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Development of a Technology Type Factor for Jacket Structures for Offshore Wind Turbines in Rhode Island

by

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Executive Summary

A marine spatial planning approach is being used to locate possible sites for offshore wind development in Rhode Island. A Technology Development Index (TDI) was developed by Spaulding et al. (2010) to quantify the technical challenges of a particular site relative to its potential power production. A component of this index is the Technology Type (TT) factor, which quantifies the relative expensive of a structure/foundation system as a function of environmental loading, water depth, and soil conditions.

This report documents the development of TT factors for jacket structures supporting offshore wind turbines in Rhode Island Sound (Hensel 2009). TT factors were calculated by the total weight of the jacket and piles for a given water depth and soil conditions normalized by the weight of a reference structure. Jacket structure weights were determined by a frequency driven finite element analysis using the program ANSYS. The structure was subjected to hydrodynamic and quasi-static turbine loads from 50-year extreme wind and the 100-year extreme wave loading in Rhode Island Sound to determine the ultimate stresses in the structural members. Pile foundation weights were determined from an analysis of the axial capacity and the lateral capacity using commercially available pile design software. Jacket and foundation weights were calculated for water depths ranging from 30m to 60m and for three representative soil types.

These analyses resulted in a Technology Type factor that varies with water depth according to a 2nd order polynomial, and also with soil type. The results were compared to the weights of two existing jacket structures in Europe as well as existing Technology Type factors from the United Kingdom, and there was good agreement between the results.

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Abstract

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This report documents the development of TT factors for jacket structures supporting offshore wind turbines in Rhode Island Sound (Hensel 2009). TT factors were calculated by the total weight of the jacket and piles for a given water depth and soil conditions normalized by the weight of a reference structure. Jacket structure weights were determined by a frequency driven finite element analysis using the program ANSYS. The structure was subjected to hydrodynamic and quasi-static turbine loads from 50-year extreme wind and the 100-year extreme wave loading in Rhode Island Sound to determine the ultimate stresses in the structural members. Pile foundation weights were determined from an analysis of the axial capacity and the lateral capacity using commercially available pile design software. Jacket and foundation weights were calculated for water depths ranging from 30m to 60m and for three representative soil types.

These analyses resulted in a Technology Type factor that varies with water depth according to a 2nd order polynomial, and also with soil type. The results were compared to the weights of two existing jacket structures in Europe as well as existing Technology Type factors from the United Kingdom, and there was good agreement between the results.

1 Introduction

Offshore wind resources have been identified as an attractive source of renewable energy along the U.S. east coast, and there are several offshore wind energy projects under various stages of development. Most of these projects are planned for deeper water depths (e.g. 30-45 m in Rhode Island) than most of the existing European wind farms, which are typically in water depths less than 30 m (Musial and Butterfield, 2004; Westgate and DeJong, 2006). Usually, a detailed technological-economical analysis (siting analysis) is performed to find an optimum location within a given area for development of the wind farm. Since the technical and economical aspects of the offshore wind turbine system are influenced by spatial variation within a given site (e.g. water depth, environmental loading, wind potential, etc.), a marine spatial planning approach is often followed to determine an optimum location.

The siting analysis developed for the Ocean SAMP utilizes the Technology Development Index (*TDI*), which quantifies the relative difficulty in siting the offshore wind turbine compared to it power production potential (Spaulding et al., 2010). The *TDI* is expressed as

$$TDI = TCI/PPP \quad (1)$$

where *TCI* is the Technology Challenge Index and *PPP* is the Power Production Potential. *TCI* quantifes the costs associated with construction of offshore wind turbines and is influenced by environmental conditions (waves, wind, water depth, and soil type). *PPP* is influenced primarily by the mean annual wind power at the hub height of the turbines, which increases with distance from shore. Low *TDI* values indicate high power production and relatively low cost of installation. *PPP* and *TCI* can be rewritten as

$$PPP = W \times CF \quad (2)$$

and

$$TCI = (TT \times FF) + CD \quad (3)$$

where *W* is the hub height, *CF* is a capacity factor for the turbine, *TT* is a Technology Type Factor, *FF* is a Foundation Factor and *CD* is the distance to the grid connection. The Technology Type factor represents the supply costs of the support structure and depends on many parameters, including type of turbine used (e.g. 3.6 MW, 5 MW, etc.), substructure type (e.g. monopile, jacket structure, gravity, floating), foundation technology (e.g. gravity base, piles, suction buckets, anchors), water depth, and geotechnical conditions. To incorporate the relative diffculty of installation in different soil types, the Technology Type Factor can be multiplied by a Foundation Factor, FF.

At the outset of the Ocean SAMP siting exercise, *TT* values were obtained from a study in the United Kingdom that described the factors as the total supply costs of a jacket support structure in a given water depth in $millions/structure (Roark, 2008). The *TT* values were grouped based on the following water depths: 5m to 25m, *TT* = 3.36; 25m to 45m, *TT* = 4.48; and from 45m to 65m, *TT* = 5.76.

