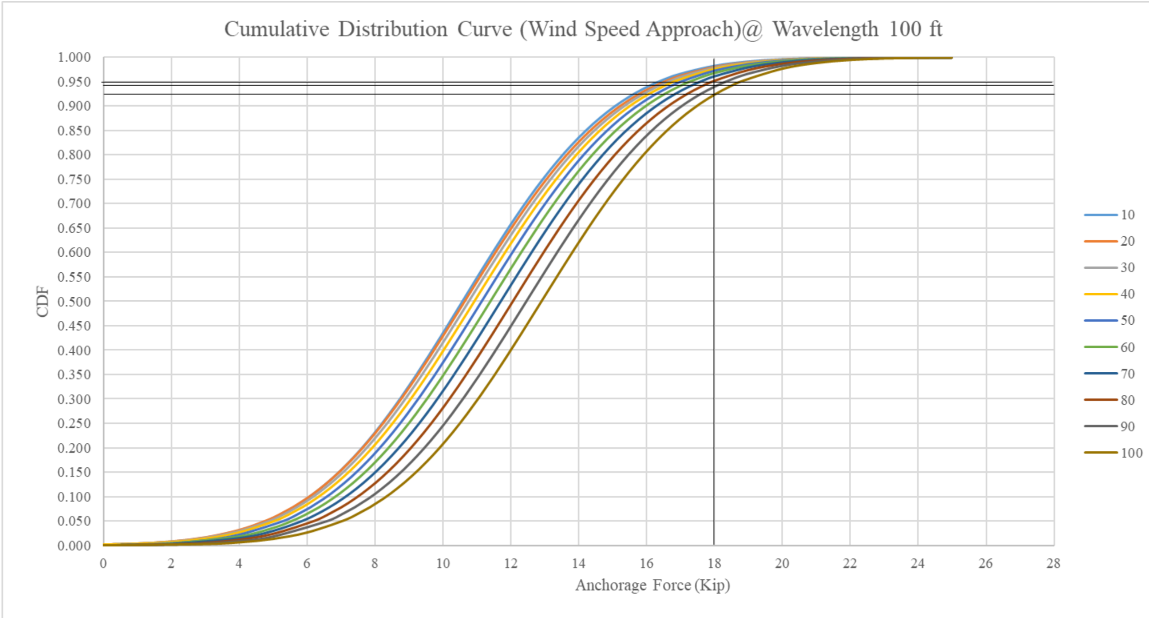

Figure 49: Cumulative Distribution Curve for Variable Wind Speeds @ Wavelength = 100'

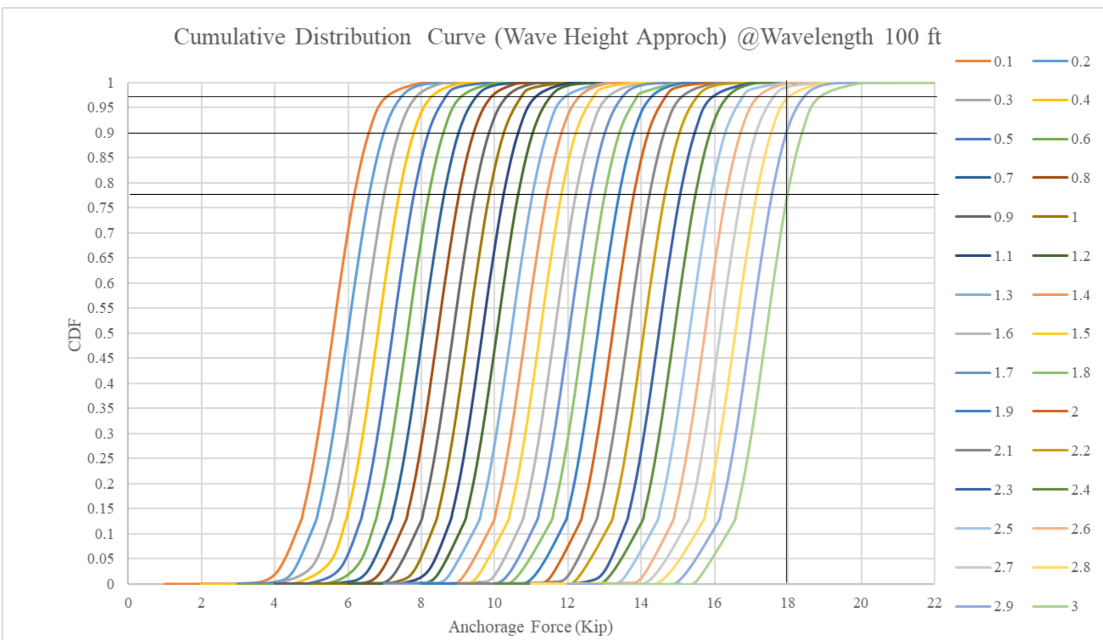

Figure 50: Cumulative Distribution Curve for Variable Wave Heights @ Wavelength = 100

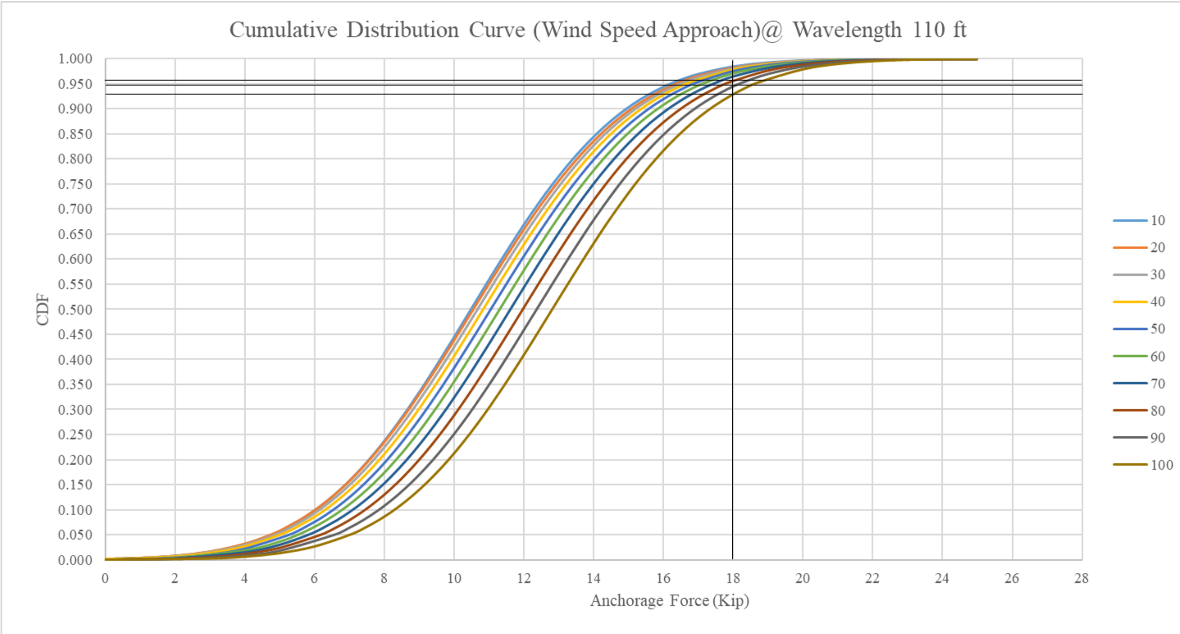

Figure 51: Cumulative Distribution Curve for Variable Wind Speeds @ Wavelength = 110'

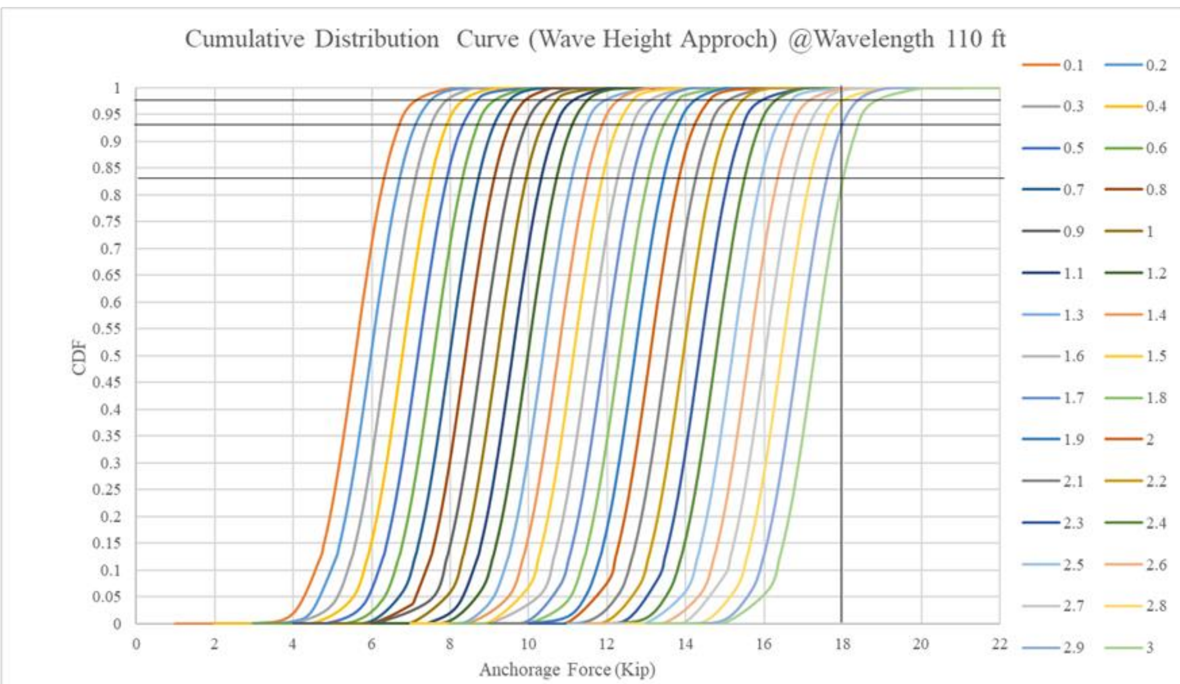

Figure 52: Cumulative Distribution Curve for Variable Wave Height @ Wavelength = 110'

