A Review on Offshore Wind Turbine Foundations

Aleeda Shaju[1], Neethu Joseph[2]

[1]Mtech Student, Dept. of Civil Engineering, St. Joseph's College of Engineering and Technology, Palai
[2]Assistant Professor, Dept. of Civil Engineering, St. Joseph's College of Engineering and Technology, Palai

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Abstract – *wind power are fastest-growing popular, sustainable and renewable energy resource that has lesser shock on the surroundings than burning conventional fuels. Offshore winds are clean and sustainable renewable energy resource with great latent value for the energy trade in the circumstance of a low carbon world. The rapid expansion of offshore wind power depends on a excellent understanding of the practical issues associated with offshore wind turbines, which drive current investigate and improvement programs. The foundation of an offshore wind turbine is one of the most challenging tasks in the design of an offshore wind turbine. This article provides an indication of the types of offshore wind turbine foundation, important design consideration, effect of vertical and horizontal loads etc.*

Key Words: **Wind Power, Renewable Energy, Offshore Wind Turbines, Offshore Wind Turbine Foundation, Design Consideration**

1.INTRODUCTION

Renewable energy source has become increasingly important over recent years as a means of achieving international goal for reduced greenhouse gas emissions while ensuring energy security. Sun is the primary source of renewable energy and wind is a secondary source of renewable energy dependent on the sun. The wind velocity is influence by topographical features and revolution of the earth. Bhattacharya et.al [6] studied that Offshore wind farms are consider most reliable energy source due to some reasons:

(1) The average wind speed is higher in offshore and it is consistent throughout the year

(2) Offshore wind turbine have minimum vibration impact and noise impact on human compare with onshore wind turbine

(3) By use of hybrid systems current and wave energies can be harvest along with wind farms.

Offshore wind farms are popular in United Kingdom, Europe and Germany. The world's first seaward wind farm was built in Denmark. Offshore wind farm industry is expected to grow over the next decades. The future scope of offshore wind farms are wide by considering the lower airstream shear, higher energy density, lower instability, and low civil complaints contrast with inland wind farms. Total cumulative capacity in the offshore wind energy turbine (OWETs) was to 35.3 GW in 2020. United Kingdom is world leader in offshore wind power harvesting and currently generating approximately 3GW. Figure 1 indicates the gradual development and installations of offshore and onshore wind energies between 2011-2020.
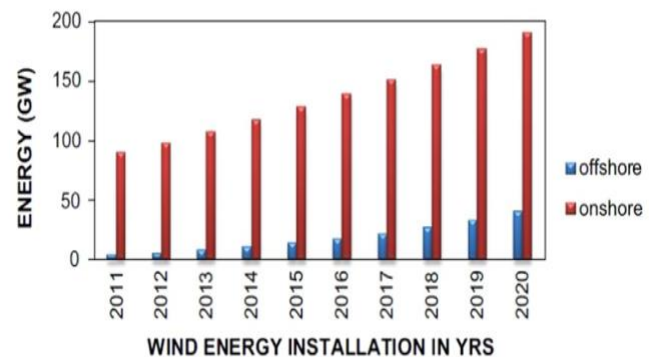

Fig -1: Wind Energy Installations [7]

2. TYPES OF FOUNDATIONS

Bhattacharya et.al [6] studied that foundations are the most crucial segment of the structure, So the design and stability of foundation determine economic viability of a project. Typically the investment in foundation account for 25% - 34% of the total cost of the project. The selection of suitable foundation is depending up on seabed conditions, weather conditions and environmental conditions. Offshore wind turbine foundations are broadly classified into two ie. Grounded system and Floating .

2.1 Grounded System Foundation

In this system the foundation is anchored or fixed in to seabed. The grounded system can be further divided into follows:

Bhattacharya et.al [6] studied the design of gravity based foundation is help to avoid overturning moment or uplift and the design of foundation is according with their self weight. In gravity based foundation there is no tensile load is conceder between seabed and substructure. The self weight of the groundwork will provide stability and also resist overturning moments. Figure 2(b) shows gravity based foundation for water depths less than 30m.

Suction caissons be also known as suction bucket. The suction bucket have long skirts around the perimeter. The diameter to length ratio of the suction bucket is around one. The components of caisson bucket are rigid circular lid and slender tubular skirt. These foundations mainly used in oils and gas manufacture platforms. Figure 2(a) shows suction bucket for water depths less than 30.

