Comparison of Foundation Systems for Offshore Wind Turbine Installation

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Abstract—**Offshore foundations includes the foundations for structures like wind turbines, oil and gas explorations units, under water pipelines, bridges on sea bed, port structures and many more. Offshore wind energy offers a huge potential for the expansion of renewable energies in many parts of the world. As a result of this, many countries are now planning to establish new wind farms with increased turbine capacity up to 5 MW. With increase in turbine size, the foundation dimension also increases necessitating the development of new foundation concepts. This paper provides an overview of various support options available for wind turbines like gravity base structure, monopiles, suction caissons, tripod/tetrapod with caissons, floating platform, and jacket structure. For all available options, the current status of use and development, future need for research, advantages, and disadvantages as discussed. Also, a comparison of all foundation systems is made to choose one according to site conditions.**

Keywords- Floating Platform; Gravity base structure; Jacket structure; Monopiles; Suction Caissons; Tripod/Tetrapod with Caissons

I. INTRODUCTION

With the growing development in activities related to offshore construction in India, need arises for development of most modest methodology, design guidelines and construction techniques to fasten and economizing the work. Offshore wind energy generation is the fastest growing source of renewable energy in the world. Many technological developments in wind energy design have contributed to the significant advances in wind energy utilization so as to get optimum power from available winds. As the demand increases for wind power generation, it is necessary to go deeper into sea. This calls for the development of new concepts and modification of existing foundation design for wind turbines. This study is focused on various available options for wind turbine foundation, recent developments in techniques, comparison of various foundation types, and the need of future research works.

II. WIND TURBINES

Wind turbines on onshore sites consume scarce land areas which can be utilized for other activities. Further, with the growing demand of wind power generation, there is enforcement to place turbines deeper and deeper in to sea. In loading condition wind turbines differs from regular offshore structures as discussed in the next section. Till now most wind turbines have capacity of 3 MW and in nearer future it will be increased up to 5 MW. A typical wind turbine structure has a height of 90 m above sea level and a rotating diameter of 100 m. The depth of foundation may be shallow or deep according to site conditions and capacity. Wind turbines are usually installed in a group, and a typical wind farm may have a capacity of 300 MW. In the sea, turbines are subjected to corrosion and deterioration. So it is advisable to remove the whole structure after completion of design life. In any wind turbine construction, foundation design and construction play a major role. According to one survey, the foundation cost component is 35% of total cost for wind turbine [1].

III. TYPICAL LOADING PATTERN OF WIND TURBINES

Most offshore structures are very huge so it has very high vertical load and only wave or seismic load acts as a lateral load. Typical wind turbines differ markedly in loading pattern compared to other offshore structures. Due to increased height and reduced plan area, it has low vertical load (up to 6 MN) but wind forces induce very high overturning moment (up to 120 MN) on the structure; and the reverse is true in the loading of regular offshore structures. The lateral loads comprise of wind and wave loads and are cyclic in nature. The worst load case is usually when the turbine is operating in moderate winds while the sea is in an extreme state [1]. The various and available foundation systems for offshore wind turbines are discussed one by one.

IV. GRAVITY BASE STRUCTURES

It is the oldest available foundation system for wind turbines and it comes under shallow foundation category. The first gravity base foundation (GBS) was installed in 1973 in the North Sea. The material used for its production is only concrete. The maximum depth achieved by this system can be 10 m. The gravity base must provide sufficient resistance against sliding and sufficient vertical bearing capacity. The required sliding resistance determines the minimum weight of the system, based on Coulomb's relation for frictional material. Vertical bearing capacity is calculated according to the theory developed by Prandtl, Terzaghi and Brinch Hansen [2]. Only the contribution of the soil weight is taken into account, because this is commonly the largest contribution to bearing capacity for an offshore GBS. Correction coefficients for inclined loading and overturning moment are included, since these affect the design to a large extent. The bearing capacity of the gravity base is checked for many phases of the incoming wave, due to its sensitivity to the ratio between vertical and horizontal loading. The weight of a gravity base has to be sufficient to avoid uplift, tilting and sliding, while at the same time avoiding failure of the subsoil. The main parameters to achieve this balance are the diameter and height of the gravity base.