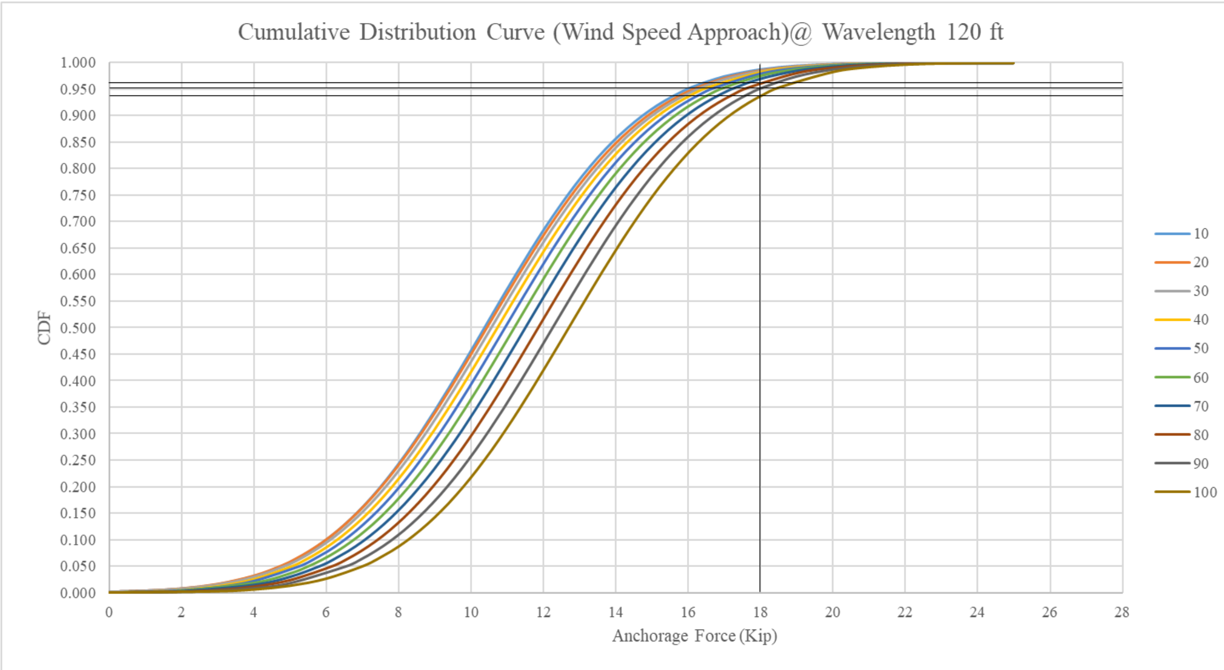

Figure 53: Cumulative Distribution Curve for Variable Wind Speeds @ Wavelength = 120'

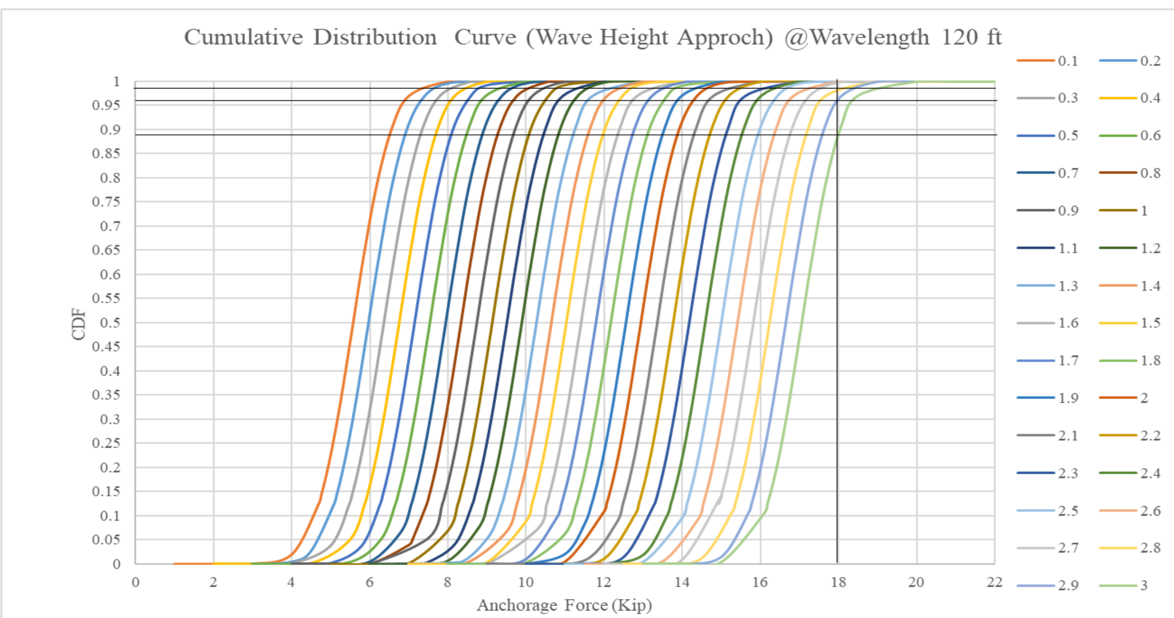

Figure 54: Cumulative Distribution Curve for Variable Wave Heights @ Wavelength = 120'

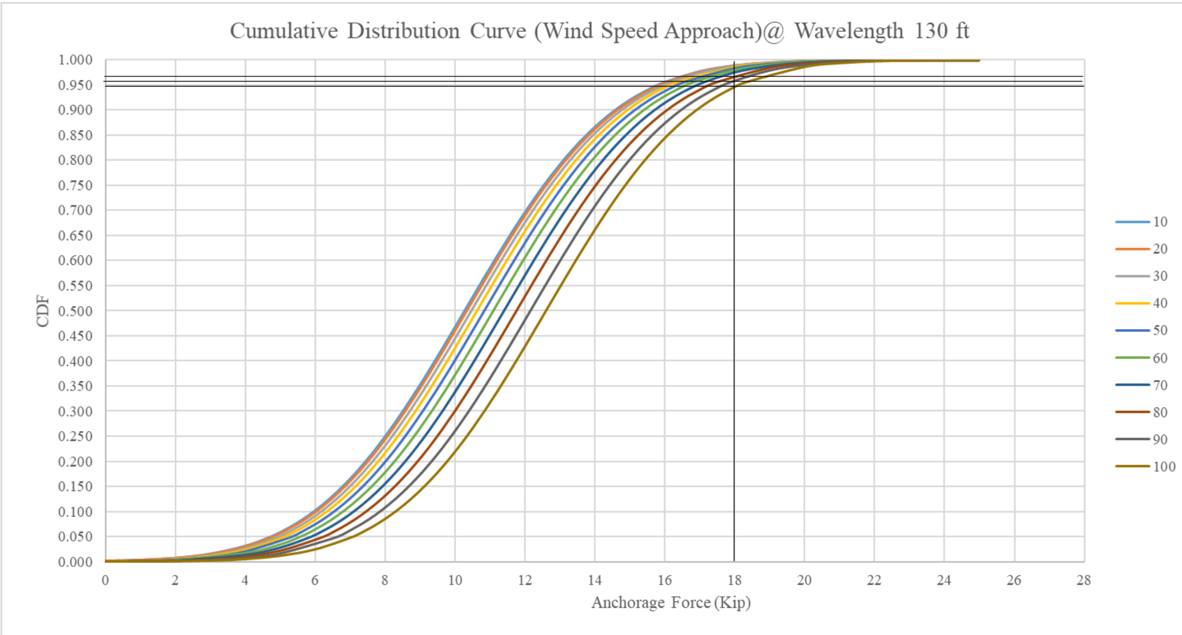

Figure 55: Cumulative Distribution Curve for Variable Wind Speeds @ Wavelength = 130'

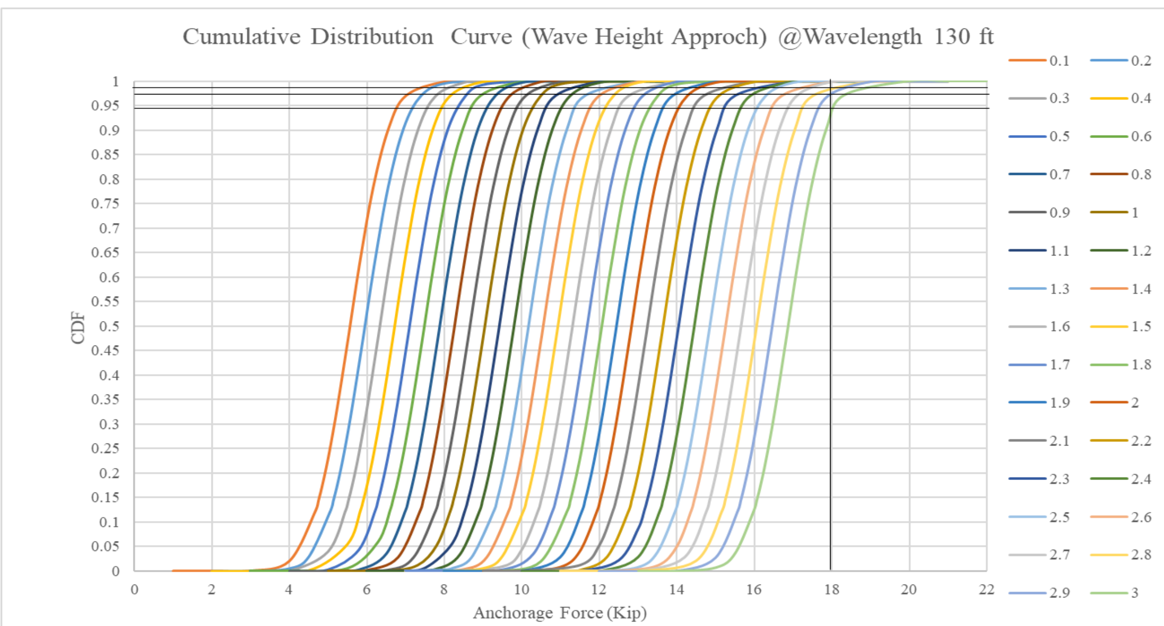

Figure 56: Cumulative Distribution Curve for Variable Wave Heights @ Wavelength = 130'

Summary of Anchorage Forces

This section shows the tables of the summarized maximum anchorage for the parallel wave cases. Chapter 4 and chapter 5 have discussed that the parallel wave cases have the most important impact on the anchorage forces. In addition, probability of exceedance can only be found for the parallel wave case with a deep draft.