The objective of this study is to develop independent values of Technology Type factors specific to jacket structures and to the environmental conditions relevant to the Ocean SAMP study area. This is accomplished by relating the *TT* factor (or cost/structure) to the weight of the steel required for the jacket and pile foundations, an approach that has been used successfully to model the costs of monopile foundations for offshore wind turbines (Papalexandrou, 2008). Based on Ocean SAMP project requirements, a 5 MW turbine mounted on a jacket structure in water depths ranging from 25m to 65m on a foundation consisting of four piles is considered in this analysis. The weight of the transition piece (see Figure 1) and the rest of the structure is considered to be constant for the varying water depths and soil conditions, and is not included in the determination of the *TT* factors. Environmental loads and representative soil conditions are specific to the Ocean SAMP study area.

To obtain the weights of the jacket structure for different water depths, a frequency driven, Ultimate Limit State design was performed using finite element analyses. A "soft-stiff" design approach was utilized to avoid resonance between the natural frequencies of the structure, environmental loads, and the turbine. Structural members and dimensions of the jacket were varied in the order to meet the soft-stiff design criterion, and the weight of the optimal design was used to develop the *TT* factors. The finite element analyses were performed using the commercial software ANSYS. As a check on the calculated structural dimensions of the jacket, a yielding stress analysis was performed with loads from wind and waves based on the Ultimate Limit State.

The weight of the foundation was determined by determining the diameter and length of four, steel pipe piles that transfer the loads from the wind, waves, turbine, and jacket structure safety into the ground. As with the design of the jacket, the foundations were designed based on the Ultimate Limit State. To evaluate pile diameter and length, the "p-y method" (Reese, 1984) was employed using the commercial software L-Pile Plus. This software allows for simulation of the lateral load bearing behavior of piles under time varying loading. Soil properties were estimated from published geophysical data.

Loads on the jacket and foundation were estimated based on recommended design standards for offshore wind turbines, specifically from 50-year extreme wind and the 100-year extreme wave loading (DNV, 2007). The wave climate for extreme storm events were derived from hind cast data according to the Ultimate Limit State and the study area. Load effects on the structure were estimated using a hydrodynamic force effect calculation implemented in ANSYS. Turbine loads were estimated for the design storm from quasi-static loads determined for a Dutch research study on a comparable turbine under comparable environmental conditions (van der Tempel, 2006). The lifespan of the structure was not considered for return-on-investment (ROI) computations.

2 Design Considerations for Jacket Structures and Foundations

Offshore structures must be designed to withstand a variety of loads, including wind, wave, current, ice and other environmental forces (e.g. earthquakes). The design principle for these structures and foundations is aimed at satisfying the safety requirements during the design life of the structures. There are three codes currently available for the design of offshore wind turbine structures: Germanischer Lloyd (2005), International Electrotechnical Commission IEC 61400-3 (2006), and Det Norske Veritas DNV-OS-J101 (2007). These guidelines are developed based on the rich experience gained from the design guidelines recommended for oil and gas platform structures (e.g American Petroleum Institute, 2000). The choice of a particular guideline is based on the local regulations and certification requirements dictated by the regulating government agency.

In DNV-OS-J101, the safety requirements are specified based on limit states of structural members at different load cases: ultimate limit state (ULS), the fatigue limit state (FLS), serviceability limit state (SLS), and accidental limit state (ALS). Ultimate limit state governs the safety requirements against the forces caused by extreme environmental conditions (e.g. 50-year return period wave) whereas fatigue limit state ensures the safety against damage accumulation caused by cyclic loading conditions. Serviceability and accidental limit states ensure safety during normal operating condition and accidental impact loads respectively. In most cases, depending on the environmental conditions in a given site, fatigue limit state governs the design of support structures of offshore wind turbine, followed by the ultimate limit state (Schaumann and Wilke, 2006).

In addition to the limit states criteria, the dynamic behavior of the coupled wind turbine structure (i.e. the Rotor-Nacelle Assembly, tower, and support structure including foundation piles) should also be considered in the design. To avoid dynamic magnification of load effects, the offshore wind turbine structures are designed as “soft-stiff” structures, meaning that the first eigen frequency of the structure is kept between the excitation frequency bands of turbine rotation and blade passing frequency (termed “1P and 3P”). The frequency band for typical ocean waves is 0.05-0.30Hz. 1P and 3P frequency bands depend on the operating speed of the turbine and are typically in the range of 0.14 - 0.20 Hz and 0.43 - 0.60 Hz (Seidel, 2007).