Ma et.al [2] studied that Monopole is a single large diameter steel tube with open ends. Typically the diameter of the monopole varies from 4 to 6 m and slenderness ratio is in the range of 4 to 8. Monopile is connected to transition piece i.e. a steel tube which support boat landings and ladders. Figure 2(c) shows monopile foundation. Monopile foundation is the simplest form of grounded system foundation. The installation process of monopile foundation is very simple than other types. Hermans et.al [15] studied that Typical monopile foundations have the diameter in the range of 3 to 8 meter and the economical water depths are considered as 20–40 meter .

Thomsen et.al [17] studied that The jaacket foundation Figure 2(e) is manufactured up of steel tubular elements that are normally assembled on land in advance by welding. The jaacket is then transported to location, and erected into the ocean floor. In terms of steel utilization, jaacket foundations are very inexpensive, but cargo space, logistics, and fixing can be costly, significantly increasing the overall cost . Dong et.al [21] studied the jaacket foundations are suitable for middle water depths such as 50-70 meter.

Tripod foundations Figure 2(d) contain three standard diameter steel metal pipe piles set in the form of a equilateral triangle and the apex of triangle supports the top tripod truss structure. Wu et.al [14] studied that tripod truss may tolerate superior loads applied to tower and convey stresses and moments to the three steel piles. The tripod groundwork is stable, lightweight, and appropriate for water depths of 10 to 35 meter.
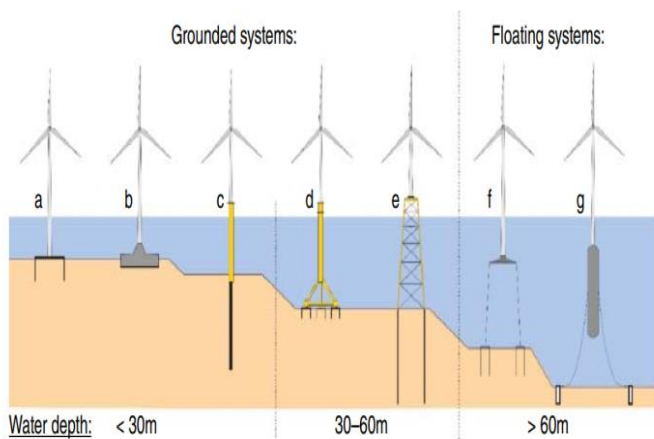

Fig -2: Foundations at different water depths [6]

Chen et. al [1] examine the main parts hybrid foundation is normal monopile and a broade–shallow bucket. During plugging wide –shallow bucket is accomplished by their dead weight, and then pump out the inside water from the bucket. The monopile is fixed to ocean bed from the center of the bucket, and linked the two parts through large strength grout materials. Compared to the normal monopole substructure, the pile of the hybrid foundation is too small, which has a smaller depth in bearing layer. It can be seen that previous research mainly focus on moment taking capacity of innovative hybrid foundations under static loading , since moment bearing capacity is the principal objective of OWTs foundations. However, there is a inadequacy of attention on other character of hybrid foundations under static loading, such as the load sharing ratio and the rotation center position, both of which are related to the bearing mechanism of foundations. Schematic representation of parts hybrid foundation shown in Figure 3.
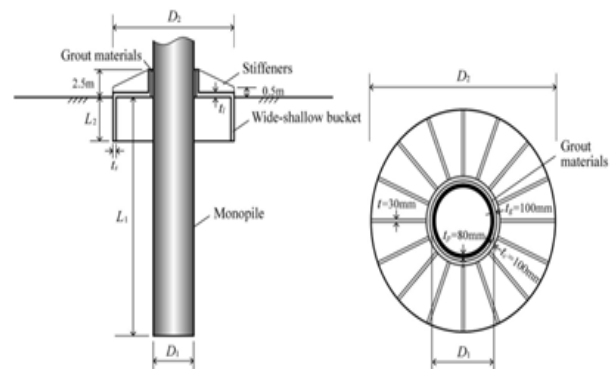

Fig -3: Hybrid Foundation [1]

2.2 Floating system foundation

Castro-Santos et.al [18] study A floating structure is the perfect choice for offshore wind exploration in waters of depth exceeding 60 meter. Anchors will help to mount the mooring system in to the seabed. The floating structure will provide adequate buoyancy to align the weight of the turbine and to restrain angle and heave movement within admissible limits studied . Wu et.al [14] studied several anchors that can be employed to moor the floating system, and they can be indexed into surface anchors and embedded anchors shown in Figure 2(f)and Figure 2(g).