Table 28: Summarized Maximum Anchorage Forces at Wavelength = 80', Parallel Wave, Deep Draft

PL										
Deep										
Wind Speed (MPH)	10	20	30	40	50	60	70	80	90	100
Wave Height (ft)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)
0.1	4.714	4.780	4.902	5.065	5.275	5.533	5.840	6.197	6.596	7.043
0.2	5.133	5.199	5.321	5.484	5.694	5.952	6.259	6.616	7.015	7.462
0.3	5.552	5.617	5.740	5.903	6.113	6.371	6.678	7.035	7.434	7.881
0.4	5.970	6.036	6.158	6.322	6.532	6.789	7.097	7.454	7.853	8.299
0.5	6.389	6.455	6.577	6.741	6.951	7.208	7.516	7.873	8.272	8.718
0.6	6.808	6.874	6.996	7.159	7.370	7.627	7.935	8.291	8.691	9.137
0.7	7.227	7.293	7.415	7.578	7.788	8.046	8.353	8.710	9.109	9.556
0.8	7.646	7.712	7.834	7.997	8.208	8.465	8.773	9.129	9.529	9.975
0.9	8.065	8.131	8.253	8.416	8.626	8.884	9.191	9.548	9.947	10.394
1	8.484	8.550	8.672	8.835	9.045	9.303	9.610	9.967	10.366	10.813
1.1	8.880	8.946	9.068	9.231	9.441	9.699	10.006	10.363	10.762	11.209
1.2	9.276	9.342	9.464	9.628	9.838	10.095	10.403	10.759	11.159	11.605
1.3	9.672	9.738	9.860	10.024	10.234	10.492	10.799	11.156	11.555	12.001
1.4	10.068	10.134	10.256	10.420	10.630	10.887	11.195	11.551	11.951	12.397
1.5	10.464	10.530	10.652	10.816	11.026	11.284	11.591	11.948	12.347	12.793
1.6	10.861	10.927	11.049	11.212	11.422	11.680	11.987	12.344	12.744	13.190
1.7	11.257	11.323	11.445	11.609	11.819	12.076	12.384	12.740	13.140	13.586
1.8	11.653	11.719	11.841	12.005	12.215	12.473	12.780	13.137	13.536	13.982
1.9	12.049	12.115	12.237	12.401	12.611	12.869	13.176	13.533	13.932	14.379
2	12.445	12.511	12.633	12.797	13.007	13.265	13.572	13.929	14.328	14.774
2.1	12.872	12.938	13.060	13.224	13.434	13.691	13.999	14.355	14.755	15.201
2.2	13.299	13.365	13.487	13.650	13.860	14.118	14.425	14.782	15.181	15.628
2.3	13.725	13.791	13.913	14.077	14.287	14.545	14.852	15.209	15.608	16.054
2.4	14.152	14.218	14.340	14.504	14.714	14.971	15.279	15.635	16.035	16.481
2.5	14.579	14.645	14.767	14.930	15.140	15.398	15.705	16.062	16.462	16.908
2.6	15.006	15.072	15.194	15.358	15.568	15.825	16.133	16.489	16.889	17.335
2.7	15.433	15.499	15.621	15.784	15.995	16.252	16.559	16.916	17.316	17.762
2.8	15.859	15.925	16.047	16.210	16.421	16.678	16.985	17.342	17.742	18.188
2.9	16.286	16.352	16.474	16.638	16.848	17.106	17.413	17.770	18.169	18.615
3	16.712	16.778	16.900	17.064	17.274	17.532	17.839	18.196	18.595	19.041

Table 29: Summarized Maximum Anchorage Forces at Wavelength = 90', Parallel Wave, Deep Draft

PL										
Deep										
Wind Speed (MPH)	10	20	30	40	50	60	70	80	90	100
Wave Height (ft)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)
0.1	4.710	4.776	4.898	5.061	5.272	5.529	5.837	6.193	6.593	7.039
0.2	5.125	5.191	5.313	5.476	5.686	5.944	6.251	6.608	7.008	7.454
0.3	5.540	5.606	5.728	5.891	6.102	6.359	6.666	7.023	7.423	7.869
0.4	5.955	6.021	6.143	6.306	6.516	6.774	7.081	7.438	7.837	8.284
0.5	6.370	6.436	6.558	6.722	6.932	7.190	7.497	7.854	8.253	8.699
0.6	6.785	6.851	6.973	7.136	7.346	7.604	7.911	8.268	8.667	9.114
0.7	7.200	7.266	7.388	7.551	7.761	8.019	8.326	8.683	9.082	9.529
0.8	7.615	7.681	7.803	7.966	8.176	8.434	8.741	9.098	9.497	9.944
0.9	8.030	8.096	8.218	8.381	8.591	8.849	9.156	9.513	9.912	10.359
1	8.445	8.511	8.633	8.796	9.006	9.264	9.571	9.928	10.327	10.774
1.1	8.842	8.907	9.030	9.193	9.403	9.661	9.968	10.325	10.724	11.171
1.2	9.238	9.304	9.426	9.590	9.800	10.058	10.365	10.722	11.121	11.567
1.3	9.635	9.701	9.823	9.987	10.197	10.454	10.762	11.118	11.518	11.964
1.4	10.032	10.098	10.220	10.384	10.594	10.851	11.159	11.515	11.915	12.361
1.5	10.429	10.495	10.617	10.780	10.991	11.248	11.556	11.912	12.312	12.758
1.6	10.826	10.892	11.014	11.177	11.387	11.645	11.952	12.309	12.708	13.155
1.7	11.223	11.289	11.411	11.574	11.784	12.042	12.349	12.706	13.105	13.552
1.8	11.619	11.685	11.807	11.971	12.181	12.439	12.746	13.103	13.502	13.948
1.9	12.016	12.082	12.204	12.368	12.578	12.836	13.143	13.500	13.899	14.345
2	12.413	12.479	12.601	12.765	12.975	13.232	13.540	13.897	14.296	14.742
2.1	12.836	12.902	13.024	13.188	13.398	13.655	13.963	14.319	14.719	15.165
2.2	13.259	13.325	13.447	13.610	13.821	14.078	14.385	14.742	15.142	15.588
2.3	13.682	13.748	13.870	14.033	14.243	14.501	14.808	15.165	15.564	16.011
2.4	14.105	14.171	14.293	14.456	14.666	14.924	15.231	15.588	15.987	16.434
2.5	14.527	14.593	14.715	14.879	15.089	15.347	15.654	16.011	16.410	16.856
2.6	14.950	15.016	15.138	15.302	15.512	15.769	16.077	16.434	16.833	17.279
2.7	15.373	15.439	15.561	15.725	15.935	16.192	16.500	16.856	17.256	17.702
2.8	15.796	15.862	15.984	16.147	16.358	16.615	16.923	17.279	17.679	18.125
2.9	16.219	16.285	16.407	16.570	16.780	17.038	17.345	17.702	18.101	18.548
3	16.642	16.708	16.830	16.993	17.203	17.461	17.768	18.125	18.524	18.971

Table 30: Summarized Maximum Anchorage Forces at Wavelength = 100', Parallel Wave, Deep Draft

PL										
Deep										
Wind Speed (MPH)	10	20	30	40	50	60	70	80	90	100
Wave Height (ft)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)
0.1	4.704	4.770	4.892	5.055	5.265	5.523	5.830	6.187	6.586	7.033
0.2	5.112	5.178	5.300	5.464	5.674	5.932	6.239	6.596	6.995	7.441
0.3	5.521	5.587	5.709	5.873	6.083	6.340	6.648	7.004	7.404	7.850
0.4	5.930	5.996	6.118	6.282	6.492	6.749	7.057	7.413	7.813	8.259
0.5	6.339	6.405	6.527	6.690	6.900	7.158	7.465	7.822	8.221	8.668
0.6	6.747	6.813	6.935	7.099	7.309	7.567	7.874	8.231	8.630	9.076
0.7	7.156	7.222	7.344	7.508	7.718	7.975	8.283	8.639	9.039	9.485
0.8	7.565	7.631	7.753	7.916	8.126	8.384	8.691	9.048	9.448	9.894
0.9	7.974	8.040	8.162	8.325	8.535	8.793	9.100	9.457	9.856	10.303
1	8.382	8.448	8.570	8.734	8.944	9.202	9.509	9.866	10.265	10.711
1.1	8.778	8.844	8.966	9.129	9.339	9.597	9.904	10.261	10.660	11.107
1.2	9.173	9.239	9.361	9.524	9.735	9.992	10.300	10.656	11.056	11.502
1.3	9.568	9.634	9.756	9.920	10.130	10.387	10.695	11.051	11.451	11.897
1.4	9.963	10.029	10.151	10.315	10.525	10.783	11.090	11.447	11.846	12.292
1.5	10.359	10.425	10.547	10.710	10.920	11.178	11.485	11.842	12.241	12.688
1.6	10.754	10.820	10.942	11.105	11.315	11.573	11.880	12.237	12.637	13.083
1.7	11.149	11.215	11.337	11.501	11.711	11.968	12.276	12.632	13.032	13.478
1.8	11.544	11.610	11.732	11.896	12.106	12.364	12.671	13.028	13.427	13.873
1.9	11.940	12.006	12.128	12.291	12.501	12.759	13.066	13.423	13.822	14.269
2	12.335	12.401	12.523	12.686	12.896	13.154	13.461	13.818	14.217	14.664
2.1	12.754	12.820	12.942	13.105	13.315	13.573	13.880	14.237	14.636	15.083
2.2	13.173	13.239	13.361	13.524	13.734	13.992	14.299	14.656	15.055	15.502
2.3	13.592	13.658	13.780	13.943	14.153	14.411	14.718	15.075	15.474	15.921
2.4	14.010	14.076	14.198	14.362	14.572	14.830	15.137	15.494	15.893	16.340
2.5	14.429	14.495	14.617	14.781	14.991	15.249	15.556	15.913	16.312	16.758
2.6	14.848	14.914	15.036	15.200	15.410	15.668	15.975	16.332	16.731	17.177
2.7	15.267	15.333	15.455	15.619	15.829	16.087	16.394	16.751	17.150	17.596
2.8	15.686	15.752	15.874	16.038	16.248	16.505	16.813	17.169	17.569	18.015
2.9	16.105	16.171	16.293	16.457	16.667	16.924	17.232	17.588	17.988	18.434
3	16.524	16.590	16.712	16.875	17.086	17.343	17.651	18.007	18.407	18.853

Table 31: Summarized Maximum Anchorage Forces at Wavelength = 110', Parallel Wave, Deep Draft