The support structure, which includes the jacket and four foundation piles, was modeled in a finite element analysis as steel tubular members (details are explained later) subjected to dynamic environmental loadings from waves and quasi-dynamic loads from turbine and wind, in addition to the self weight of the entire structure. The influence of soil stiffness in the dynamic response of the structure is considered by extending the foundation to a depth of six times the diameter of the piles (van der Tempel, 2006; Zaaijer, 2002). A fixity constraint was applied at this depth, and this condition has been shown to reasonably capture the nonlinear response of the foundation. The first natural frequency of the jacket structure was used as a design driver for determining the structure weight. The first mode of the natural frequency of the jacket structure was kept between 0.33-0.36Hz and the second mode was kept greater than 0.70Hz. The structures are designed in the ULS for a load combination of the 50-year extreme wind and the 100-year extreme wave loading. Ice and current loadings are not considered. Fatigue limit state was not considered in the design due to lack of time and insufficient load data. Moreover, the focus of this study was on estimating the relative change in weight of the support structure with water depth and soil conditions for a given turbine, it is assumed that fatigue consideration would not affect the relative change.

The foundation piles are designed for ultimate axial compression, axial tension and lateral loads obtained from the coupled structural analysis. The penetration depth of the piles for the jacket structure is determined based on the no-toe-kick-out criterion.

3 Estimation of Wind and Wave Loading

The water depth in the Ocean SAMP study area varies from approximately 5m to over 60m, and jacket support structures are designed for water depths ranging from 30m to 60m. Met-ocean data analysis for the study area resulted in an extreme wave height for a 100-year return period ($H_{max,100\text{-}year}$) of 16.2 m, and wave period (T) of 15s (Spaulding et al., 2010). Based on the range of water depth and wave parameters in the study area, Stokes 5th order wave theory was used to simulate wave kinematics time series (Det Norske Veritas, 2007). Wave forces on the slender tubular structures were calculated using Morison's equation within the ANSYS program. The influence of the attacking angle on the structure was investigated and the frontal attack was found to be the worst case scenario, resulting in the highest loads at the mudline.

Wind loads and moments on the turbine are dependent on the support structure stiffness, site specific wind conditions and the turbine itself. In this study, we used wind loads and moments reported by van der Tempel (2006) for a 5.5 MW turbine which is comparable to the turbine used in this study. Table 1 shows the forces and moments in the horizontal (x and y) and vertical (z) directions. These loads and moments were applied quasi-statically at the top of the tower. Additional wind loads and moments on the tower (with a cylindrical cross section) were estimated based on the extreme 50-year return period wind speed of 37m/s and then applied statically at the base of the tower.

Table 1. Estimated loads at the top of the tower from a 5.5MW GE Energy turbine. Design load case: ULS; turbine parked; extreme wind speed model (van der Tempel, 2006).

F_x (N)	F_y (N)	F_z (N)	M_x (Nm)	M_y (Nm)	M_z (Nm)
1.28E+5	2.10E+5	3.48E+5	4.25E+6	8.20E+6	1.24E+6

Due to the lack of detailed information about geotechnical data in the study area, three basic soil profiles (dense sand, soft clay and stiff clay) were considered in this study. These types are idealized soils and represent three major types of soils in the study zone: sand, till, and soft rock. This simplification of real soil conditions allows for distinguishing between weak, average, and strong soil conditions and helps to quantify the influence of the soil conditions on the foundation weight.

4 Methods

4.1 Jacket Weight Estimation

As the design of the jacket structure was optimized for various water depths, certain assumptions were made throughout the design process. Many of these assumptions were made to be consistent with both the Beatrice and Alpha Ventus projects. The geometry of the modeled jacket structure was arbitrarily fixed to have an area of 10m by 10m above the water line at the beginning of the transition piece. In addition, the four legs of the jacket structure were assumed to be inclined at an angle of 3.5^o degrees outward, thereby increasing the foot print with increasing water depth. A typical jacket structure geometry modeled using ANSYS is shown in Figure 1.

The structural model of the wind turbine system was analyzed at water depths of 30m, 38m, 45m, 53m, and 60m. At each water depth, only the jacket height and the corresponding self weight of the jacket were changed, while the rest of the components of wind turbine system, such as the Rotor-Nacelle Assemble (RNA), tower, transition piece and foundation piles, were kept constant in the analysis. The RNA was represented as a lumped mass of 435t on top of the tower. The tower was modeled as a tubular beam of 5.5m diameter and height of 75m. The transition piece was idealized as a rigid beam having a lumped mass of 160t connecting the tower and jacket. An additional four concentrated mass points (60t each) were included to idealize the pipe sleeve connecting the jacket and the foundation piles (Seidel, 2007). The foundation piles were modeled as tubular elements of 1.8m diameter and 0.05m wall thickness. The length of the piles below seabed was extended up to six times the diameter in the finite element analysis to ensure some incorporation of soil-structure interaction in the design. The structural members including tower, jacket legs and bracings and foundation piles were assumed to be tubular steel.