3. DESIGN CONSIDERATIONS

Negro et.al [12] study the design of supporting structure and foundation of wind turbine is very complex. The crucial loadings are weight of wind turbine generator and loads due to the wind action, current and wave loads, operation and maintenance loads, etc. Also other important aspects are terrain situation and its main features, construction and action issues, and so on. The effect of all these makes the design of these structures very complex the design.

Transition piece is one of the most discussed uncertainties in the wind turbine sector. The transition piece is a connector between the support structure and the wind turbine generator. It is one of the main weakness of the monopile foundation concept studied by Negro et.al.

Cox et.al [13] study Inshore wind turbines are extremely sensitive for dynamic loading , because of the combination of the thin structural nature of the turbine and the large range of cyclic loads to which the turbine is subjected. The unplanned resonance effects of the wind turbine can be minimized by proper designing of magnitude of the dynamic load. In seismic areas tilting will be consider as an important design parameter with liquefaction susceptibility. . Bhattacharya et.al [6] studied that typically, 8–16 m soil may liquefy in loose to medium dense deposit under moderate to strong earthquakes. This will reduce the rotational stiffness of the substructure, causing higher tilting along with settlement studied by. Figure 4 shows schematic representation of monopile, gravity and jacket foundations.
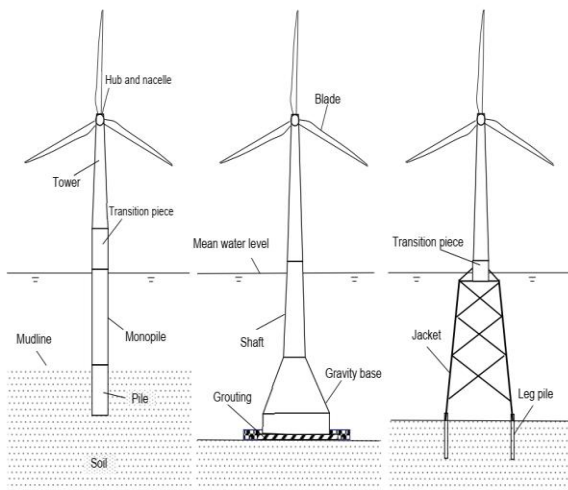

Fig -4: Schematic Representation of Monopile, Gravity and Jacket Foundations [6]

4. EFFECT OF LOADS

Bhattacharya et.al [6] studied loads applied on the foundation is depending on the foundation system. These loads can be categorized into two ie. static loads due to the dead weight of the components and dynamic loads due to wave, 1P, 3P and wind loads. The dynamic load due to wind is calculated by turbulence intensity in the wind velocity and it is acted at the hub level. The cyclic load due to wave is acting at the sub structure level of foundation and it is depending on water depth, wave height, wave period etc. The rotor and hub mass imbalance and the blade aerodynamic imbalance cause overturning moment and vibrations at the hub level settlement. Figure 5 shows loads on a monopole. Malhotra et.al [16] found that monopile foundation of in sea wind turbines experience a vertical load by the weight of the superstructure containing the turbine and transition pieces.

Typical vertical load on a 2- to 5-MW OWT foundation is 2.4–10 MN settlement .The installation of OWT is unique due to their geometry and the cyclic/dynamic loads acting on it. in sea Figure 6 shows twist and lateral deformation of monopile under static loading. Where D is monopile diameter, L is embedment depth, h is the distance between pile head and the soil surface and H is the lateral load .
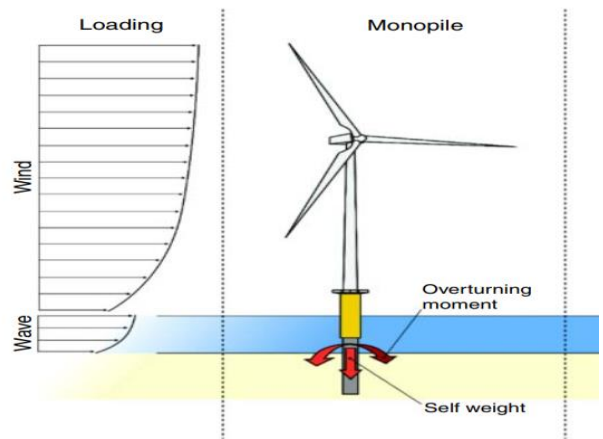