Figure 1 shows that gravity bases provide a stable foundation and where boundaries of failure mechanism occurs [3]. The correction factors on bearing capacity reduce to zero at severely inclined loads or tilting, making the boundary for bearing an envelope for all failure mechanisms. Many disadvantages are associated with GBS foundation system. As it achieves stability by its own weight, it is a very huge and massive structure. Installation process may result in special requirements such as the capacity of the installation vessel or the size of the workspace. Scour is also the one of important factors due to its high reliance on surface soil.

V. MONOPILES

A monopile foundation consists of a large-diameter steel pile, which is in principle simply a prolongation of the tower shaft into the ground. They are frequently installed as foundations for offshore wind energy converters, e.g. at Horns Rev in Denmark or Arklow Bank in Ireland [4]. Besides its simplicity the major advantage of this design concept is that the loading due to wave, currents and ice can be clearly defined. Another aspect is the limited consumption of the ground, which is favourable for the ecological acceptance of an offshore wind farm. It is made up of concrete or steel and according to it, it termed as steel monopile or concrete monopile. The depth achieved by monopile is in the range of 25 to 30 m. It is a steel tabular structure and the manufacturing is simple and quick. The diameter varies from 6 to 8 m. The bearing capacity of monopile comprises of end bearing resistance and shaft skin friction. Figure 2 show the schematic diagram of the bearing resistance of monopile.

The design guidelines for monopiles are based on the standard p-y method of American Petroleum Institute (API) [5]. Many researchers have shown through finite element analyses that the standard p-y method overestimates the pile-soil-stiffness of large diameter monopiles at great depths which may result in an insufficient pile length [6].

For monopiles of large diameter meant for high design loads, the p-y curve method is found to underestimate pile deformations. The main reason for these results is probably an overestimation of the initial soil stiffness in large depths by the API method. Moreover, for a large-diameter pile the shearing resistance in the pile tip area may play an important role compared to small-diameter piles. Since this method is not verified by measurements at large-diameter piles, it should in general be not used for the design of monopile foundations. Thus, for the time being the execution of numerical investigations is recommended for the design of the large monopiles. The lateral loads on the monopile are counteracted by a pressure difference between both sides of the pile that is initiated by a displacement of the pile.

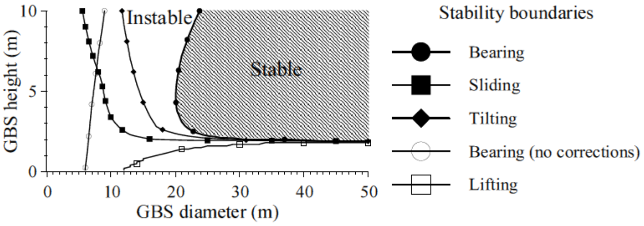

Figure 1. Stability boundaries for gravity based structures.

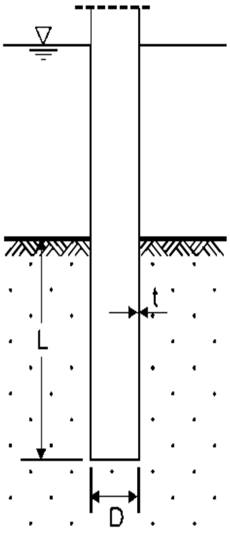

Figure 2. Schematic view of monopole.

The disadvantage of large diameter monopiles is that no proper design guidelines and installation methods are yet available. Large diameter also causes has problem of removal after completion of design life.

VI. SUCTION CAISSONS

It is a flat foundation with skirts around the periphery; rather like an upturned bucket Suction caissons have been extensively used as anchors, principally in clays, and have also been used as foundations for a small number of offshore platforms in the North Sea. Right now it is a very popular foundation option in the offshore oil industry. They are currently being considered as possible foundations for offshore wind turbines also. The first possible use of caissons as wind turbine foundation was described in 1995 [7].

Before 2002, all wind turbine foundations were mostly GBS or monopiles. Nowadays, due to its limited depth application, use of GBS is minimal. Due to increased capacity of wind turbines, it is necessary to go deeper in sea, where monopiles are preferred though no well-defined methods are available for design of monopiles having diameter more that 6 m. Under such circumstances, the need arises for new foundation concepts. It seems that these pitfalls can be overcome by using suction caissons as wind turbine foundation. Depending upon the size of turbine, caissons may be single or multiple.