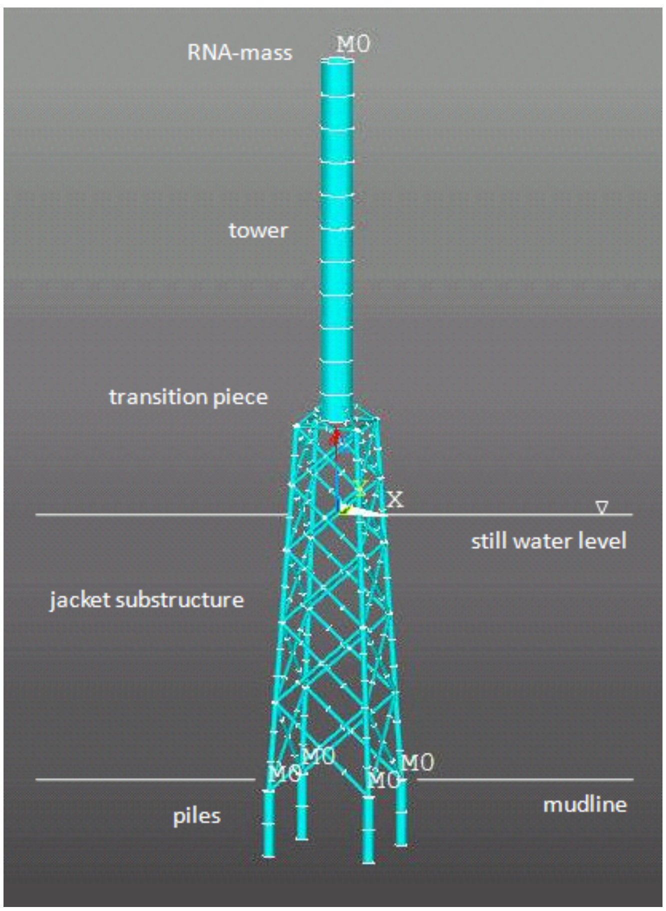


Figure 1. Typical geometry of the finite element model used to model the jacket support structure modeled using the program ANSYS.

For a given water depth, the total mass of the jacket structure was varied and the natural frequency of the entire system was estimated. During the modal analysis, for a given total mass of the jacket, the ratio of mass of the legs to mass of bracings was also varied and the appropriate jacket structure masses were estimated based on the first natural frequency that was within 0.33-0.36Hz and the second mode of the natural frequency that was greater than 0.7Hz. This frequency criterion resulted in a set of possible jacket structure weights which were further analyzed based on the ULS criterion.

Following the modal analysis, a transient analysis in the time domain was performed to check the ULS requirements and also to determine the loads and moments at the mudline for foundation pile design. In this transient analysis, the structure was subjected to time varying loads from the waves and quasi-static loads from wind as explained above. An analysis time of 120s was chosen with time increments of 1s. A series of eight waves with a wave period of 15s were simulated. This duration was found to be sufficient to model the dynamic behavior of the structure. A relatively low damping is expected for the parked turbine and therefore 2% Rayleigh damping was used to model structural and material damping in the analysis (van der Tempel, 2006; Det Norske Veritas, 2007).

The structural integrity of the jacket in response to the transient loads was evaluated by comparing the maximum von-Mises stress within each structural member to the allowable yield stress of the steel member. This is consistent with U.S. guidelines for the design of offshore structures (American Petroleum Institute, 2000).

This analysis resulted in many combinations of leg and bracing sizes that satisfied both the frequency criterion and the structural integrity (i.e. ULS) criterion. Both the lower and upper bound of admissible jacket weights were obtained from the mean values of the lowest and highest jacket masses estimated for each first natural frequency varying from 0.33Hz to 0.36Hz. The lower bound mass represents the most economical structure with the smallest material consumption. The upper bound mass represents a less economic solution with higher material consumption.

This procedure was then repeated for different water depths and the variation of lower and upper bound weights for each water depth is shown in Figure 2. Figure 2 shows that jacket structure weight followed a quadratic relationship with water depth in contrast to the monopile structure for which a cubic polynomial relationship was proposed (Papalexandrou, 2008). Figure 2 also includes weight and water depth data for the Alpha Ventus (Seidel, 2007a) and Beatrice jacket structures (Talisman Energy, 2007). There is reasonable agreement between the weight of the actual structures and the estimated trends from the finite element analyses.

