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Performance Testing of a Novel Gravity Base Foundation for Offshore Wind

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ABSTRACT: In recent years, the international demand to produce green energy has been growing to address the issues of energy security and climate change. To date, the wind sector has probably advanced the most due to high availability of wind resources. Erecting wind turbines offshore, however, presents significant new engineering challenges. Offshore foundations for these energy converters must be able to resist large overturning moments as well as numerous cycles of lateral loading caused by wave and wind. Thus, the need for an efficient cost-effective foundation to support the turbines is becoming more important. In this paper, a specific design of a gravity base foundation system developed for offshore wind turbines is considered. The foundation is a conical hollow concrete gravity type structure which rests on the seabed and utilises its self-weight to support the turbine. A scale-model of the proposed foundation has been experimentally tested at the University College Dublin test site in Blessington, Ireland. This paper presents the findings of this research.

KEY WORDS: Offshore Wind, Gravity Base Foundation, GBF.

1 INTRODUCTION

The current interest in greener sources of energy has arisen to address the issue of climate change that threatens to endanger the stability of the world's climate. The phenomenon of global warming is mainly caused by the emission of carbon dioxide (CO_2) from the combustion of fossil fuels. In order to tackle this environmental issue as well as to provide energy security, sustainable sources of energy such as wind, wave, solar, biomass and geothermal power are being substituted for fossil fuels [1]. Among these clean sources of energy; wind technology has been most frequently employed due to high availability of its resources [2].

Onshore wind farms provide green energy; however, they are inhibited by site availability restrictions and tend to cause some public objections due to aesthetic and noise-producing principles [3],[4]. Developers therefore have begun to investigate exploiting the offshore wind resource.

Erecting wind turbines in the ocean presents significant new engineering challenges. Offshore wind foundations must be able to resist large overturning moments as well as numerous cycles of lateral loading caused by waves and wind. Moreover, wind turbines are becoming larger with taller wind towers and rotor blades in greater diameters. This complicates the loads that are applied to the supporting structure and foundations [5]. The foundation for the new generation of offshore wind turbines should maintain its stiffness and satisfy its design objectives throughout its design life in harsh coastal environments. Thus, the need for an efficient cost-effective foundation to support the turbines is becoming more important.

Multiple solutions have been proposed to support offshore wind turbines, such as, monopiles, gravity base foundations, suction caissons and multi-pod support structures (namely tripods and jackets). Since almost 27 percent of the capital costs of the construction of a wind turbine offshore relate to foundation costs, the cost of a foundation is a major factored to be considered [6]. This places more focus on the choice of foundation solution. For each wind farm, the foundation system is selected based on several factors such as the magnitude of design loads, seabed conditions, wave and current velocities, ice climate, water depths at the site and site geology [5] among other factors.

GBFs are suitable foundation options employed in the wind energy industry as well as oil and gas sector. Gravity foundations are less expensive to construct than monopiles, but the installation costs are higher, largely due to the need for dredging and subsurface preparation and the use of specialized heavy-lift vessels [7]. But certainly, a more effective design with suitable economic considerations and suitable geotechnical performance, will justify more frequent employment of GBFs in future offshore wind farms in deeper water.

In recent years, various designs have been proposed for gravity structures in order to develop a self-buoyant foundation that minimises the costs for marine operations [8]. The different designs aim to enhance the performance and stability of the foundation as well as to reduce the costs associated with its construction and deployment [8]. With the current interest in building wind farms in deeper water depths, the limitations associated with monopiles will limit their usage. Thus, gravity base structures with suitable specifications should be designed to fill an important niche for the deeper water depth regions. This paper presents an analysis of the geotechnical performance of a novel floating gravity base structure as a potential cost-effective foundation solution for future offshore wind farms.