PL

Deep

Wind Speed (MPH)	10	20	30	40	50	60	70	80	90	100
Wave Height (ft)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)
0.1	4.696	4.762	4.884	5.048	5.258	5.515	5.823	6.180	6.579	7.025
0.2	5.098	5.164	5.286	5.449	5.659	5.917	6.224	6.581	6.980	7.427
0.3	5.499	5.565	5.687	5.850	6.061	6.318	6.625	6.982	7.382	7.828
0.4	5.900	5.966	6.088	6.252	6.462	6.719	7.027	7.384	7.783	8.229
0.5	6.302	6.368	6.490	6.653	6.863	7.121	7.428	7.785	8.184	8.631
0.6	6.703	6.769	6.891	7.054	7.265	7.522	7.830	8.186	8.586	9.032
0.7	7.104	7.170	7.292	7.456	7.666	7.923	8.231	8.588	8.987	9.433
0.8	7.506	7.572	7.694	7.857	8.067	8.325	8.632	8.989	9.388	9.835
0.9	7.907	7.973	8.095	8.258	8.469	8.726	9.033	9.390	9.790	10.236
1	8.308	8.374	8.496	8.660	8.870	9.127	9.435	9.792	10.191	10.637
1.1	8.698	8.764	8.886	9.050	9.260	9.517	9.825	10.182	10.581	11.027
1.2	9.088	9.154	9.277	9.440	9.650	9.908	10.215	10.572	10.971	11.418
1.3	9.479	9.544	9.667	9.830	10.040	10.298	10.605	10.962	11.361	11.808
1.4	9.869	9.934	10.057	10.220	10.430	10.688	10.995	11.352	11.751	12.198
1.5	10.259	10.325	10.447	10.610	10.820	11.078	11.385	11.742	12.141	12.588
1.6	10.649	10.715	10.837	11.000	11.210	11.468	11.775	12.132	12.531	12.978
1.7	11.039	11.105	11.227	11.390	11.600	11.858	12.165	12.522	12.921	13.368
1.8	11.429	11.495	11.617	11.780	11.990	12.248	12.555	12.912	13.311	13.758
1.9	11.819	11.885	12.007	12.170	12.381	12.638	12.945	13.302	13.702	14.148
2	12.209	12.275	12.397	12.560	12.771	13.028	13.335	13.692	14.092	14.538
2.1	12.627	12.693	12.815	12.979	13.189	13.446	13.754	14.111	14.510	14.956
2.2	13.046	13.112	13.234	13.397	13.607	13.865	14.172	14.529	14.928	15.375
2.3	13.464	13.530	13.652	13.815	14.025	14.283	14.590	14.947	15.347	15.793
2.4	13.882	13.948	14.070	14.234	14.444	14.701	15.009	15.365	15.765	16.211
2.5	14.300	14.366	14.488	14.652	14.862	15.120	15.427	15.784	16.183	16.629
2.6	14.719	14.785	14.907	15.070	15.280	15.538	15.845	16.202	16.601	17.048
2.7	15.137	15.203	15.325	15.489	15.699	15.956	16.264	16.620	17.020	17.466
2.8	15.555	15.621	15.743	15.907	16.117	16.374	16.682	17.039	17.438	17.884
2.9	15.974	16.039	16.162	16.325	16.535	16.793	17.100	17.457	17.856	18.303
3	16.392	16.458	16.580	16.743	16.954	17.211	17.518	17.875	18.275	18.721

Table 32: Summarized Maximum Anchorage Forces at Wavelength = 120', Parallel Wave, Deep Draft

PL										
Deep										
Wind Speed (MPH)	10	20	30	40	50	60	70	80	90	100
Wave Height (ft)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)
0.1	4.690	4.756	4.878	5.041	5.251	5.509	5.816	6.173	6.572	7.019
0.2	5.085	5.151	5.273	5.436	5.646	5.904	6.211	6.568	6.967	7.414
0.3	5.480	5.546	5.668	5.831	6.041	6.299	6.606	6.963	7.362	7.809
0.4	5.875	5.941	6.063	6.226	6.436	6.694	7.001	7.358	7.757	8.204
0.5	6.270	6.335	6.458	6.621	6.831	7.089	7.396	7.753	8.152	8.599
0.6	6.664	6.730	6.852	7.016	7.226	7.484	7.791	8.148	8.547	8.993
0.7	7.059	7.125	7.248	7.411	7.621	7.879	8.186	8.543	8.942	9.388
0.8	7.454	7.520	7.642	7.806	8.016	8.274	8.581	8.938	9.337	9.783
0.9	7.849	7.915	8.037	8.201	8.411	8.668	8.976	9.333	9.732	10.178
1	8.244	8.310	8.432	8.596	8.806	9.063	9.371	9.727	10.127	10.573
1.1	8.625	8.691	8.813	8.977	9.187	9.445	9.752	10.109	10.508	10.954
1.2	9.007	9.073	9.195	9.358	9.568	9.826	10.133	10.490	10.889	11.336
1.3	9.388	9.454	9.576	9.740	9.950	10.207	10.515	10.871	11.271	11.717
1.4	9.770	9.835	9.958	10.121	10.331	10.589	10.896	11.253	11.652	12.099
1.5	10.151	10.217	10.339	10.502	10.712	10.970	11.277	11.634	12.034	12.480
1.6	10.532	10.598	10.720	10.884	11.094	11.351	11.659	12.015	12.415	12.861
1.7	10.914	10.979	11.102	11.265	11.475	11.733	12.040	12.397	12.796	13.243
1.8	11.295	11.361	11.483	11.646	11.857	12.114	12.421	12.778	13.178	13.624
1.9	11.676	11.742	11.864	12.028	12.238	12.495	12.803	13.159	13.559	14.005
2	12.058	12.124	12.246	12.409	12.619	12.877	13.184	13.541	13.940	14.387
2.1	12.469	12.535	12.657	12.821	13.031	13.289	13.596	13.953	14.352	14.799
2.2	12.881	12.947	13.069	13.233	13.443	13.701	14.008	14.365	14.764	15.210
2.3	13.293	13.359	13.481	13.645	13.855	14.112	14.420	14.777	15.176	15.622
2.4	13.705	13.771	13.893	14.057	14.267	14.524	14.832	15.188	15.588	16.034
2.5	14.117	14.183	14.305	14.469	14.679	14.936	15.244	15.600	16.000	16.446
2.6	14.529	14.595	14.717	14.880	15.091	15.348	15.656	16.012	16.412	16.858
2.7	14.941	15.007	15.129	15.292	15.502	15.760	16.067	16.424	16.823	17.270
2.8	15.353	15.419	15.541	15.704	15.914	16.172	16.479	16.836	17.235	17.682
2.9	15.764	15.830	15.952	16.116	16.326	16.584	16.891	17.248	17.647	18.093
3	16.176	16.242	16.364	16.528	16.738	16.996	17.303	17.660	18.059	18.505

Table 33: Summarized Maximum Anchorage Forces at Wavelength = 130', Parallel Wave, Deep Draft

PL										
Deep										
Wind Speed (MPH)	10	20	30	40	50	60	70	80	90	100
Wave Height (ft)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)	Force (Kip)
0.1	4.681	4.747	4.869	5.032	5.242	5.500	5.807	6.164	6.564	7.010
0.2	5.067	5.133	5.255	5.418	5.629	5.886	6.193	6.550	6.950	7.396
0.3	5.453	5.519	5.641	5.804	6.015	6.272	6.580	6.936	7.336	7.782
0.4	5.839	5.905	6.027	6.190	6.401	6.658	6.966	7.322	7.722	8.168
0.5	6.225	6.291	6.413	6.576	6.787	7.044	7.351	7.708	8.108	8.554
0.6	6.611	6.677	6.799	6.962	7.173	7.430	7.737	8.094	8.494	8.940
0.7	6.997	7.063	7.185	7.348	7.559	7.816	8.124	8.480	8.880	9.326
0.8	7.383	7.449	7.571	7.734	7.945	8.202	8.510	8.866	9.266	9.712
0.9	7.769	7.835	7.957	8.120	8.331	8.588	8.895	9.252	9.652	10.098
1	8.155	8.221	8.343	8.506	8.716	8.974	9.281	9.638	10.037	10.484
1.1	8.534	8.600	8.722	8.886	9.096	9.353	9.661	10.017	10.417	10.863
1.2	8.913	8.979	9.102	9.265	9.475	9.733	10.040	10.397	10.796	11.243
1.3	9.293	9.359	9.481	9.644	9.854	10.112	10.419	10.776	11.175	11.622
1.4	9.672	9.738	9.860	10.023	10.234	10.491	10.799	11.155	11.555	12.001
1.5	10.051	10.117	10.239	10.403	10.613	10.870	11.178	11.535	11.934	12.380
1.6	10.431	10.497	10.619	10.782	10.992	11.250	11.557	11.914	12.313	12.760
1.7	10.810	10.876	10.998	11.161	11.372	11.629	11.936	12.293	12.693	13.139
1.8	11.189	11.255	11.377	11.541	11.751	12.008	12.316	12.672	13.072	13.518
1.9	11.568	11.634	11.756	11.920	12.130	12.388	12.695	13.052	13.451	13.897
2	11.948	12.014	12.136	12.299	12.509	12.767	13.074	13.431	13.830	14.277
2.1	12.352	12.418	12.540	12.703	12.913	13.171	13.478	13.835	14.234	14.681
2.2	12.756	12.822	12.944	13.108	13.318	13.575	13.883	14.239	14.639	15.085
2.3	13.160	13.226	13.348	13.511	13.722	13.979	14.287	14.643	15.043	15.489
2.4	13.564	13.630	13.752	13.916	14.126	14.383	14.691	15.047	15.447	15.893
2.5	13.968	14.034	14.156	14.320	14.530	14.787	15.095	15.451	15.851	16.297
2.6	14.372	14.438	14.560	14.724	14.934	15.192	15.499	15.856	16.255	16.701
2.7	14.776	14.842	14.964	15.128	15.338	15.596	15.903	16.260	16.659	17.105
2.8	15.181	15.246	15.369	15.532	15.742	16.000	16.307	16.664	17.063	17.510
2.9	15.585	15.651	15.773	15.936	16.146	16.404	16.711	17.068	17.467	17.914
3	15.989	16.055	16.177	16.340	16.550	16.808	17.115	17.472	17.871	18.318

Sample Result of Strain Computation (Wavelength = 75.9', Parallel Wave, Deep Draft, Section 0, and Top of the Member)