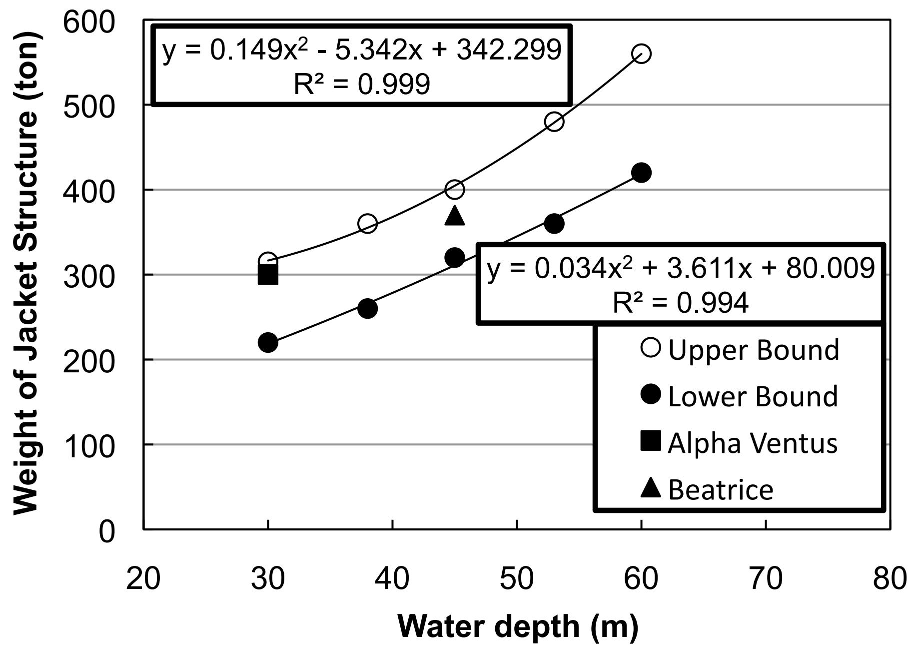
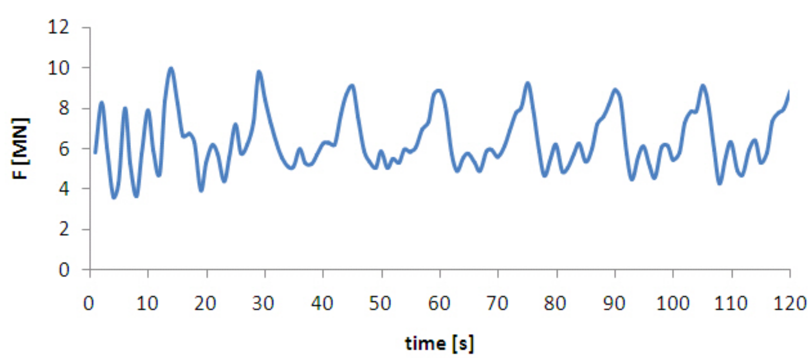
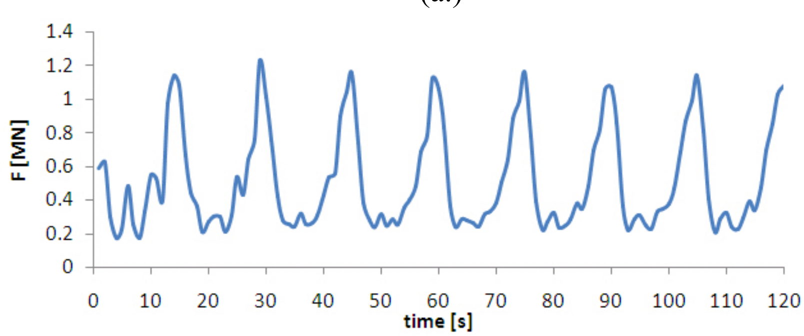


Figure 2. Variation of estimated jacket weight with water depth. Installed weights of two jackets from the Alphus Ventus and Beatrice projects are included for comparison.

The transient analysis was also performed to estimate the time history of forces and moments at mudline that would be applied to the head of the four foundation piles. A typical time history of axial load, horizontal load and moments at mudline is shown in Figure 3. The absolute maximum of loads and moments on the pile heads at the mudline were estimated for lower and upper bound cases of jacket weight at each water depth. These maximum loads and moments were then used for foundation pile design as explained below.



(a.)



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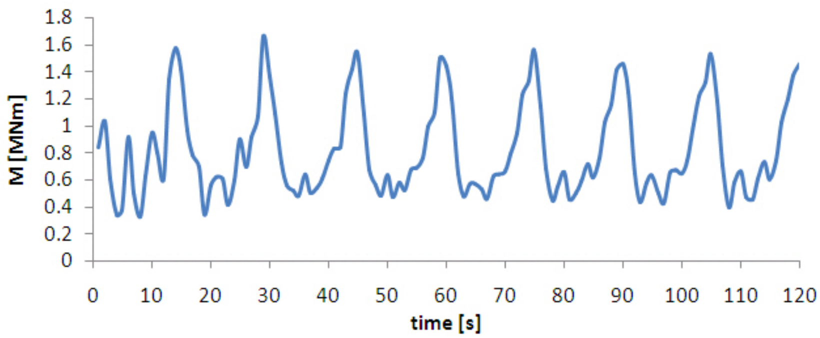


(c.)

Figure 3. Transient loads generated at the mudline for use in the geotechnical pile design, including a.) vertical force, b.) horizontal force, and c.) moments (45m water depth, f = 0.33Hz).

4.2 Foundation Pile Weight Estimation

The foundation piles consisted of four, vertically driven tubular steel piles. These piles were designed to carry the ultimate axial and lateral forces and moments at the pile head. The axial and lateral pile capacity was estimated according to the standard practice recommended in API (2000). The lateral capacity was estimated using a nonlinear soil stiffness model (p-y model) available within the software program L-Pile Plus. Based on the applied static ultimate loads, the pile penetration length was estimated using the zero deflection at pile toe (no toe-kick out) criterion. From the length and diameter of the pile the weight of the foundation piles were calculated for each water depths.