2 LITERATURE REVIEW

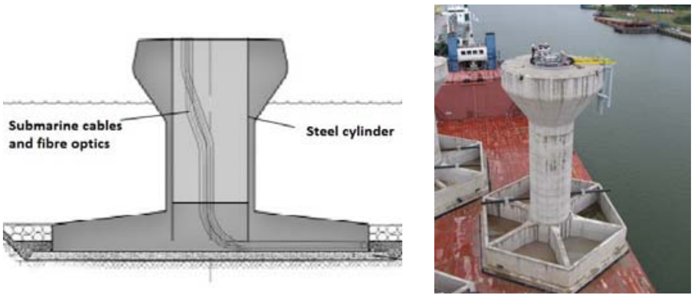
The concept of gravity structures was first implemented in the oil and gas sector. Gravity base foundations are heavy concrete structures utilising their self-weight to withstand overturning moments and sliding shear applied on them by means of wave and wind loading [9]. However, when the foundation is deployed in the sea, the buoyancy effect reduces its self-weight resulting in less resistance against overturning compared to those installed onshore [10]. Despite the fact that GBFs rely on their self-weight to resist service loads, their design should be optimised in a way that the overall material consumption, manufacture, transport and installation costs also stand within reasonable limits. GBFs are constructed as hollow concrete shells to facilitate transport and installation. In order to provide sufficient dead weight to support the turbine against lateral loads, the GBFs are ballasted, once in place [10]. Ballast material can be sand, rock and iron-ore which are all available at a relatively low cost [11]. Using concrete in manufacturing gravity base structures makes the foundation design less dependent on fluctuating steel prices and also reduces the need for piling [9].

Gravity base foundations are usually built from reinforced concrete. Foundation slabs for onshore gravity structures can be poured in situ. However, this method cannot be applied to offshore wind turbines. This means that the foundation has to be constructed near the coast and be transported to the proposed location in the sea by special barges. The foundation is then lowered onto the seabed. The transportation issue puts a limit on the maximum weight of the offshore gravity structure; they are usually designed to be hollow [10]. When the structure is deployed in the water, it can be filled with ballast to increase the supporting weight. Gravity foundations are most likely to be used where piles cannot be driven [12] or in ice-prone regions [13]. Up to now, gravity foundations have been the second most widely used foundation after monopiles, currently covering 16% of the total operational offshore wind farms [14].

GBFs are suitable for deeper water (up to 60 metres) with low maintenance needs, since concrete is inherently durable in the marine environment [15]. Construction of gravity structures is fast and routine and usually cheaper than other foundation types since concrete is not subjected to high price fluctuations like steel [16], [17]. They do not need any piling operations and may also be repositioned [18], [19]. One of the plus points of GBFs is that the main parts of the structure are visible for inspection and further checks unlike monopoles and other deep embedded foundations [18]. However, Seabed preparation is necessary before deployment of these structures [15]. The welding details for self-buoyant structures might be time-consuming, and more importantly, their transportation and deployment need specific facilities and heavy-lift vessels that can resist the heavy weight of the structure [20], [17], [18].

GBFs are installed in several offshore wind farms, including Middelgrunden, Nysted, Thornton Bank, and Lillgrund. A more effective design with suitable economic considerations and suitable geotechnical performance may justify more frequent employment of GBFs in future offshore wind farms in deeper water. The design method for GBFs has originated from the conventional methods applied for the design of shallow foundations. In recent years, novel self-buoyant GBF concepts have been proposed, that can be floated and towed to the specified location and ballasted to the seabed. Successful application of these alternative foundations can significantly limit the associated cost of transport and installation (BVG Associates 2013). Installation of gravity base foundations requires competent homogeneous seabed, comprised of dense sand, stiff clay or shallow bedrock, as the massive weight of the foundation can induce large settlements and bearing capacity issues in less competent soil types [9], [11].

The design configuration of GBFs has been altered over time. The first generation of GBFs were manufactured as reinforced concrete structures with an overall shape as illustrated in Figure 1.a. They were mainly constructed in dry docks that were later flooded when the foundation was ready to be floated-out [7]. The second generation of GBFs started with Nysted I project (see Figure 1.b.); their improved design comprised of a wide base, hollow pipe with thick walls and an ice cone at the top [7]. Aside from the novelty in manufacture, their installation was also improved by using floating pontoons or submergible barges as manufacturing platform [7]. This method reduces the occupation of large onshore space in ports or yards, and also eliminates the load-out and float-out operations [21].