Wind Speed (MPH)			10	20	30	40	50	60	70	80	90	100
Member	**Section**	**Wave Hight (ft)**	**Strain top**	**Strain top**	**Strain top**	**Strain top**	**Strain top**	**Strain top**	**Strain top**	**Strain top**	**Strain top**	**Strain top**
1	0	0.1	5.157E-05	5.153E-05	5.15E-05	5.141E-05	5.131E-05	5.119E-05	5.105E-05	5.089E-05	5.071E-05	5.05E-05
1	0	0.2	5.116E-05	5.112E-05	5.11E-05	5.099E-05	5.09E-05	5.078E-05	5.064E-05	5.048E-05	5.029E-05	5.009E-05
1	0	0.3	5.074E-05	5.071E-05	5.07E-05	5.058E-05	5.048E-05	5.036E-05	5.022E-05	5.006E-05	4.988E-05	4.968E-05
1	0	0.4	5.033E-05	5.029E-05	5.02E-05	5.017E-05	5.007E-05	4.995E-05	4.981E-05	4.965E-05	4.947E-05	4.926E-05
1	0	0.5	4.992E-05	4.988E-05	4.98E-05	4.975E-05	4.966E-05	4.954E-05	4.94E-05	4.924E-05	4.905E-05	4.885E-05
1	0	0.6	4.95E-05	4.947E-05	4.94E-05	4.934E-05	4.924E-05	4.912E-05	4.898E-05	4.882E-05	4.864E-05	4.844E-05
1	0	0.7	4.909E-05	4.905E-05	4.9E-05	4.893E-05	4.883E-05	4.871E-05	4.857E-05	4.841E-05	4.823E-05	4.802E-05
1	0	0.8	4.868E-05	4.864E-05	4.86E-05	4.851E-05	4.842E-05	4.83E-05	4.816E-05	4.8E-05	4.781E-05	4.761E-05
1	0	0.9	4.826E-05	4.823E-05	4.82E-05	4.81E-05	4.8E-05	4.788E-05	4.774E-05	4.759E-05	4.74E-05	4.72E-05
1	0	1	4.785E-05	4.782E-05	4.78E-05	4.769E-05	4.759E-05	4.747E-05	4.733E-05	4.717E-05	4.699E-05	4.678E-05
1	0	1.1	4.746E-05	4.742E-05	4.74E-05	4.73E-05	4.72E-05	4.708E-05	4.694E-05	4.678E-05	4.66E-05	4.639E-05
1	0	1.2	4.707E-05	4.703E-05	4.7E-05	4.69E-05	4.68E-05	4.668E-05	4.655E-05	4.639E-05	4.62E-05	4.6E-05
1	0	1.3	4.667E-05	4.664E-05	4.66E-05	4.651E-05	4.641E-05	4.629E-05	4.615E-05	4.599E-05	4.581E-05	4.56E-05
1	0	1.4	4.628E-05	4.624E-05	4.62E-05	4.612E-05	4.602E-05	4.59E-05	4.576E-05	4.56E-05	4.542E-05	4.521E-05
1	0	1.5	4.589E-05	4.585E-05	4.58E-05	4.572E-05	4.563E-05	4.551E-05	4.537E-05	4.521E-05	4.502E-05	4.482E-05
1	0	1.6	4.549E-05	4.546E-05	4.54E-05	4.533E-05	4.523E-05	4.511E-05	4.497E-05	4.482E-05	4.463E-05	4.443E-05
1	0	1.7	4.51E-05	4.507E-05	4.5E-05	4.494E-05	4.484E-05	4.472E-05	4.458E-05	4.442E-05	4.424E-05	4.403E-05
1	0	1.8	4.471E-05	4.467E-05	4.46E-05	4.455E-05	4.445E-05	4.433E-05	4.419E-05	4.403E-05	4.385E-05	4.364E-05
1	0	1.9	4.432E-05	4.428E-05	4.42E-05	4.415E-05	4.406E-05	4.394E-05	4.38E-05	4.364E-05	4.345E-05	4.325E-05
1	0	2	4.392E-05	4.389E-05	4.38E-05	4.376E-05	4.366E-05	4.354E-05	4.34E-05	4.324E-05	4.306E-05	4.286E-05
1	0	2.1	4.35E-05	4.347E-05	4.34E-05	4.334E-05	4.324E-05	4.312E-05	4.298E-05	4.282E-05	4.264E-05	4.243E-05
1	0	2.2	4.308E-05	4.305E-05	4.3E-05	4.292E-05	4.282E-05	4.27E-05	4.256E-05	4.24E-05	4.222E-05	4.201E-05
1	0	2.3	4.266E-05	4.262E-05	4.26E-05	4.25E-05	4.24E-05	4.228E-05	4.214E-05	4.198E-05	4.18E-05	4.159E-05
1	0	2.4	4.224E-05	4.22E-05	4.22E-05	4.208E-05	4.198E-05	4.186E-05	4.172E-05	4.156E-05	4.138E-05	4.117E-05
1	0	2.5	4.182E-05	4.178E-05	4.17E-05	4.165E-05	4.156E-05	4.144E-05	4.13E-05	4.114E-05	4.095E-05	4.075E-05
1	0	2.6	4.14E-05	4.136E-05	4.13E-05	4.123E-05	4.113E-05	4.102E-05	4.088E-05	4.072E-05	4.053E-05	4.033E-05
1	0	2.7	4.097E-05	4.094E-05	4.09E-05	4.081E-05	4.071E-05	4.059E-05	4.046E-05	4.03E-05	4.011E-05	3.991E-05
1	0	2.8	4.055E-05	4.052E-05	4.05E-05	4.039E-05	4.029E-05	4.017E-05	4.003E-05	3.988E-05	3.969E-05	3.949E-05
1	0	2.9	4.013E-05	4.01E-05	4E-05	3.997E-05	3.987E-05	3.975E-05	3.961E-05	3.945E-05	3.927E-05	3.906E-05
1	0	3	3.971E-05	3.968E-05	3.96E-05	3.955E-05	3.945E-05	3.933E-05	3.919E-05	3.903E-05	3.885E-05	3.864E-05
2	0	0.1	1.614E-05	1.582E-05	1.52E-05	1.44E-05	1.336E-05	1.208E-05	1.055E-05	8.766E-06	6.785E-06	4.571E-06
2	0	0.2	1.472E-05	1.441E-05	1.38E-05	1.298E-05	1.194E-05	1.067E-05	9.136E-06	7.351E-06	5.37E-06	3.156E-06
2	0	0.3	1.33E-05	1.299E-05	1.24E-05	1.156E-05	1.053E-05	9.252E-06	7.72E-06	5.936E-06	3.955E-06	1.74E-06
2	0	0.4	1.189E-05	1.158E-05	1.1E-05	1.015E-05	9.111E-06	7.836E-06	6.304E-06	4.52E-06	2.539E-06	3.245E-07
2	0	0.5	1.047E-05	1.016E-05	9.54E-06	8.733E-06	7.696E-06	6.421E-06	4.889E-06	3.104E-06	1.123E-06	1.091E-06
2	0	0.6	9.058E-06	8.747E-06	8.13E-06	7.318E-06	6.28E-06	5.006E-06	3.474E-06	1.689E-06	2.918E-07	2.506E-06
2	0	0.7	7.643E-06	7.332E-06	6.71E-06	5.903E-06	4.865E-06	3.59E-06	2.058E-06	2.737E-07	1.707E-06	3.922E-06
2	0	0.8	6.227E-06	5.916E-06	5.29E-06	4.487E-06	3.449E-06	2.174E-06	6.424E-07	1.142E-06	3.123E-06	5.338E-06
2	0	0.9	4.812E-06	4.501E-06	3.88E-06	3.072E-06	2.034E-06	7.596E-07	7.724E-07	2.557E-06	4.538E-06	6.752E-06
2	0	1	3.397E-06	3.085E-06	2.46E-06	1.657E-06	6.188E-07	6.56E-07	2.188E-06	3.972E-06	5.954E-06	8.168E-06
2	0	1.1	2.049E-06	1.737E-06	1.12E-06	3.085E-07	7.291E-07	2.004E-06	3.536E-06	5.321E-06	7.302E-06	9.516E-06
2	0	1.2	7.018E-07	3.904E-07	2.31E-07	1.038E-06	2.076E-06	3.351E-06	4.883E-06	6.667E-06	8.648E-06	1.086E-05
2	0	1.3	6.459E-07	9.574E-07	1.58E-06	2.386E-06	3.424E-06	4.699E-06	6.23E-06	8.015E-06	9.996E-06	1.221E-05
2	0	1.4	1.994E-06	2.305E-06	2.93E-06	3.734E-06	4.772E-06	6.047E-06	7.579E-06	9.363E-06	1.134E-05	1.356E-05
2	0	1.5	3.342E-06	3.653E-06	4.27E-06	5.082E-06	6.12E-06	7.394E-06	8.926E-06	1.071E-05	1.269E-05	1.491E-05
2	0	1.6	4.688E-06	5E-06	5.62E-06	6.429E-06	7.466E-06	8.741E-06	1.027E-05	1.206E-05	1.404E-05	1.625E-05
2	0	1.7	6.037E-06	6.348E-06	6.97E-06	7.777E-06	8.814E-06	1.009E-05	1.162E-05	1.341E-05	1.539E-05	1.76E-05
2	0	1.8	7.384E-06	7.696E-06	8.32E-06	9.124E-06	1.016E-05	1.144E-05	1.297E-05	1.475E-05	1.673E-05	1.895E-05
2	0	1.9	8.731E-06	9.042E-06	9.66E-06	1.047E-05	1.151E-05	1.278E-05	1.432E-05	1.61E-05	1.808E-05	2.03E-05
2	0	2	1.008E-05	1.039E-05	1.1E-05	1.182E-05	1.286E-05	1.413E-05	1.566E-05	1.745E-05	1.943E-05	2.164E-05
2	0	2.1	1.152E-05	1.183E-05	1.25E-05	1.326E-05	1.43E-05	1.557E-05	1.711E-05	1.889E-05	2.087E-05	2.309E-05
2	0	2.2	1.296E-05	1.328E-05	1.39E-05	1.47E-05	1.574E-05	1.702E-05	1.855E-05	2.033E-05	2.231E-05	2.453E-05
2	0	2.3	1.44E-05	1.472E-05	1.53E-05	1.614E-05	1.718E-05	1.846E-05	1.999E-05	2.177E-05	2.376E-05	2.597E-05
2	0	2.4	1.585E-05	1.616E-05	1.68E-05	1.759E-05	1.863E-05	1.99E-05	2.143E-05	2.322E-05	2.52E-05	2.741E-05
2	0	2.5	1.729E-05	1.76E-05	1.82E-05	1.903E-05	2.007E-05	2.134E-05	2.287E-05	2.466E-05	2.664E-05	2.885E-05
2	0	2.6	1.873E-05	1.904E-05	1.97E-05	2.047E-05	2.151E-05	2.278E-05	2.432E-05	2.61E-05	2.808E-05	3.029E-05
2	0	2.7	2.017E-05	2.048E-05	2.11E-05	2.191E-05	2.295E-05	2.423E-05	2.576E-05	2.754E-05	2.952E-05	3.174E-05
2	0	2.8	2.162E-05	2.193E-05	2.25E-05	2.336E-05	2.439E-05	2.567E-05	2.72E-05	2.898E-05	3.097E-05	3.318E-05
2	0	2.9	2.306E-05	2.337E-05	2.4E-05	2.48E-05	2.584E-05	2.711E-05	2.864E-05	3.043E-05	3.241E-05	3.462E-05
2	0	3	2.45E-05	2.481E-05	2.54E-05	2.624E-05	2.728E-05	2.855E-05	3.008E-05	3.187E-05	3.385E-05	3.606E-05