In principle its behaviour can be considered as a combination of gravity base and pile foundation systems. There are two aspects to the engineering design of this foundation: installation method, and in-service performance. During installation the skirt is partially embedded under the self-weight of the caisson and structure. The installation is completed by reducing the water pressure inside the caisson, thus forcing the skirts into the seafloor. In clay the net downward force caused by the pressure differential inside and outside the caisson drives the bucket into the ground. In sand, the hydraulic gradients set up in the soil around the bucket skirt also contribute to the process, as they reduce the soil resistance at the skirt tip, and within the caisson, to almost zero, allowing the bucket to penetrate easily into even very dense sand. The complete installation procedure is illustrated in Figure 3. The depth limitation for suction caissons is typically 25 m. However, investigation is continuing for increasing the depth applications [8].

The cylindrical suction caisson has a cap that is sealed after installation. Since no active suction is applied after installation of the bucket, the geotechnical principles of axially loaded piles also apply here: skin friction and point resistance. Thus, the bearing capacity comprises of these two parameters. The point resistance of the pile tip is typically negligible, but the cap of the bucket causes very significant bearing capacity by pressing on the soil plug inside the bucket. Furthermore, it is assumed that the suction force is always sufficient to withstand dynamic loads, and that the relatively large static wind loading on the rotor and tower dominate the geotechnical design.

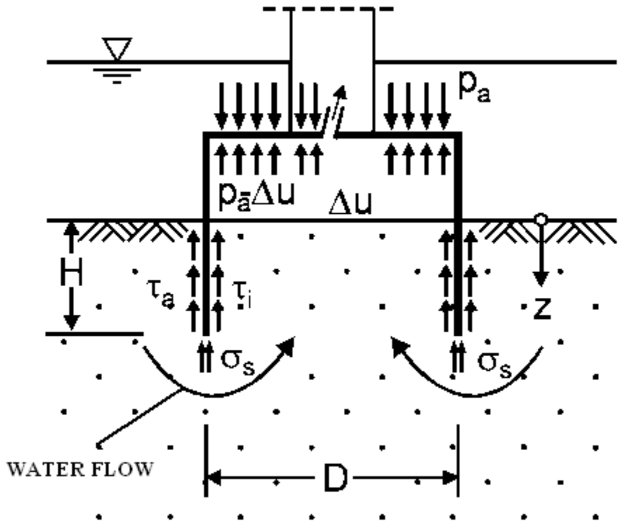

Figure 3. Installation method for suction caissons.

The study of suction caissons involves lab model testing, centrifuge test, field trials, numerical studies with plasticity based model etc. One important point of consideration is moment capacity of caissons as it transfers load by inducing moment. The advantages of suction caissons involve great depth application, simple manufacturing and transportations, easy installation and removal, low foundation cost, and increased horizontal load resistance capacity due to skirt resistance.

VII. TRIPOD/TETRAPOD WITH CAISSONS

As wind turbine size and depth application increases suction caissons diameter increases and practically becomes impossible to design such large size caissons. In such cases, the caissons can be used in multiples of 3 or 4 as a tripod or tetrapod [9]. They are connected with a steel 3-D truss structure (Fig. 4). The load transfer mechanism follows the push pull systems as shown in Fig. 5. The relative high moment is counteracted by a push-pull system between the caissons. Maximum pull force is critical for failure of this foundation. It is clear from the figure that design criteria include the diameter of caissons and the spacing between them.

The diameter of caissons is fixed by using regular API design methods of caissons. The distance between caissons in calculated by simple laws of mechanics by considering all applied forces and induced moment and vertical forces of caissons.

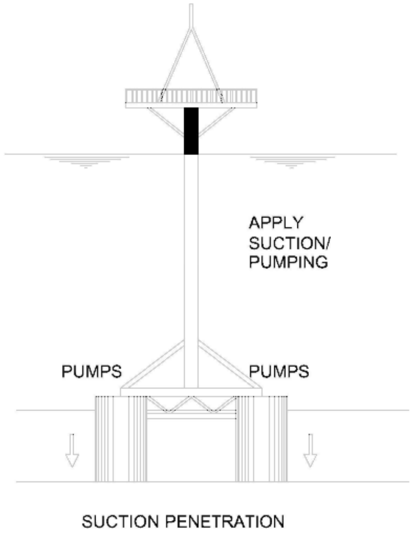

Figure 4. Tetrapod as wind turbine foundation.