(a) (b)

Figure 1. (a) First and (b) second generation of GBFs (www.ontario-sea.org), (http://www.gs-seacon.pl)

The third type of GBFs were designed to have a thinner base, a conical hollow shaft (with thinner walls) instead of a pipe-shaped middle structure and a pipe at the top to attach to the turbine tower. Figure 2 shows a schematic view of this design. This approach was first introduced for the Thornton Bank offshore wind farm, located off the coast of Belgium [21].

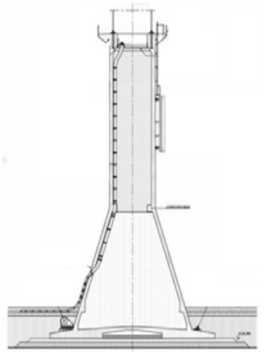


Figure 2. Third generation design of GBFs [22]

So far, gravity base foundations have been installed in shallow to moderate water, relatively close to the shore [9]. In order to justify the application of this foundation concept for deeper water, modifications in design, manufacture and installation are necessary. To address this issue, novel concepts in installation and design, such as, self-floating and crane-free GBFs are being introduced.

Optimisation of a gravity base foundation should be performed with a focus on minimising material consumption, reducing manufacture and design complexity and at the same time, maintaining the required lateral capacity against service loads. This study attempts to investigate the performance of a novel gravity based concept which is believed to significantly reduce the manufacturing efforts and hence, contribute to reducing the overall cost of the original foundation. In this paper, a proposed design for a GBF will be introduced and the test methodology followed for the experimental validation of the performance of this novel concept, as well as the implemented numerical simulation approach will be outlined.

3 EXPERIMENTAL METHOD

Understanding the behaviour of a foundation is essential in order to ensure suitable performance during its service life. Novel foundation concepts need to be carefully studied and tested in small or full-scale models before they can be deployed in industry. Evaluation of an offshore wind turbine foundation requires a thorough understanding of its load bearing mechanism. In this paper, in order to investigate the performance of the proposed concept, a 1:15 scaled model of the proposed GBF design was constructed and underwent a series of field tests. The experiments aimed at applying lateral loads to the scaled structure, in order to represent the actual wind and wave loads in the offshore site. The objective of the load tests is to analyse the load transfer process between the foundation and the underlying soil and to assess the lateral load bearing capacity of the foundation. Furthermore, the magnitude of displacements and rotations the structure experiences during these tests confirms if the foundation is capable of satisfying the limit states specified by the relevant design guidelines for offshore foundations. Accordingly, the results of the tests are carefully analysed to draw a conclusion on the soil behaviour, foundation capacity and viability of this concept.

The proposed foundation is a conical shaped concrete GBF. Its overall shape (Figure 3) resembles the third type of GBFs, similar to those used on the Thornton Bank Wind farm [23]. To study the viability of this foundation design, a concrete model of the proposed prototype was constructed by Bullivant Taranto and transported to UCD's research site located in Blessington, approximately 25 km south-west of Dublin. This structure was subjected to a set of planned tests to analyse its performance when it is subjected to lateral loads resembling the offshore wind and wave load effects. Load-testing the prototype indicates the failure mechanism as well as the magnitude of the lateral loads that can be applied before failure.