3	0	0.1	4.985E-05	4.979E-05	4.97E-05	4.953E-05	4.934E-05	4.91E-05	4.882E-05	4.849E-05	4.812E-05	4.771E-05
3	0	0.2	4.949E-05	4.943E-05	4.93E-05	4.916E-05	4.897E-05	4.874E-05	4.845E-05	4.812E-05	4.776E-05	4.735E-05
3	0	0.3	4.912E-05	4.906E-05	4.89E-05	4.88E-05	4.861E-05	4.837E-05	4.809E-05	4.776E-05	4.739E-05	4.698E-05
3	0	0.4	4.876E-05	4.87E-05	4.86E-05	4.844E-05	4.824E-05	4.801E-05	4.772E-05	4.74E-05	4.703E-05	4.662E-05
3	0	0.5	4.839E-05	4.834E-05	4.82E-05	4.807E-05	4.788E-05	4.764E-05	4.736E-05	4.703E-05	4.667E-05	4.626E-05
3	0	0.6	4.803E-05	4.797E-05	4.79E-05	4.771E-05	4.752E-05	4.728E-05	4.7E-05	4.667E-05	4.63E-05	4.589E-05
3	0	0.7	4.767E-05	4.761E-05	4.75E-05	4.734E-05	4.715E-05	4.692E-05	4.663E-05	4.631E-05	4.594E-05	4.553E-05
3	0	0.8	4.73E-05	4.724E-05	4.71E-05	4.698E-05	4.679E-05	4.655E-05	4.627E-05	4.594E-05	4.557E-05	4.516E-05
3	0	0.9	4.694E-05	4.688E-05	4.68E-05	4.662E-05	4.642E-05	4.619E-05	4.591E-05	4.558E-05	4.521E-05	4.48E-05
3	0	1	4.658E-05	4.652E-05	4.64E-05	4.625E-05	4.606E-05	4.582E-05	4.554E-05	4.521E-05	4.485E-05	4.444E-05
3	0	1.1	4.623E-05	4.617E-05	4.61E-05	4.591E-05	4.571E-05	4.548E-05	4.519E-05	4.487E-05	4.45E-05	4.409E-05
3	0	1.2	4.588E-05	4.582E-05	4.57E-05	4.556E-05	4.537E-05	4.513E-05	4.485E-05	4.452E-05	4.415E-05	4.374E-05
3	0	1.3	4.553E-05	4.548E-05	4.54E-05	4.521E-05	4.502E-05	4.478E-05	4.45E-05	4.417E-05	4.381E-05	4.34E-05
3	0	1.4	4.519E-05	4.513E-05	4.5E-05	4.487E-05	4.467E-05	4.444E-05	4.415E-05	4.383E-05	4.346E-05	4.305E-05
3	0	1.5	4.484E-05	4.478E-05	4.47E-05	4.452E-05	4.433E-05	4.409E-05	4.381E-05	4.348E-05	4.311E-05	4.27E-05
3	0	1.6	4.449E-05	4.443E-05	4.43E-05	4.417E-05	4.398E-05	4.374E-05	4.346E-05	4.313E-05	4.277E-05	4.236E-05
3	0	1.7	4.415E-05	4.409E-05	4.4E-05	4.382E-05	4.363E-05	4.34E-05	4.311E-05	4.278E-05	4.242E-05	4.201E-05
3	0	1.8	4.38E-05	4.374E-05	4.36E-05	4.348E-05	4.328E-05	4.305E-05	4.277E-05	4.244E-05	4.207E-05	4.166E-05
3	0	1.9	4.345E-05	4.339E-05	4.33E-05	4.313E-05	4.294E-05	4.27E-05	4.242E-05	4.209E-05	4.172E-05	4.131E-05
3	0	2	4.311E-05	4.305E-05	4.29E-05	4.278E-05	4.259E-05	4.235E-05	4.207E-05	4.174E-05	4.138E-05	4.097E-05
3	0	2.1	4.274E-05	4.268E-05	4.26E-05	4.241E-05	4.222E-05	4.198E-05	4.17E-05	4.137E-05	4.101E-05	4.06E-05
3	0	2.2	4.236E-05	4.231E-05	4.22E-05	4.204E-05	4.185E-05	4.161E-05	4.133E-05	4.1E-05	4.064E-05	4.023E-05
3	0	2.3	4.199E-05	4.193E-05	4.18E-05	4.167E-05	4.148E-05	4.124E-05	4.096E-05	4.063E-05	4.027E-05	3.986E-05
3	0	2.4	4.162E-05	4.156E-05	4.15E-05	4.13E-05	4.111E-05	4.087E-05	4.059E-05	4.026E-05	3.99E-05	3.949E-05
3	0	2.5	4.125E-05	4.119E-05	4.11E-05	4.093E-05	4.074E-05	4.05E-05	4.022E-05	3.989E-05	3.952E-05	3.912E-05
3	0	2.6	4.088E-05	4.082E-05	4.07E-05	4.056E-05	4.037E-05	4.013E-05	3.985E-05	3.952E-05	3.915E-05	3.874E-05
3	0	2.7	4.051E-05	4.045E-05	4.03E-05	4.019E-05	4E-05	3.976E-05	3.948E-05	3.915E-05	3.878E-05	3.837E-05
3	0	2.8	4.014E-05	4.008E-05	4E-05	3.982E-05	3.963E-05	3.939E-05	3.911E-05	3.878E-05	3.841E-05	3.8E-05
3	0	2.9	3.977E-05	3.971E-05	3.96E-05	3.945E-05	3.926E-05	3.902E-05	3.874E-05	3.841E-05	3.804E-05	3.763E-05
3	0	3	3.94E-05	3.934E-05	3.92E-05	3.908E-05	3.889E-05	3.865E-05	3.837E-05	3.804E-05	3.767E-05	3.726E-05
4	0	0.1	2.404E-05	2.484E-05	2.63E-05	2.823E-05	3.073E-05	3.38E-05	3.746E-05	4.169E-05	4.645E-05	5.176E-05
4	0	0.2	2.946E-05	3.026E-05	3.17E-05	3.365E-05	3.616E-05	3.922E-05	4.288E-05	4.712E-05	5.187E-05	5.718E-05
4	0	0.3	3.489E-05	3.568E-05	3.71E-05	3.907E-05	4.158E-05	4.464E-05	4.83E-05	5.254E-05	5.729E-05	6.26E-05
4	0	0.4	4.031E-05	4.11E-05	4.25E-05	4.449E-05	4.7E-05	5.007E-05	5.372E-05	5.796E-05	6.271E-05	6.803E-05
4	0	0.5	4.573E-05	4.652E-05	4.8E-05	4.991E-05	5.242E-05	5.549E-05	5.914E-05	6.338E-05	6.813E-05	7.345E-05
4	0	0.6	5.115E-05	5.194E-05	5.34E-05	5.534E-05	5.784E-05	6.091E-05	6.456E-05	6.88E-05	7.355E-05	7.887E-05
4	0	0.7	5.657E-05	5.736E-05	5.88E-05	6.076E-05	6.326E-05	6.633E-05	6.998E-05	7.422E-05	7.897E-05	8.429E-05
4	0	0.8	6.199E-05	6.279E-05	6.42E-05	6.618E-05	6.868E-05	7.175E-05	7.541E-05	7.964E-05	8.44E-05	8.971E-05
4	0	0.9	6.741E-05	6.821E-05	6.96E-05	7.16E-05	7.41E-05	7.717E-05	8.082E-05	8.506E-05	8.982E-05	9.513E-05
4	0	1	7.283E-05	7.363E-05	7.51E-05	7.702E-05	7.952E-05	8.259E-05	8.625E-05	9.048E-05	9.524E-05	0.0001006
4	0	1.1	7.799E-05	7.879E-05	8.02E-05	8.218E-05	8.468E-05	8.775E-05	9.141E-05	9.564E-05	0.0001004	0.0001057
4	0	1.2	8.315E-05	8.394E-05	8.54E-05	8.734E-05	8.984E-05	9.291E-05	9.656E-05	0.0001008	0.0001056	0.0001109
4	0	1.3	8.831E-05	8.91E-05	9.05E-05	9.249E-05	9.5E-05	9.807E-05	0.0001017	0.000106	0.0001107	0.000116
4	0	1.4	9.347E-05	9.426E-05	9.57E-05	9.765E-05	0.0001002	0.0001032	0.0001069	0.0001111	0.0001159	0.0001212
4	0	1.5	9.863E-05	9.942E-05	0.000101	0.0001028	0.0001053	0.0001084	0.000112	0.0001163	0.000121	0.0001263
4	0	1.6	0.0001038	0.0001046	0.000106	0.000108	0.0001105	0.0001135	0.0001172	0.0001214	0.0001262	0.0001315
4	0	1.7	0.0001089	0.0001097	0.000111	0.0001131	0.0001156	0.0001187	0.0001224	0.0001266	0.0001313	0.0001367
4	0	1.8	0.0001141	0.0001149	0.000116	0.0001183	0.0001208	0.0001239	0.0001275	0.0001318	0.0001365	0.0001418
4	0	1.9	0.0001193	0.0001201	0.000121	0.0001234	0.0001259	0.000129	0.0001327	0.0001369	0.0001417	0.000147
4	0	2	0.0001244	0.0001252	0.000127	0.0001286	0.0001311	0.0001342	0.0001378	0.0001421	0.0001468	0.0001521
4	0	2.1	0.0001299	0.0001307	0.000132	0.0001341	0.0001366	0.0001397	0.0001434	0.0001476	0.0001523	0.0001577
4	0	2.2	0.0001355	0.0001363	0.000138	0.0001397	0.0001422	0.0001452	0.0001489	0.0001531	0.0001579	0.0001632
4	0	2.3	0.000141	0.0001418	0.000143	0.0001452	0.0001477	0.0001507	0.0001544	0.0001586	0.0001634	0.0001687
4	0	2.4	0.0001465	0.0001473	0.000149	0.0001507	0.0001532	0.0001563	0.0001599	0.0001642	0.0001689	0.0001742
4	0	2.5	0.000152	0.0001528	0.000154	0.0001562	0.0001587	0.0001618	0.0001654	0.0001697	0.0001744	0.0001798
4	0	2.6	0.0001576	0.0001584	0.00016	0.0001617	0.0001642	0.0001673	0.000171	0.0001752	0.00018	0.0001853
4	0	2.7	0.0001631	0.0001639	0.000165	0.0001673	0.0001698	0.0001728	0.0001765	0.0001807	0.0001855	0.0001908
4	0	2.8	0.0001686	0.0001694	0.000171	0.0001728	0.0001753	0.0001784	0.000182	0.0001863	0.000191	0.0001963
4	0	2.9	0.0001741	0.0001749	0.000176	0.0001783	0.0001808	0.0001839	0.0001875	0.0001918	0.0001965	0.0002018
4	0	3	0.0001797	0.0001804	0.000182	0.0001838	0.0001863	0.0001894	0.0001931	0.0001973	0.0002021	0.0002074