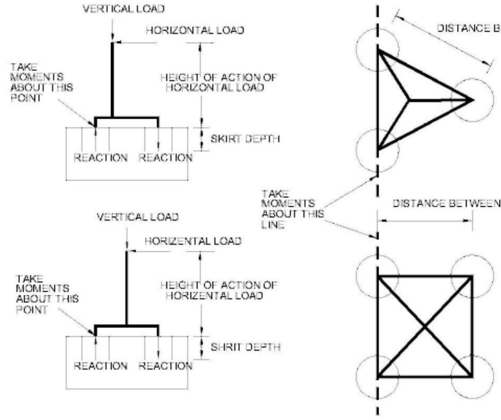

Figure 5. Load transfer mechanism for tripod and tetrapod foundation.

The main advantage is that they can be designed to withstand the loads occurring on offshore wind turbines even in relatively deep water up to 50 m [10]. They can also make the structure stiffer thereby decreasing the maximum deflection. The installation costs will be significantly lower than for other foundation types [11].

VIII. FLOATING PLATFORM

Till now whatever foundation systems are available for wind turbines, maximum depth can be up to 50 m. But nowadays there is requirement to go beyond this limits and the problem to this solution is replacement of fixed foundation with floating platform. The vision for large-scale offshore floating wind turbines was introduced in 1972 [12]. But it was not until the mid 1990's, after the commercial wind industry was well established, that the topic was taken up again by the mainstream research community.

The floating structure must provide enough buoyancy to support the weight of turbine and to restrain pitch, wave as well as roll motion within acceptable limits. The floating platform configurations may vary widely. Typically, the overall architecture of a floating platform will be determined by a first-order static stability analysis, although there are many other critical factors that will determine the size and character of the final design. However, once the platform topology has been established, a crude economic feasibility analysis becomes possible. Therefore, a classification system was developed that divides all platforms into three general categories based on the physical principle or strategy that is used to achieve static stability.

1) Ballast: Platforms that achieve stability by using ballast weights hung below a central buoyancy tank which creates a righting moment and high inertial resistance to pitch and roll and usually enough draft to offset heave motion. Spar-buoys like the one shown in Fig. 6 apply this strategy to achieve stability.

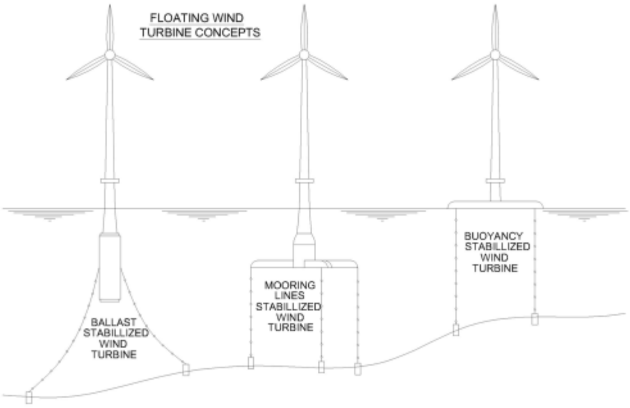

Figure 6. Types of floating platforms.

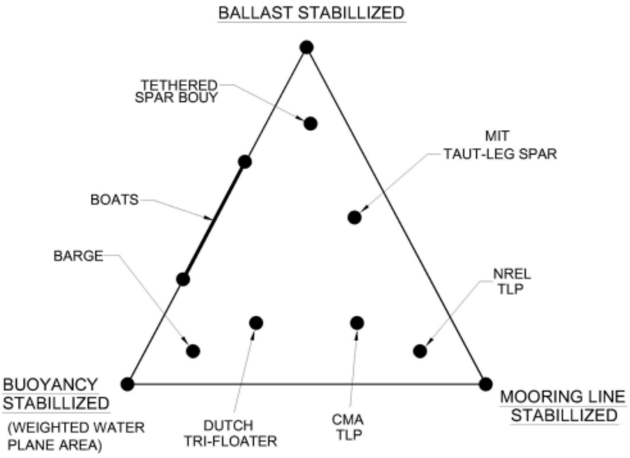

Figure 7. Floating platform stability triangle showing methods of achieving static stability.