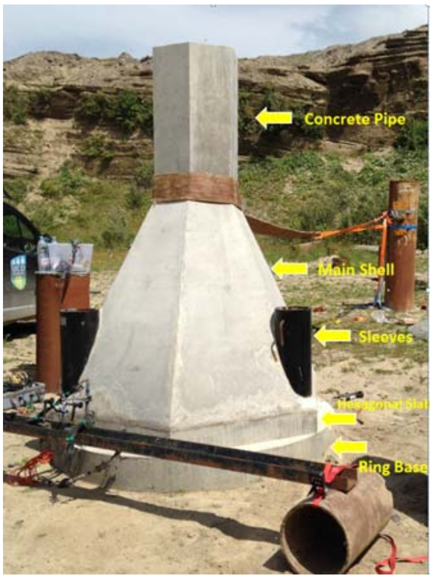


Figure 3. Overall shape and components of the GBF

A scale-model experiment for analysing the performance of the proposed foundation concept was performed on the scaled-structure at the University College Dublin (UCD) test site at Blessington, County Wicklow, Ireland. The Blessington test site has been developed over the last decade and has been used to test numerous prototypes and scale foundations [24], [25], [26], [27] and [28]. Therefore, several tests have already been performed with the geotechnical properties of the Blessington sand. The experiments show that the test site is made up of very dense, glacially derived sand with a relative density of approximately 100%, unit weight of 20 kN/m^3 and specific gravity of particles equal to 2.69 [24] and [29]. The main properties of the Blessington soil, according to the conducted tests by UCD geotechnical research group, are provided in Table 1.

Table 1. Properties of Blessington Sand [29]

Description	Value
Soil unit weight	20 kN m^{-3}
Soil specific gravity	2.69
Sand relative density	Approximately 100%
Ground water level	13 metres below ground level (bgl)
Degree of saturation above the water table	63% - 75%
D_{50}	0.1 - 0.15 mm
Percentage of coarse-grained particles (Particles with diameters less than 0.6 mm)	Less than 10%
Constant volume friction angle	37 degrees
Peak friction angle	42 – 57 degrees
Residual friction angle	39 to 31 degrees (with an average of 36)

The experimental method consisted of static and cyclic load tests with and without piles attached to the structure. In this section, information about the instrumentation, load test set-up and data acquisition method are presented.

A lateral load test was designed and conducted in Blessington, 25 kilometres south-west of Dublin, to evaluate the lateral response of the foundation. The aim is to provide a setup for pulling the structure laterally. The load test setting is shown in Figure 4. In order to reach a suitable layout for pulling the structure, firstly, a loading pile in the vicinity of the structure was chosen. A hydraulic jack was then horizontally fastened to the loading pile using ratcheting straps. A steel shaft connects the hydraulic jack to a load cell. The load cell was then bolted into a steel plate. This steel plate was attached to the main structure with a high strength ratcheting strap (see Figure 5). The other end of the ratcheting strap is attached to a strap which goes around the neck of the GBF to enable the load transfer. The monotonic loading of the structure is comprised of applying horizontal loads of 2 kN increments, while each load step was maintained for 2 minutes after the stabilisation (see Figure 6 for loading sequence).