5	0	0.1	0.0001013	0.0001023	0.000104	0.0001067	0.0001099	0.0001139	0.0001186	0.0001241	0.0001303	0.0001371
5	0	0.2	0.0001082	0.0001092	0.000111	0.0001136	0.0001168	0.0001208	0.0001255	0.000131	0.0001371	0.000144
5	0	0.3	0.000115	0.000116	0.000118	0.0001204	0.0001236	0.0001276	0.0001323	0.0001378	0.0001439	0.0001508
5	0	0.4	0.0001218	0.0001229	0.000125	0.0001273	0.0001305	0.0001345	0.0001392	0.0001447	0.0001508	0.0001577
5	0	0.5	0.0001287	0.0001297	0.000132	0.0001341	0.0001373	0.0001413	0.000146	0.0001515	0.0001576	0.0001645
5	0	0.6	0.0001355	0.0001366	0.000138	0.0001409	0.0001442	0.0001481	0.0001529	0.0001583	0.0001645	0.0001714
5	0	0.7	0.0001424	0.0001434	0.000145	0.0001478	0.000151	0.000155	0.0001597	0.0001652	0.0001713	0.0001782
5	0	0.8	0.0001492	0.0001503	0.000152	0.0001546	0.0001579	0.0001618	0.0001666	0.000172	0.0001782	0.000185
5	0	0.9	0.0001561	0.0001571	0.000159	0.0001615	0.0001647	0.0001687	0.0001734	0.0001789	0.000185	0.0001919
5	0	1	0.0001629	0.000164	0.000166	0.0001683	0.0001716	0.0001755	0.0001803	0.0001857	0.0001919	0.0001987
5	0	1.1	0.0001694	0.0001705	0.000172	0.0001748	0.0001781	0.000182	0.0001868	0.0001922	0.0001984	0.0002053
5	0	1.2	0.000176	0.000177	0.000179	0.0001814	0.0001846	0.0001886	0.0001933	0.0001988	0.0002049	0.0002118
5	0	1.3	0.0001825	0.0001835	0.000185	0.0001879	0.0001911	0.0001951	0.0001998	0.0002053	0.0002114	0.0002183
5	0	1.4	0.000189	0.00019	0.000192	0.0001944	0.0001976	0.0002016	0.0002063	0.0002118	0.0002179	0.0002248
5	0	1.5	0.0001955	0.0001965	0.000198	0.0002009	0.0002041	0.0002081	0.0002128	0.0002183	0.0002244	0.0002313
5	0	1.6	0.000202	0.000203	0.000205	0.0002074	0.0002106	0.0002146	0.0002193	0.0002248	0.000231	0.0002378
5	0	1.7	0.0002085	0.0002095	0.000211	0.0002139	0.0002172	0.0002211	0.0002259	0.0002313	0.0002375	0.0002443
5	0	1.8	0.000215	0.0002161	0.000218	0.0002204	0.0002237	0.0002276	0.0002324	0.0002378	0.000244	0.0002508
5	0	1.9	0.0002215	0.0002226	0.000224	0.000227	0.0002302	0.0002342	0.0002389	0.0002444	0.0002505	0.0002574
5	0	2	0.0002281	0.0002291	0.000231	0.0002335	0.0002367	0.0002407	0.0002454	0.0002509	0.000257	0.0002639
5	0	2.1	0.000235	0.0002361	0.000238	0.0002404	0.0002437	0.0002476	0.0002524	0.0002578	0.000264	0.0002709
5	0	2.2	0.000242	0.000243	0.000245	0.0002474	0.0002507	0.0002546	0.0002593	0.0002648	0.000271	0.0002778
5	0	2.3	0.000249	0.00025	0.000252	0.0002544	0.0002576	0.0002616	0.0002663	0.0002718	0.0002779	0.0002848
5	0	2.4	0.000256	0.000257	0.000259	0.0002614	0.0002646	0.0002686	0.0002733	0.0002788	0.0002849	0.0002918
5	0	2.5	0.0002629	0.000264	0.000266	0.0002684	0.0002716	0.0002756	0.0002803	0.0002858	0.0002919	0.0002988
5	0	2.6	0.0002699	0.0002709	0.000273	0.0002753	0.0002786	0.0002825	0.0002873	0.0002927	0.0002989	0.0003057
5	0	2.7	0.0002769	0.0002779	0.00028	0.0002823	0.0002855	0.0002895	0.0002942	0.0002997	0.0003059	0.0003127
5	0	2.8	0.0002839	0.0002849	0.000287	0.0002893	0.0002925	0.0002965	0.0003012	0.0003067	0.0003128	0.0003197
5	0	2.9	0.0002909	0.0002919	0.000294	0.0002963	0.0002995	0.0003035	0.0003082	0.0003137	0.0003198	0.0003267
5	0	3	0.0002978	0.0002989	0.000301	0.0003032	0.0003065	0.0003104	0.0003152	0.0003206	0.0003268	0.0003336
6	0	0.1	5.563E-05	5.581E-05	5.61E-05	5.649E-05	5.701E-05	5.764E-05	5.838E-05	5.923E-05	6.021E-05	6.129E-05
6	0	0.2	5.724E-05	5.741E-05	5.77E-05	5.81E-05	5.861E-05	5.924E-05	5.999E-05	6.084E-05	6.181E-05	6.29E-05
6	0	0.3	5.885E-05	5.902E-05	5.93E-05	5.971E-05	6.022E-05	6.085E-05	6.159E-05	6.245E-05	6.342E-05	6.451E-05
6	0	0.4	6.045E-05	6.063E-05	6.09E-05	6.131E-05	6.183E-05	6.246E-05	6.32E-05	6.406E-05	6.503E-05	6.612E-05
6	0	0.5	6.206E-05	6.224E-05	6.25E-05	6.292E-05	6.344E-05	6.407E-05	6.481E-05	6.566E-05	6.664E-05	6.772E-05
6	0	0.6	6.367E-05	6.384E-05	6.41E-05	6.453E-05	6.505E-05	6.568E-05	6.642E-05	6.727E-05	6.825E-05	6.933E-05
6	0	0.7	6.528E-05	6.545E-05	6.57E-05	6.614E-05	6.665E-05	6.728E-05	6.803E-05	6.888E-05	6.985E-05	7.094E-05
6	0	0.8	6.689E-05	6.706E-05	6.73E-05	6.774E-05	6.826E-05	6.889E-05	6.963E-05	7.049E-05	7.146E-05	7.255E-05
6	0	0.9	6.849E-05	6.867E-05	6.9E-05	6.935E-05	6.987E-05	7.05E-05	7.124E-05	7.21E-05	7.307E-05	7.416E-05
6	0	1	7.01E-05	7.028E-05	7.06E-05	7.096E-05	7.148E-05	7.211E-05	7.285E-05	7.37E-05	7.468E-05	7.576E-05
6	0	1.1	7.163E-05	7.18E-05	7.21E-05	7.249E-05	7.3E-05	7.364E-05	7.438E-05	7.523E-05	7.621E-05	7.729E-05
6	0	1.2	7.316E-05	7.333E-05	7.36E-05	7.402E-05	7.453E-05	7.516E-05	7.591E-05	7.676E-05	7.773E-05	7.882E-05
6	0	1.3	7.469E-05	7.486E-05	7.51E-05	7.555E-05	7.606E-05	7.669E-05	7.743E-05	7.829E-05	7.926E-05	8.035E-05
6	0	1.4	7.622E-05	7.639E-05	7.67E-05	7.707E-05	7.759E-05	7.822E-05	7.896E-05	7.982E-05	8.079E-05	8.188E-05
6	0	1.5	7.774E-05	7.792E-05	7.82E-05	7.86E-05	7.912E-05	7.975E-05	8.049E-05	8.135E-05	8.232E-05	8.341E-05
6	0	1.6	7.927E-05	7.945E-05	7.97E-05	8.013E-05	8.065E-05	8.128E-05	8.202E-05	8.288E-05	8.385E-05	8.494E-05
6	0	1.7	8.08E-05	8.098E-05	8.13E-05	8.166E-05	8.218E-05	8.281E-05	8.355E-05	8.44E-05	8.538E-05	8.646E-05
6	0	1.8	8.233E-05	8.25E-05	8.28E-05	8.319E-05	8.37E-05	8.434E-05	8.508E-05	8.593E-05	8.691E-05	8.799E-05
6	0	1.9	8.386E-05	8.403E-05	8.43E-05	8.472E-05	8.523E-05	8.586E-05	8.661E-05	8.746E-05	8.843E-05	8.952E-05
6	0	2	8.539E-05	8.556E-05	8.58E-05	8.625E-05	8.676E-05	8.739E-05	8.813E-05	8.899E-05	8.996E-05	9.105E-05
6	0	2.1	8.703E-05	8.72E-05	8.75E-05	8.789E-05	8.84E-05	8.903E-05	8.977E-05	9.063E-05	9.16E-05	9.269E-05
6	0	2.2	8.866E-05	8.884E-05	8.91E-05	8.952E-05	9.004E-05	9.067E-05	9.141E-05	9.227E-05	9.324E-05	9.433E-05
6	0	2.3	9.03E-05	9.048E-05	9.08E-05	9.116E-05	9.168E-05	9.231E-05	9.305E-05	9.391E-05	9.488E-05	9.597E-05
6	0	2.4	9.194E-05	9.212E-05	9.24E-05	9.28E-05	9.332E-05	9.395E-05	9.469E-05	9.555E-05	9.652E-05	9.761E-05
6	0	2.5	9.358E-05	9.376E-05	9.4E-05	9.444E-05	9.496E-05	9.559E-05	9.633E-05	9.718E-05	9.816E-05	9.924E-05
6	0	2.6	9.522E-05	9.539E-05	9.57E-05	9.608E-05	9.659E-05	9.722E-05	9.797E-05	9.882E-05	9.98E-05	0.0001009
6	0	2.7	9.686E-05	9.703E-05	9.73E-05	9.772E-05	9.823E-05	9.886E-05	9.961E-05	0.0001005	0.0001014	0.0001025
6	0	2.8	9.85E-05	9.867E-05	9.9E-05	9.936E-05	9.987E-05	0.0001005	0.0001012	0.0001021	0.0001031	0.0001042
6	0	2.9	0.0001001	0.0001003	0.000101	0.000101	0.0001015	0.0001021	0.0001029	0.0001037	0.0001047	0.0001058
6	0	3	0.0001018	0.0001019	0.000102	0.0001026	0.0001032	0.0001038	0.0001045	0.0001054	0.0001064	0.0001074