2) Mooring Lines: Platforms that achieve stability through the use of mooring line tension. The tension leg platform (TLP), as shown in the centre of Fig. 6, relies on mooring line tension for righting stability.

3) Buoyancy: Platforms that achieve stability through the use of distributed buoyancy, taking advantage of weighted water plane area for righting moment (Fig. 6).

In practice, all floating concepts are actually hybrid designs that gain static stability from all three methods, although generally relying on one primary source for stability. Physical hybrid floating platform designs will almost exclusively lie inside the triangle, between the primary points (Fig. 7). Designers will seek the optimum platform from a unique balance of stability options that will achieve the best functionality and lowest cost [13].

One of the immediate challenges common to all support structure designs is the ability to predict loads and resulting dynamic responses of the coupled wind turbine and platform system to combined wave and wind loading. In the offshore environment, additional load sources impart new and difficult challenges for wind turbine analysts.

XI. JACKET STRUCTURES

The jacket foundation concept is widely used in the oil and gas industry, and has also found use in the offshore wind industry, e.g. in the Beatrice Offshore Wind Farm, Scotland [14]. As shown in Fig. 8, the jacket foundation concept consists of three parts: piles, jacket and transition piece [15].

The jacket is characterized by three or four legs stiffened with K-, N- or X-braces. It appears that the 4-legged jacket stiffened by X-braces and supported by main piles is particularly suitable for the offshore wind industry. The design therefore includes a 4-legged jacket and a concrete transition piece in the tower interface. Due to the much higher stiffness of a jacket structure, it has not been possible to keep the first natural frequency within the specified range. If the frequency must be lowered, a more slender tower is needed.

The behavior of jacket foundation is similar to behavior of fixed offshore structures. The advantage of jacket substructures is that they are not very sensitive to wave loading as the structure attracts only small wave loads and is very stiff. The benefits of using the jacket foundation concept are found to be a lower wave load, a higher level of stiffness and lower soil dependency. The design will therefore be suitable for installations in deeper water or in waters with high waves and at sites with poor soil. It is assumed that by using jacket structure as foundation, greater maximum depth application is feasible compared to all other foundation options available for wind turbines [14].

X. CONCLUSIONS

The design features, applications and limitations of various support options available for wind turbines have been described in the paper and a summary is presented in Table 1. Several conclusions have been made regarding the choice of foundation. But choice is site specific decision as various systems behave differently in different soil conditions.

From future research point of view, foundation which gives higher depth application should be more thoroughly analyzed and field-tested with prototype models. More attention should be given to suction caissons as it almost balances all parameters. In suction caissons research study, more emphasis should be given on moment capacity analysis, frictional bearing capacity analysis, effect of installation methods on bearing capacity, and design methods for large diameters suction caissons.

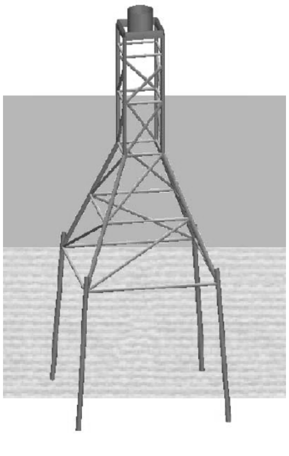

Figure 8. Jacket foundation.

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Table I. Comparison of available foundation systems

Comparison points	**Types of Foundations**					
	GBS	***Monopiles***	***Suction Caissons***	***Tripod / Tetrapod with Caissons***	***Floating Platform***	***Jacket Foundations***
Design Methods	Available	Available but for less than 6 m diameter	Available but for less than 6 m diameter	Available but for less than 6 m diameter	Research work in needed	Available (pile design)
Installation	Difficult	Moderate	Moderate	Moderate	Easy	Moderate
Manufacturing	No on site	Easy	Easy	Easy	Easy	Easy
Transportability	Difficult	Moderate	Moderate	Moderate	Easy	Moderate
Scour	Very high	Moderate	Moderate	Moderate	Less	Less
Dependency on subsoil condition	Very high	Moderate	Moderate	Moderate	Low	Low
Self weight	High	Less	Less	High	Less	Moderate
Depth application	5-10m	25-30m	25-30m	25-50m	More than 50m	Around 50m
Removal after design life	Difficult	Moderate	Easy	Easy	Easy	Moderate