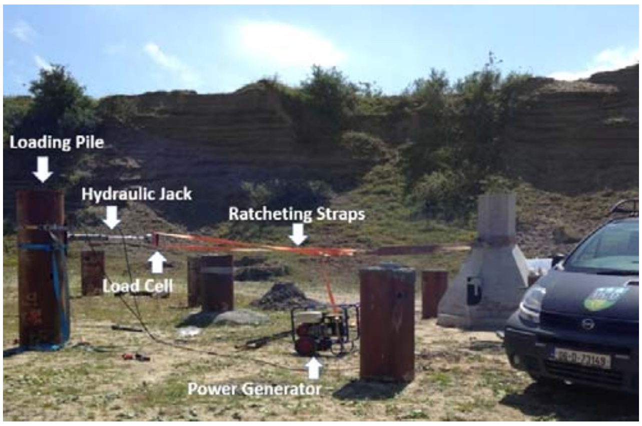


Figure 4. Load test layout of the scale-model

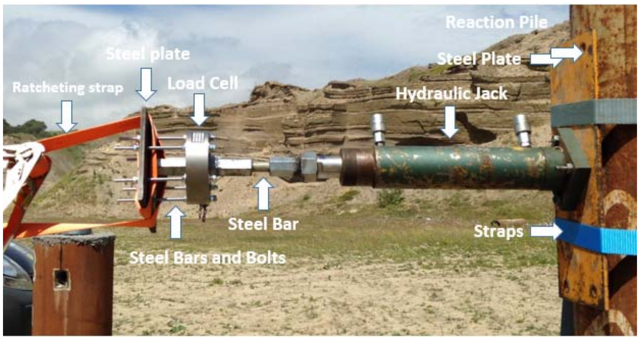


Figure 5. Setup of load cell and hydraulic jack

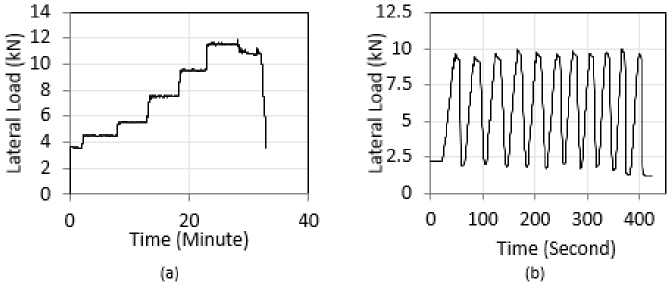
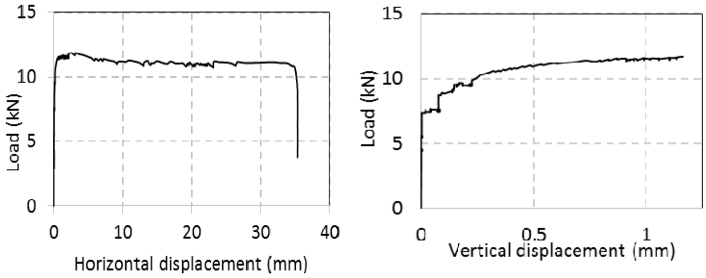


Figure 6 (a) Monotonic, (b) cyclic loading sequence of the structure

The graph of load versus horizontal displacement (See **Error! Reference source not found.**.a) shows that the maximum horizontal load that the structure can sustain before reaching failure in the form of horizontal sliding is 11.7 kN. Once this load is achieved, the structure experiences a sudden failure; the horizontal displacements continue to increase at a constant horizontal load, until the foundation is unloaded. The stiffness of the foundation, which is defined as the slope of the load vs. displacement graph, is relatively constant during the loading process until it reaches the ultimate load, when the stiffness suddenly drops and the foundation slides on the soil surface. The maximum horizontal displacement of the scaled structure after failure, is approximately 35 millimetres.



(a) (b)

Figure 7. (a) Load-Horizontal displacement, (b) Load-Vertical displacement diagrams

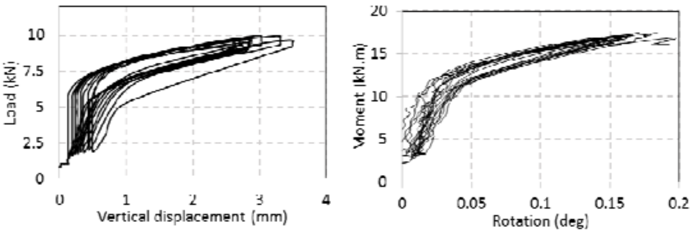
Vertical displacement of the scaled foundation due to horizontal loading is also presented in **Error! Reference source not found.**.b. The vertical displacement has progressed with a more gradual slope compared to the case of horizontal displacements. The graph shows the positive vertical displacements recorded at the toe of the foundation which is gradually rising from the soil surface due to the applied horizontal load. The maximum vertical displacement reached before the structure slides is 1.2 millimetres (at the ultimate load).

After the failure of the structure due to static loading, a set of load cycles were applied to the scaled foundation. This type of loading was aimed at replicating the cyclic effect of the sea waves and wind loads applied on the offshore wind turbine support structures in service. The reaction of the foundation due to cyclic loading is studied by interpreting the displacements and rotations generated in the structure during these load cycles. It shall be noted that the maximum loads applied in these cycles are less than the maximum load-bearing capacity of the foundation observed in the previous stage, in order to allow for multiple load cycles to be applied to the structure before sliding occurs.