Fig -5: Loads on Monopile Foundation [6]

Wu et.al [14] studied the lateral stability, offshore wind turbine monopile foundations must be constructed with suitable embedment depth and diameter. In practice, monopile stability assessments are frequently done separately for axial and lateral load scenarios. A thorough, detailed investigation is necessary due to the relatively limited information available on the interaction effect of monopole behaviour under combined axial and lateral pressure .The ultimate axial load-carrying capacity (Q_d) of a monopile is calculated as follows:

$$Q_d = Q_f + Q_p = f A_s + q A_p$$

Where Q_f is skin friction resistance (kN), Q_p is total end bearing (kN), f is unit skin friction capacity, (kPa), A_s is side surface area of pile (m^2), q is unit end bearing capacity (kPa), and A_p is gross end area of pile (m^2) .
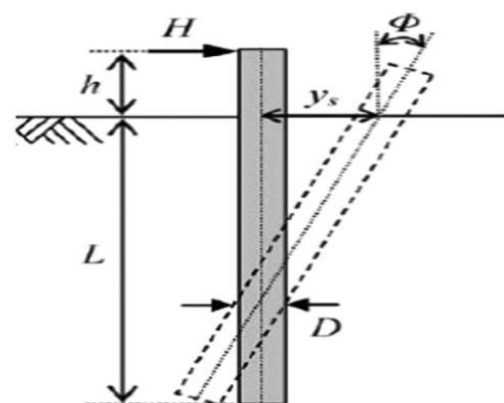

Fig -6: Lateral Deformation Monopile [8]

Wang et.al [3] investigates bucket foundation settles gradually as the vertical axis load increases, resulting in the formation of a local shear failure zone. As the external loading increases, a triangular wedge-shaped zone of soil is forced down that will results the pushing of surrounding soil sideways and upwards. At the ultimate condition the soil will reach a state of plastic equilibrium, then the foundation undergoes a large settlement without increase of vertical loadings. The bearing capacity of soil is increase with the skirts length. Lian et.al [20] study the larger digging depth and contact surface area will enhance friction resistance of bucket foundation. constraint effect on the inside soil enhance strength of bucket skirt at larger penetration depth, and hence resulting in higher internal soil pressure. Bhattacharya et.al [6] studied the stress caused by the thrust of the wind on the rotor blades and tower. The periodic component of the load depends on the turbulence of the wind at that location (Changes in wind speed with time) and characteristics of turbine operations . The equation for thrust force (Th) due to wind is given by

$$Th = 0.5\, \rho_a A_R C_T U^2$$

where ρ_a is the density of air, A_R is the rotor swept area, C_T is the thrust coefficient, and U is the wind speed.

Usually Morison equation is adopted to calculate the waves load acting on cylindrical component of fixed ocean structures, whose diameter should less than one by fifth of the wave length [19]. Chen et. al [1] examines Morison equation is given

$$dF = \tfrac{1}{4}\,(\pi D^2)\, CM\, \rho\, u\, dz + \rho/2\, CD\, Du' |u''|\, dz$$

where dF is the horizontal wave load acting on a strip length of dz in N, D is the diameter of the cylindrical members in m, u' and u'' are the wave induced velocity (v) and acceleration (a) of water particles respectively in the horizontal direction, CM and CD are the mass and drag coefficients, ρ is the water density.

5. SOIL STRUCTURE INTERACTION

Soil-structure interaction (SSI) is a process it is defined as the, response from the soil affects the motion of the structure and the vibration of the given structure influences the response from the soil. Bhattacharya et.al [6] studied that structural shifts and the earth displacements are free of each other. SSI forces can happens for any structure. But these are impossible to change the soil drift in all conditions. Soil –structure interaction (SSI) affects the overall behavior of the wind turbine system in mainly three ways ie. load transfer mechanism ,modes of vibration and long-term performance. When the subsoil resistance assumed with constant depth, ground conditions then soils fails first and the pile failure is not through the plastic hinges shown in Figure 7. Then the ultimate capacity can be calculated by