7	0	0.1	5.039E-05	5.079E-05	5.16E-05	5.265E-05	5.399E-05	5.565E-05	5.764E-05	5.997E-05	6.254E-05	6.542E-05
7	0	0.2	5.194E-05	5.233E-05	5.31E-05	5.419E-05	5.554E-05	5.72E-05	5.919E-05	6.151E-05	6.409E-05	6.696E-05
7	0	0.3	5.348E-05	5.388E-05	5.47E-05	5.574E-05	5.709E-05	5.874E-05	6.074E-05	6.306E-05	6.563E-05	6.851E-05
7	0	0.4	5.503E-05	5.543E-05	5.62E-05	5.729E-05	5.864E-05	6.029E-05	6.228E-05	6.461E-05	6.718E-05	7.006E-05
7	0	0.5	5.658E-05	5.698E-05	5.78E-05	5.884E-05	6.018E-05	6.184E-05	6.383E-05	6.616E-05	6.873E-05	7.161E-05
7	0	0.6	5.813E-05	5.852E-05	5.93E-05	6.039E-05	6.173E-05	6.339E-05	6.538E-05	6.771E-05	7.028E-05	7.315E-05
7	0	0.7	5.968E-05	6.007E-05	6.09E-05	6.193E-05	6.328E-05	6.493E-05	6.693E-05	6.925E-05	7.183E-05	7.47E-05
7	0	0.8	6.122E-05	6.162E-05	6.24E-05	6.348E-05	6.483E-05	6.648E-05	6.848E-05	7.08E-05	7.337E-05	7.625E-05
7	0	0.9	6.277E-05	6.317E-05	6.4E-05	6.503E-05	6.638E-05	6.803E-05	7.002E-05	7.235E-05	7.492E-05	7.78E-05
7	0	1	6.432E-05	6.472E-05	6.55E-05	6.658E-05	6.792E-05	6.958E-05	7.157E-05	7.39E-05	7.647E-05	7.935E-05
7	0	1.1	6.58E-05	6.619E-05	6.7E-05	6.805E-05	6.94E-05	7.105E-05	7.305E-05	7.537E-05	7.795E-05	8.082E-05
7	0	1.2	6.727E-05	6.767E-05	6.85E-05	6.953E-05	7.087E-05	7.253E-05	7.452E-05	7.685E-05	7.942E-05	8.23E-05
7	0	1.3	6.875E-05	6.914E-05	7E-05	7.1E-05	7.235E-05	7.4E-05	7.6E-05	7.832E-05	8.09E-05	8.377E-05
7	0	1.4	7.022E-05	7.062E-05	7.14E-05	7.248E-05	7.383E-05	7.548E-05	7.747E-05	7.98E-05	8.237E-05	8.525E-05
7	0	1.5	7.17E-05	7.209E-05	7.29E-05	7.396E-05	7.53E-05	7.696E-05	7.895E-05	8.128E-05	8.385E-05	8.672E-05
7	0	1.6	7.317E-05	7.357E-05	7.44E-05	7.543E-05	7.678E-05	7.843E-05	8.042E-05	8.275E-05	8.532E-05	8.82E-05
7	0	1.7	7.465E-05	7.505E-05	7.59E-05	7.691E-05	7.825E-05	7.991E-05	8.19E-05	8.423E-05	8.68E-05	8.967E-05
7	0	1.8	7.612E-05	7.652E-05	7.73E-05	7.838E-05	7.973E-05	8.138E-05	8.338E-05	8.57E-05	8.827E-05	9.115E-05
7	0	1.9	7.76E-05	7.8E-05	7.88E-05	7.986E-05	8.12E-05	8.286E-05	8.485E-05	8.718E-05	8.975E-05	9.263E-05
7	0	2	7.908E-05	7.947E-05	8.03E-05	8.133E-05	8.268E-05	8.433E-05	8.633E-05	8.865E-05	9.123E-05	9.41E-05
7	0	2.1	8.065E-05	8.105E-05	8.19E-05	8.291E-05	8.426E-05	8.591E-05	8.79E-05	9.023E-05	9.28E-05	9.568E-05
7	0	2.2	8.223E-05	8.262E-05	8.34E-05	8.449E-05	8.583E-05	8.749E-05	8.948E-05	9.181E-05	9.438E-05	9.725E-05
7	0	2.3	8.38E-05	8.42E-05	8.5E-05	8.606E-05	8.741E-05	8.906E-05	9.106E-05	9.338E-05	9.595E-05	9.883E-05
7	0	2.4	8.538E-05	8.578E-05	8.66E-05	8.764E-05	8.898E-05	9.064E-05	9.263E-05	9.496E-05	9.753E-05	0.0001004
7	0	2.5	8.696E-05	8.735E-05	8.82E-05	8.921E-05	9.056E-05	9.221E-05	9.421E-05	9.653E-05	9.911E-05	0.000102
7	0	2.6	8.853E-05	8.893E-05	8.97E-05	9.079E-05	9.214E-05	9.379E-05	9.578E-05	9.811E-05	0.0001007	0.0001036
7	0	2.7	9.011E-05	9.05E-05	9.13E-05	9.237E-05	9.371E-05	9.537E-05	9.736E-05	9.968E-05	0.0001023	0.0001051
7	0	2.8	9.168E-05	9.208E-05	9.29E-05	9.394E-05	9.529E-05	9.694E-05	9.894E-05	0.0001013	0.0001038	0.0001067
7	0	2.9	9.326E-05	9.366E-05	9.45E-05	9.552E-05	9.686E-05	9.852E-05	0.0001005	0.0001028	0.0001054	0.0001083
7	0	3	9.484E-05	9.523E-05	9.6E-05	9.709E-05	9.844E-05	0.0001001	0.0001021	0.0001044	0.000107	0.0001099
8	0	0.1	6.292E-06	5.835E-06	5.05E-06	3.961E-06	2.565E-06	8.558E-07	1.17E-06	3.511E-06	6.155E-06	9.109E-06
8	0	0.2	2.67E-06	2.214E-06	1.43E-06	3.394E-07	1.057E-06	2.766E-06	4.791E-06	7.133E-06	9.776E-06	1.273E-05
8	0	0.3	9.509E-07	1.407E-06	2.2E-06	3.282E-06	4.678E-06	6.387E-06	8.412E-06	1.075E-05	1.34E-05	1.635E-05
8	0	0.4	4.573E-06	5.029E-06	5.82E-06	6.904E-06	8.3E-06	1.001E-05	1.203E-05	1.438E-05	1.702E-05	1.997E-05
8	0	0.5	8.194E-06	8.651E-06	9.44E-06	1.053E-05	1.192E-05	1.363E-05	1.566E-05	1.8E-05	2.064E-05	2.36E-05
8	0	0.6	1.182E-05	1.227E-05	1.31E-05	1.415E-05	1.554E-05	1.725E-05	1.928E-05	2.162E-05	2.426E-05	2.722E-05
8	0	0.7	1.544E-05	1.589E-05	1.67E-05	1.777E-05	1.916E-05	2.087E-05	2.29E-05	2.524E-05	2.788E-05	3.084E-05
8	0	0.8	1.906E-05	1.952E-05	2.03E-05	2.139E-05	2.279E-05	2.45E-05	2.652E-05	2.886E-05	3.151E-05	3.446E-05
8	0	0.9	2.268E-05	2.314E-05	2.39E-05	2.501E-05	2.641E-05	2.812E-05	3.014E-05	3.248E-05	3.513E-05	3.808E-05
8	0	1	2.63E-05	2.676E-05	2.75E-05	2.863E-05	3.003E-05	3.174E-05	3.376E-05	3.61E-05	3.875E-05	4.17E-05
8	0	1.1	2.975E-05	3.02E-05	3.1E-05	3.208E-05	3.347E-05	3.518E-05	3.721E-05	3.955E-05	4.219E-05	4.515E-05
8	0	1.2	3.319E-05	3.365E-05	3.44E-05	3.552E-05	3.692E-05	3.863E-05	4.065E-05	4.299E-05	4.564E-05	4.859E-05
8	0	1.3	3.664E-05	3.709E-05	3.79E-05	3.897E-05	4.036E-05	4.207E-05	4.41E-05	4.644E-05	4.908E-05	5.204E-05
8	0	1.4	4.008E-05	4.054E-05	4.13E-05	4.241E-05	4.381E-05	4.552E-05	4.754E-05	4.989E-05	5.253E-05	5.548E-05
8	0	1.5	4.353E-05	4.398E-05	4.48E-05	4.586E-05	4.726E-05	4.896E-05	5.099E-05	5.333E-05	5.597E-05	5.893E-05
8	0	1.6	4.697E-05	4.743E-05	4.82E-05	4.93E-05	5.07E-05	5.241E-05	5.443E-05	5.678E-05	5.942E-05	6.237E-05
8	0	1.7	5.042E-05	5.087E-05	5.17E-05	5.275E-05	5.415E-05	5.585E-05	5.788E-05	6.022E-05	6.286E-05	6.582E-05
8	0	1.8	5.386E-05	5.432E-05	5.51E-05	5.619E-05	5.759E-05	5.93E-05	6.132E-05	6.367E-05	6.631E-05	6.926E-05
8	0	1.9	5.731E-05	5.776E-05	5.86E-05	5.964E-05	6.104E-05	6.274E-05	6.477E-05	6.711E-05	6.975E-05	7.271E-05
8	0	2	6.075E-05	6.121E-05	6.2E-05	6.308E-05	6.448E-05	6.619E-05	6.822E-05	7.056E-05	7.32E-05	7.616E-05
8	0	2.1	6.444E-05	6.49E-05	6.57E-05	6.677E-05	6.817E-05	6.988E-05	7.191E-05	7.425E-05	7.689E-05	7.984E-05
8	0	2.2	6.813E-05	6.859E-05	6.94E-05	7.047E-05	7.186E-05	7.357E-05	7.56E-05	7.794E-05	8.058E-05	8.354E-05
8	0	2.3	7.182E-05	7.228E-05	7.31E-05	7.416E-05	7.555E-05	7.726E-05	7.929E-05	8.163E-05	8.427E-05	8.723E-05
8	0	2.4	7.552E-05	7.597E-05	7.68E-05	7.785E-05	7.924E-05	8.095E-05	8.298E-05	8.532E-05	8.796E-05	9.092E-05
8	0	2.5	7.921E-05	7.966E-05	8.04E-05	8.154E-05	8.293E-05	8.464E-05	8.667E-05	8.901E-05	9.165E-05	9.461E-05
8	0	2.6	8.29E-05	8.335E-05	8.41E-05	8.523E-05	8.662E-05	8.833E-05	9.036E-05	9.27E-05	9.534E-05	9.83E-05
8	0	2.7	8.659E-05	8.704E-05	8.78E-05	8.892E-05	9.031E-05	9.202E-05	9.405E-05	9.639E-05	9.903E-05	0.000102
8	0	2.8	9.028E-05	9.073E-05	9.15E-05	9.261E-05	9.4E-05	9.571E-05	9.774E-05	0.0001001	0.0001027	0.0001057
8	0	2.9	9.397E-05	9.442E-05	9.52E-05	9.63E-05	9.769E-05	9.94E-05	0.0001014	0.0001038	0.0001064	0.0001094
8	0	3	9.766E-05	9.811E-05	9.89E-05	9.999E-05	0.0001014	0.0001031	0.0001051	0.0001075	0.0001101	0.0001131