Figure 8.a shows the accumulated vertical displacements of the foundation versus horizontal cyclic loading. Figure 8.a shows that after the cycles of loading, a maximum of 3.5 millimetres vertical displacement of the foundation is recorded. After the unloading of the structure in these cycles, the structure still has a residual vertical settlement of 0.5 millimetres vertical displacement. This graph also points that minimal vertical displacement occurs to the structure when loads up to 7 kN are applied. After this point, the slope of the

load-displacement graph changes and vertical displacements develop more rapidly.

The moments generated in the foundation during cyclic tests were calculated based on the recorded loads. Figure 8.b shows the rotations recorded in the structure due to the cycles of applied moments. The moments generate minimal rotations up to 12 kN-m, after which the rotations reach from 0.05 degrees to a maximum of 0.19 degrees with a steeper slope.



(a) (b)

Figure 8. (a) Load-displacement graph, and (b) Moment-rotation graph for cyclic loading

The obtained graphs give an overview of the performance of the scaled gravity structure and provide a platform to calibrate the numerical models planned to be developed for the same tests.

4 CONCLUSION

This paper investigates the performance of a novel offshore gravity structure, which was developed with the aim of reducing the cost and the associated risks of installation of the offshore wind substructures. The proposed modifications are believed to improve the load-bearing capacity and efficiency of the foundation. A summary of the field tests and measurements that have been conducted to evaluate the performance of this novel foundation concept, known as the proposed structure were provided in this paper.

For the purpose of evaluating the foundation design, a scale-model of the proposed structure was constructed. The model was tested at the UCD test site in Blessington, where the soil profile resembles North Sea sand properties. A set of monotonic and cyclic lateral load tests were performed on the scaled foundation with the aim of assessing the potential load-bearing capacity of the foundation when subjected to simulated offshore wind and wave loads. Rotation and displacements of the structure were recorded during these load tests. These results represented the performance of the scaled structure and provided a basis for the development of a numerical model to replicate the foundation's behaviour. This model will be further employed to analyse the full-scale foundations and fully validate the novel design. The details of further analysis will be presented in future publications.

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REFERENCES

[1] F. Breu, S. Guggenbichler, and J. Wollmann, "Wind and Solar Power Systems: Design, Analysis, and Operation," *Vasa*, pp. 87–101, 2008.

[2] R. Koekkoek, "Gravity Base Foundations for Offshore Wind Farms Gravity Base Foundations for Offshore Wind Farms," no. April, 2015.

[3] P. Stuart, "What Are The Challenges Of Installing, Operating And Maintaining Wind Turbines Offshore." 2007.

[4] B. W. Byrne and G. T. Houlsby, "Assessing novel foundation options for offshore wind turbines," *World Marit. Technol. Conf.*, pp. 1–10, 2006.

[5] S. Malhotra, "Selection, Design and Construction of Offshore Wind Turbine Foundations, Wind Turbines," 2011. [Online]. Available: http://cdn.intechopen.com/pdfs/14804/InTech-Selection_design_and_construction_of_offshore_wind_turbine_foundations.pdf. [Accessed: 02-Oct-2015].

[6] M. I. Blanco, "The economics of wind energy," *Renew. Sustain. Energy Rev.*, vol. 13, no. 6–7, pp. 1372–1382, 2009.

[7] M. D. Esteban, B. Couñago, J. S. López-Gutiérrez, V. Negro, and F. Vellisco, "Gravity based support structures for offshore wind turbine generators: Review of the installation process," *Ocean Eng.*, vol. 110, pp. 281–291, 2015.

[8] A. Attari, P. Doherty, E. Reig Amoros, and C. Paulotto, "Design drivers for buoyant gravity-based foundations," *Wind Energy*, p. n/a–n/a, 2015.