$$M_R = F_R (e + 1.5D_P + 0.5f) = 2.25 D_P g^2 s_u$$

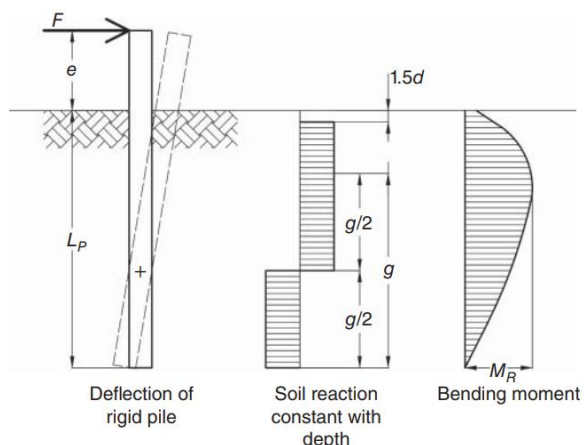$$L_P = 1.5D_P + f + g$$

$$f = F_R / 9 s_u D_P$$

Fig -7: Lateral Pile Capacity -Ground Stiffness constant with depth [6]

where e is the loading eccentricity , s_u is the undrained shear strength of soil , M_R is the moment capacity, F_R is the pile horizontal load carrying capacity , D_P is the diameter and L_P is the embedded length of the pile. Similarly when the subsoil resistance assumed that increasing linearly with depth, in this case soil is fails first and no plastic hinges is formed in the pile that is shown in Figure 8.
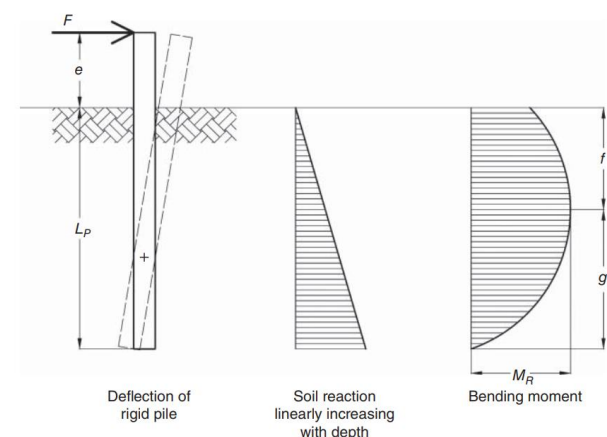

Fig -8: Lateral Pile Capacity -Ground Stiffness Linearly with depth [6]

Then the ultimate capacity can be calculated by

$$F_R = \tfrac{3}{2}\, \gamma' D_P K_P f^2$$

$$K_P = (1 + \sin \phi')/(1 - \sin \phi')$$

$$M_R = F_R (e + 0.667f)$$

Where e is the loading eccentricity , s_u is the undrained shear strength of soil , M_R is the moment capacity, F_R is the pile horizontal load carrying capacity, γ' and ϕ' are the submerged unit weight and angle of internal friction respectively.

Bhattacharya et.al [6] studied monopiles and jackets have very different load transfer mechanism in soil. For a monopile, the interaction is trasverse pile–soil interaction (LPSI) due to the lateral load and the overturning moment. In the case of jaacket the dominent interaction is due to the axial load transfer. Hence the SSI depends on the type of soil near the pile and the choice of foundation. Types of foundation are the main factor that will affect modes of vibration .

The shapes of shallow foundations are often square, circular, or rectangular, in plan. They will be even multi cellular and for mudmats the form are often irregular. The addition of skirts will help to improve the load bearing capacity of foundations. The main loads acting on the foundation are horizontal load (H), vertical load (V) and moment (M). The moment capacity is defined as the product of eccentric loading point and vertical load. Terzaghi's bearing capacity equations are used to find bearing capacity of stip footing and it is given as follows

$$q_{ult} = c'N_c + \gamma z N_q + 12\gamma B N_\gamma$$

where q_{ult} is the ultimate bearing capacity which is expressed in N/m^2, c' is the apparent soil cohesion, z is the depth of foundation , B is the breath of foundation , γ is the unit weight of soil and N_c, N_q, N_γ are the bearing capacity factors.

Bhattacharya et.al [6] studied that monopole is a long pipe having large diameter from a geotechnical point of view, so proper substructure modeling is very crucial for the design of OWT monopole foundation. This pile foundations experience heavy bending moments due to horizontal(H) loads exerted by waves and wind on the slender WT towers. In traditional monopile response examinations, the sand resistance is typically modeled by discrete uncoupled springs that is attached to the typical nodes.