There is a lack of geotechnical data with depth throughout the study area, so three different uniform soil profiles that represent the range of soils that can be expected were considered in the pile design: sand, stiff clay, and soft clay. Assumed values of buoyant unit weight, undrained shear strength ratio, and effective stress strength parameters are shown in Table 2. The stiff clay is assumed to have an over consolidation ratio (OCR) of 5. The soft clay is assumed to be normally consolidated (OCR = 1). Pile capacity was estimated for all the three soil types and for the lower and upper bound loads and moments at different water depths. Based on these factors, the penetration length and hence the weight of the foundation piles for different soil conditions and water depths was determined, and the weights are shown in Figure 4.

Figure 4 shows that the influence of water depth on the foundation pile weight is negligible. This is due to the increasing size of the jacket footprint at the mudline with increasing water depth, which changes the distribution of axial loads, lateral loads, and moments at the pile head. Figure 4 also illustrates that the influence of soil type is significant on the weight of the foundations. The weight of the piles in the sand deposit is 50% less than the weight of the piles in soft clay. It is also noted that in the sand deposit the lateral capacity governs the pile design and there is no difference in foundation pile weight for lower and upper bound jacket weights. In the soft and stiff clay deposits, the lower bound loads resulted in marginally lower penetration depths in the range of 2m to 5m when compared to upper bound loads.

The weight of the foundation piles at the Beatrice site is also shown in Figure 4. Soil conditions at the Beatrice site are dominated by clay of various densities and medium dense sands (Talisman Energy, 2007). There is good agreement between the weight of the Beatrice foundation and the weight estimated in this study for stiff clay at the same water depth.

Table 2. Soil types and geotechnical parameters assumed for estimation of pile lengths and weights.

Soil type	γ' (kN/m^3)	S_u/σ'_v	φ' (deg)	D_r (%)
Sand	11	-	34	65
Stiff clay	8	0.5	-	-
Soft clay	7	0.3	-	-

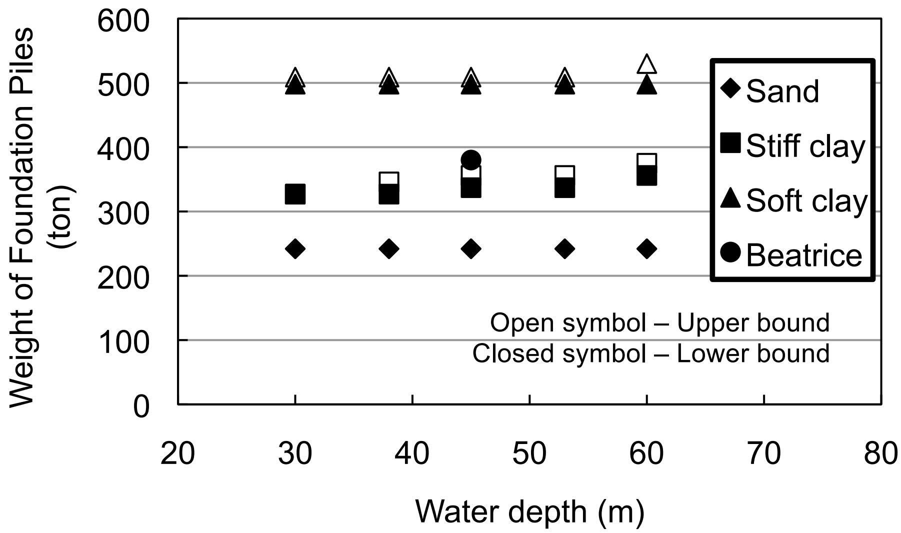


Figure 4. Estimated weight of foundation piles for different soil types and water depths. The weight of the Beatrice foundation piles are included for comparison.

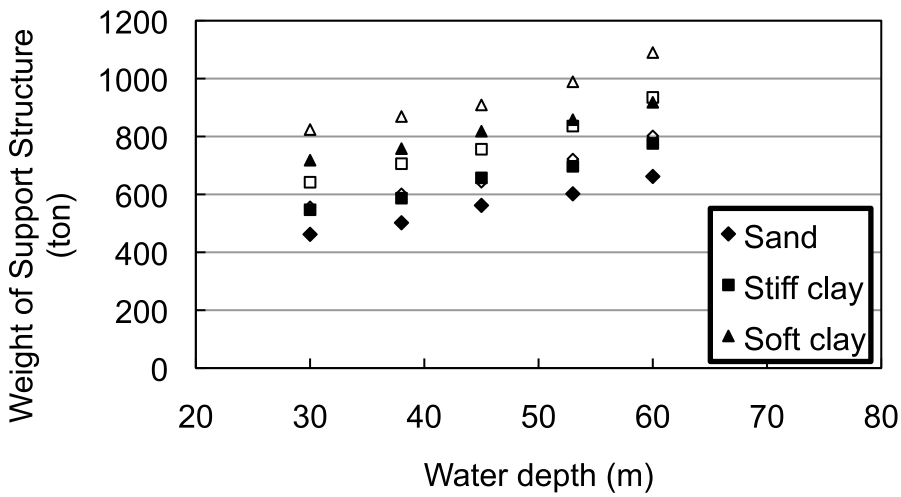
5 Development of Technology Type Factors and Relative Cost Model