[9] LEANWIND, "Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments WP Framework / Industry Challenges Report – construction , deployment and installation," no. 614020, 2014.

[10] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, *Wind Energy Handbook*, vol. 25, no. 3. 2001.

[11] Z. J. Westgate and J. T. Dejong, "Geotechnical Considerations for Offshore Wind Turbines," *Offshore (Conroe, TX)*, pp. 1–130, 2005.

[12] P. Vølund, "Concrete is the Future for Offshore Foundations," *Wind Eng.*, vol. 29, no. 6, pp. 531–539, 2005.

[13] H. Gravesen, S. L. Sørensen, P. Vølund, A. Barker, and G. Timco, "Ice loading on Danish wind turbines: Part 2. Analyses of dynamic model test results," *Cold Reg. Sci. Technol.*, vol. 41, no. 1, pp. 25–47, 2005.

[14] European Wind Energy Association, *Deep water*, no. July. 2013.

[15] Arup, "GRAVITY BASE," 2011.

[16] A. Miehe, "Omae2012-8 Geotechnical Stability of Gravity Base Foundations for Offshore Wind Turbines," pp. 1–7, 2012.

[17] M. J. Kaiser and B. F. Snyder, "Offshore Wind Energy Cost Modeling Chapter 2 Offshore Wind Energy System Components," *Offshore Wind Energy Cost Model.*, pp. 189–200, 2012.

[18] Z. Saleem, “Technique for Noise Mitigation,” no. April, pp. 1–68, 2011.

[19] T. Feld, J. . Rasmussen, and P. H. Sørensen, “Aalborg Universitet Structural and Economic Optimization of Offshore Wind Turbine Support Structure and Foundation Feld , Tove ; Rasmussen , J . L ; Sørensen , P . H .,” 1999.

[20] I. Ruiz, “Gravity Base Foundations for Offshore Wind Farms Gravity Base Foundations for Offshore Wind Farms,” 2013.

[21] M. D. Esteban, J. J. Diez, J. S. López, and V. Negro, “Why offshore wind energy?,” *Renew. Energy*, vol. 36, no. 2, pp. 444–450, 2006.

[22] P. Van den Bergh and L. Ponnet, “Offshore Wind Farm THORNTON BANK PHASE I Presentation,” vol. 2009, pp. 1–83, 2009.

[23] K. Peire, H. Nonneman, and E. Bosschem, “GRAVITY BASE FOUNDATIONS FOR THE THORNTON BANK OFFSHORE WIND FARM,” *Terra Aqua*, vol. 115, pp. 19–29, 2009.

[24] K. G. Gavin and B. C. O. Kelly, “Effect of Friction Fatigue on Pile Capacity in Dense Sand,” no. January, pp. 63–71, 2007.

[25] K. Gavin and B. Lehane, “Base load – displacement response of piles in sand,” vol. 1063, no. 2005, pp. 1053–1063, 2007.

[26] D. J. P. Igoe, K. G. Gavin, and B. C. O. Kelly, “Shaft Capacity of Open-Ended Piles in Sand,” *Am. Soc. Civl Eng.*, no. October, pp. 903–913, 2011.

[27] A. Tolooiyan and K. Gavin, “Computers and Geotechnics Modelling the Cone Penetration Test in sand using Cavity Expansion and Arbitrary Lagrangian Eulerian Finite Element Methods,” *Comput. Geotech.*, vol. 38, no. 4, pp. 482–490, 2011.

[28] L. J. Prendergast, D. Hester, K. Gavin, and J. J. O. Sullivan, “An investigation of the changes in the natural frequency of a pile affected by scour,” *J. Sound Vib.*, vol. 332, no. 25, pp. 6685–6702, 2013.

[29] P. Doherty, L. Kirwan, K. Gavin, D. Igoe, S. Tyrrell, D. Ward, and B. O’Kelly, “Soil properties at the UCD geotechnical research site at Blessington,” in *Proceedings of the Bridge and Concrete Research in Ireland Conference*, 2012, pp. 499–504.