The monopile is designed to withstand axial and lateral static or dynamic loadings, and its corresponding deformation should satisfy structural and serviceability . For pile axial load-settlement test the soil spring response is expressed by nonlinear t-z curves , where t and z indicates mobilized shaft friction and local pile deflection. For lateral load-deflection test the soil spring response is indicate by nonlinear p-y curves that is as shown in Figure 9. API [11] will provide the procedure for construction of t-z and p-y curves.
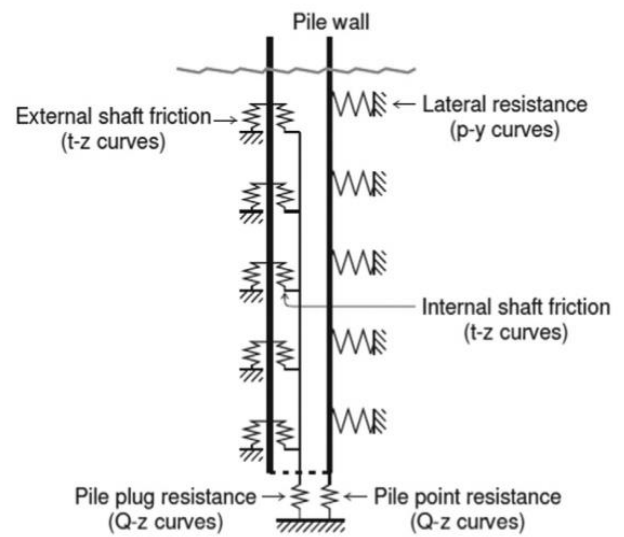

Fig -9: Soil –Pile Interaction Spring Model [9]

6. GEOTECHNICAL CONSIDERATIONS

Bhattacharya et.al [6] studied the geotechnical studies will help to determine the foundation capacity, the installation cost and procedure, foundation modeling and fatigue analysis etc. Based on study, the engineering behavior of standard ocean soils like pure sand or pure clay can be anticipated with some level of confidence. Sometimes it is difficult to forecast the conduct of intermediate soil i.e. clayey-silt or sandy-silt , as the main questions are whether the samples will conduct like clay or sand material. Particularly the behavior of soil with varying fines content is difficult to forecast and cyclic triaxial tests are very useful. That will have a great impact on the long-term behavior soil.

Harris et.al [22] studied Scouring is one the important challenge in foundation design and it is a combination of geotechnical and hydrodynamic process that affects soil-structure-fluid interactions. Scouring will badly affects the bearing capacity of monopile, the dynamic characters of OWT systems and it will lead to structural instability. De et.al [23] studied The studies are mainly focus on forecasting of scour depth, scour protection design and structural response assessment etc.
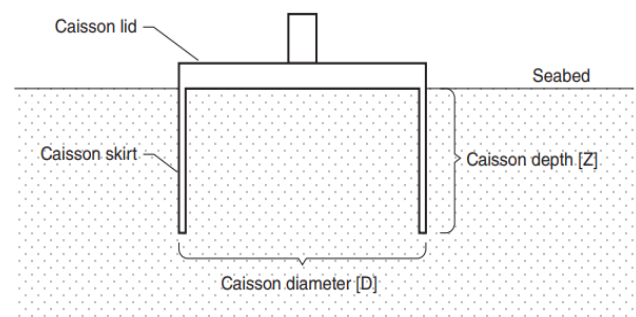

Fig -10: Suction Bucket Foundation [6]

Bucket foundations are commonly used for offshore gas and oil productions shown in Figure 10 . Achmus et.al [24] and Wang et.al [25] studied the main loads on the suction bucket OWT foundations are vertical load from the self weight, lateral loads from the wind, water and overturning moments etc. Studies of OWT bucket foundations are mainly concentrated on the bearing capacities under various cyclic loading and monotonic loading and the primary aim is to provide a suitable and economical design methodology for bucket foundation.

7. CONCLUSION

This paper provides the overview of types of offshore wind turbine foundations. The first part of the paper represents the history and background of OWT foundations, the importance of renewable energy resources, advantages of offshore wind turbine than onshore wind turbine etc. Then review follows the order of types of foundations ie, grounded system foundations and floating system foundations, OWT design considerations and effects of various loads etc. Various existing geotechnical issues are critically reviewed, and challenges along with scouring of foundations are discussed. Finally the detailed fixing process of monopile and caisson bucket are discussed.

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