The total cost of development of a wind farm includes many factors, including the turbine, tower, support structures (e.g. transition piece, jacket, foundation piles, scour protection, etc.), electrical infrastructure, operation and maintenance (Papalexandrou, 2008). The cost of all the above components are influenced by the supply costs (e.g. materials used, manufacturing process, transportation and installation costs). However, in this study only the variation of supply costs for the jacket type support structure are considered. It is assumed that the unit cost for transportation and installation would remain the same for a given wind farm and therefore the relative cost model (and the related Technology Type factors) developed based on weight of the structural members is a reasonable approximation for support structure cost.

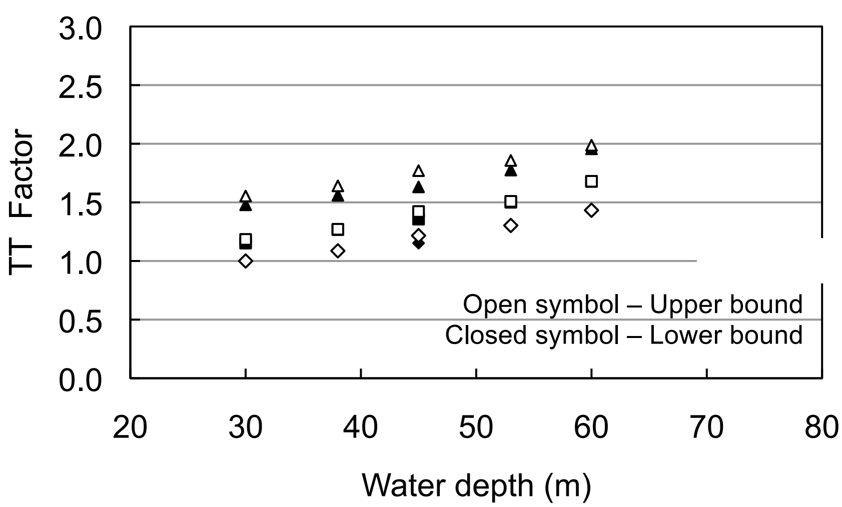
5.1 Technology Type Factors for the Ocean SAMP Study Area

The combined jacket and foundation weights for the upper and lower bound solutions and different soil types are shown in Figure 5a. Although the magnitude of the values differs between the upper and lower bound, the trends are almost identical. The Technology Type factors (*TT*) were obtained by normalizing the support structure weights by the weight at 30m water depth (Fig. 5b). Figure 5b shows that the *TT* factor increases with both water depth and soil type. For a given soil type the increase in the *TT* factor (and thus the supply costs) of a structure from 30m to 60m is approximately 30%. As the *TT* factors between upper bound solution and lower bound solution did not vary significantly, only the upper bound solution was used in the further analysis.

Roark (2008) provided relative costs for lattice jacket type wind turbine support structures for varying water depths (Table 3). These costs were not very sensitive to moderate changes in water depth and did not distinguish between variations in soil conditions. These costs were also normalized by the cost at 30m water depth (i.e. $ 4.48M), and Figure 6 shows that there is reasonable agreement with the *TT* factors established independently in this study. Since Roark's costs are typical for North Sea conditions where soil types often consist of sands and stiff clays, the agreement of his *TT* values with the values for sand and stiff clays from this study is encouraging.



(a.)



(b.)

Figure 5. Variation of a.) support structure weight and b.) Technology Type (*TT*) factor with soil type and water depth. The *TT* factors are the support structure weights at a given water depth divided by the support structure weight at 30m water depth.

Table 3. Published relative costs of jacket support structures of offshore wind turbines used as *TT* factors (Roark, 2008).

Water Depth (m)	Costs (Million USD)	*TT* Factor
5-25	3.36	1.75
25-45	4.48	1.0
45-65	5.76	1.28

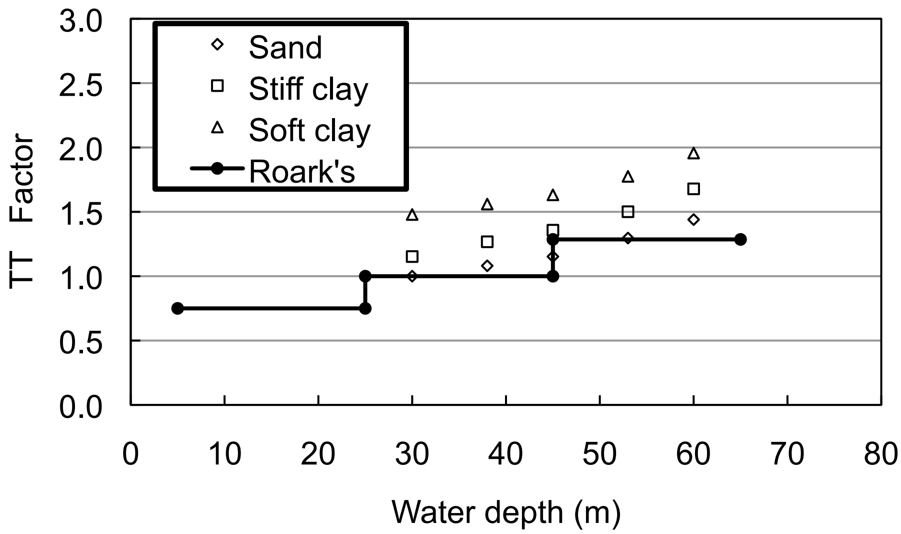


Figure 6. Comparison of Technology Type factor developed in this study with relative costs proposed by Roark (2008).

5.2 Relative Cost Model for Jacket Structures

The concept of using support structure weights to develop Technology Type factors can be expanded to a relative cost model for jacket structures. The simplest form of a cost model involves factoring the weight of the support structure by a supply and fabrication cost multiplier. To do this, it must first be recognized that the supply costs of a jacket are more than the supply costs of the foundation piles due to the additional effort required for fabrication. The relative cost of a jacket support structure (C_{ss}) can thus be expressed as:

$$C_{ss} = a\ W_j + b\ W_f \tag{4}$$

where W_j is the weight of jacket for a given water depth and soil type; W_f is the weight of piles; a is the material and manufacturing cost multiplier for jacket structure (e.g. \$/ton); and b is the material and manufacturing cost multiplier for the piles.

Using the upper bound estimates of weight, W_j and W_f can be written as a function of water depth and soil type as shown in Table 4. With these relationships and accurate estimates of multipliers a and b, the variation of the cost of the support structure within the Ocean SAMP study area can be evaluated.

Table 4. List of weight functions

Support Structure Component	Soil Type	Weight (W) as a Function of Water Depth (d) (W in tons, d in m)	R^2
Jacket	all	W_j=0.149d^2 – 5.342d + 342.299	0.99
Foundation	Sand	W_f = 241.6	-
Foundation	stiff clay	W_f = 0.005d^3 – 0.777d^2 +35.77d – 200.5	0.98
Foundation	soft clay	W_f = 0.004d^3 – 0.559d^2 + 22.380d + 217.5	0.98

6 Conclusions

This study supports the Ocean SAMP *TDI* screening analysis by developing an independent measure of Technology Type (*TT*) factors for jacket structures supporting offshore wind turbines. *TT* factors are used to quantify the relative expense of a jacket structure and pile foundation system as the water depth increases and the soil conditions change, and is expressed as a dimensionless number. The factor is calculated from the total weight of the jacket and piles for a given water depth and soil conditions normalized by the weight of a reference structure. It takes into account environmental conditions from wind and waves specific to the Ocean SAMP study area.

Support structures were designed to safely carry a 5MW turbine. The structures were composed of a jacket substructure and a four pile foundation. The design of the jacket was based on two criteria. The first natural frequency of the structure had to be between the excitation frequencies of the rotating turbine and the passing blades. This is typically called a soft-stiff design and is important to avoid resonance during environmental loading. In addition, the allowable stresses in the structure and piles were kept below the yield strength of the material. This criterion is called the Ultimate Limit state.

Jacket weights were determined using the finite element program ANSYS. Thousands of combinations of different sized jacket legs and bracing were evaluated, and the designs that satisfied the two loading criteria were binned. Both upper and lower bound weights were determined for different water depths, and there was a consistent trend of increasing jacket weight with water depth. The foundation piles were designed using the API code (2000) for axial loads and the program L-Pile Plus for lateral loads. Designs were made for water depths ranging from 30m to 60m and for three different soil types: sand, stiff clay, and soft clay.

The combined weights of the jacket and piles were then compared to published values of weights from the Alpha Ventus jacket in Germany and the Beatrice jacket in Scotland. There was good agreement between the calculated and published values, which supports the validity of the design approach used in this study.

The combined weights of the jacket and piles were then used to directly calculate *TT* factors. The three weight functions (one for each soil type) were normalized by the weight of the support structure in the shallowest water depth (30m) and for sandy soil, and the resulting *TT* factors range from approximately 1 to 1.44 for sandy soil condition , from 1.15 to 1.68 for stiff clay, and from 1.48 to 1.96 for soft clay. The results were compared to the weights of two existing jacket structures in Europe as well as existing Technology Type factors from the United Kingdom, and there was good agreement between the results.

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