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Analysis and Geotechnical Design of Hybrid Foundation for Tall Wind Turbine

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Abstract: The significance of wind turbines in meeting the expanding energy demand is critical. Taller towers should be employed to boost the power producing capability. The foundation must be efficient in order to securely carry the heavier loads of taller towers. When sustaining loads from superstructure are considered then bearing capacity of raft is taken into account for pile raft foundation. Piles help to strengthen the raft's bearing capacity while also regulating settlement in this arrangement, particularly differential settlement. A hybrid foundation, i.e. a pile raft foundation, is investigated and geotechnically designed here. The effectiveness of this system is demonstrated using the measures total settlement, differential settlement, and rotation.
Keywords: Pile raft foundation, differential settlement, total settlement, wind turbin, bearing capacity

I. INTRODUCTION

To satisfy the ever-increasing demand, wind turbine power output has risen dramatically during the last several decades. Various government bodies, companies, and research scientists from all over the world have worked tirelessly to enhance wind energy output. It is more environmentally sustainable than fossil fuels since the problems of hazardous gas emissions in the air, large quantity of waste generation, and greenhouse gas emissions are not connected with wind energy production. It has also been discovered to be reliable and effective source of electricity in terms of cost and efficiency if planned and constructed at most suitable site. Building wind turbine with greater heights to reach higher wind velocities is a cost-effective approach for increasing wind energy output. However, as the height increases, so does the size of the base and the design gets more complicated.

In a tower construction for wind turbine, the weight of the structure is very large and due to the stringent safety requirements, the allowable differential settlement of the structure is very small. Controlling differential and total settlements is critical. Differential settlement specially, can have a detrimental impact on superstructure by increasing internal stress and, have consequence like lessening service life of building. As a output within acceptable range are required. The several types of foundations are used to support wind turbines. P-R foundation is now globally used for reduction of an effective total and differential settlement for heavy loads. This foundation structure is composed of piles, and raft, with piles having the most important function in minimizing settlements. However, from an economical perspective, the settlement of this foundation is also in acceptable limits. However, from an economic standpoint, the settlements of P-R foundation should be regulated for an affordable design while achieving an safety.

The loading pattern, shape and dimensions of the raft, number of piles, c-c spacing in piles, radius and length of the piles, relative stiffness of system are all physical properties that directly affects settlement of a piled raft foundation. These qualities must be taken into account while calculating and designing a piled raft foundation.

In this paper piled-raft is studied thoroughly to withstand a wind turbine having 130 m hub height tower at wind farm location in Tamil Nadu. The pile raft foundation is discovered to be efficient foundation system for given site and loads.

II. GEOTECHNICAL DESIGN OF PILE-RAFT FOUNDATION

Pile raft is primarily used to increase the foundation's bearing capacity by using a raft and to reduce total and differential settlements by using deep foundations[1].The most difficult component of designing a pile-raft foundation, however, is quantifying the percentages of loads borne by the piles and the raft [1]. This problem arises mostly from a less knowledge of interaction between soil, raft, and piles. As a result, no reliable design guidelines exist, particularly for foundations subjected to lateral load, moment and vertical load. A preliminary design of the pile-raft foundation using geotechnical perspective is carried out in this work using Hemsley's (2000) approach, which included the procedures described by Poulos and Davis (1980) and Randolph (1994). The ultimate lateral, moment and vertical geotechnical capacities, total elastic and differential settlements, rotation of tower owing to wind load, and foundation lateral movement are all elements considered in the preliminary design [1].

In the preliminary design stage, raft's size also the number of piles and dimensions of pile need to meet the design requirements are calculated. The pile-raft foundation's capacity is tested for vertical, lateral, and bending loads, as well as total and differential settlements and rotation[1]. According to Hemsley (2000), a safety factor of minimum 2 is judged safe for the lateral, vertical load and bending moment, while a vertical misalignment of 3 mm/m is regarded safe for the rotational stability of tower (Grünberg and Göhlmann 2013). To automate the iterative calculations and undertake parametric experiments, a spreadsheet is created (Not shown).

A. Design for Vertical Load

The pile raft's vertical capacity is calculated as the minimum of 1) The sum of the ultimate capacities of the piles, Pu-P and the raft, Pu-R such that Pu-PR = Pu-P + Pu-R; and 2) The block's ultimate capacity Pu-B, made up of the piles and the raft plus the portion of the raft excluding portion up to outer perimeter of piles (Hemsley 2000). Vesic (1973, 1975) used the general bearing capacity equation to compute the raft's ultimate capacity Pu-R, and the piles' ultimate capacity Pu-P, is calculated as the total of all the piles' ultimate capacity in downward direction [1]. Pu-P = Np Pult-dn, here Np is number of piles and Pult-dn means single pile's ultimate downward capacity, which is the addition of the toe resistance, Pt and ultimate skin resistance Ps[1] . Das (2011) gave the methods for calculating the ultimate skin and toe resistance of a single pile in this work, which are utilised to determine the ultimate skin and toe resistance of a single pile. The vertical load safety factor is determined such as :

$$FS_P = \min \frac{(Pu-PR,\ Pu-B)}{P} \qquad (1)$$

Where P is design vertical load.

The ultimate vertical capacity determined by treating the piles and raft as a single block is found to be smaller than that obtained by summing the pile and raft's ultimate capacities [1]. The vertical load capacity's final factor of safety is calculated as 4.08, which is satisfied.

B. Design for the Moment Load

The pile-raft foundation's ultimate moment capacity is calculated as the lesser of 1) the ultimate moment capacity of a block containing the piles, raft, and soil 2) the raft plus the piles' ultimate moment capacity [2]. Using the approach described in Hemsley, the ultimate moment capacity of the pile group, raft, and block of the pile raft are determined (2000) [1] . For the sake of thoroughness, the main equations are summarized in the subsections below.

1) Case1- Pile Raft's Ultimate Moment Capacity Considering Individual Capacity:

Using Eq.(2)(Hemsley2000), the raft's ultimate moment capacity, Mu-R, is computed as follows:

$$\frac{Mur}{Mm} = \frac{27}{4}.\frac{P}{Pu}.[1 - \frac{P}{Pu}^{(\frac{1}{2})}] \qquad (2)$$

where Mm is the maximum moment supported by the soil; When no moment is applied, P is applied vertical load; Pu is ultimate centric load on the raft.

The maximum moment for a circular raft, Mm, is calculated as,

$$Mm = \frac{quD^3}{4}.(\frac{\pi}{4} - \frac{1}{3}) \qquad (3)$$

Where qu = the raft's ultimate carrying capacity and D = diameter of the circular raft. Using Eq.(4)(Hemsley2000), the ultimate moment of all the piles Mu-P, is calculated as follows:

$$Mup = \sum_{i=1}^{Np} Puui\ |xi| \qquad (4)$$

Where Puui is the pile's ultimate uplift capacity, |xi| is the pile's absolute distance from the group's centre, and Np is the number of piles.

In terms of individual capacity, pile raft's ultimate moment capacity, Mu-PR, system is given by

$$M_{u-PR} = Mu_{-R} + Mu_{-P} \qquad (5)$$

2) Case2- Pile Raft's Ultimate Moment Capacity Considered as a Single Block:

Using Eq.(6) (Hemsley 2000), the block's ultimate moment capacity, a single unit comprising of the raft and the piles, MuB, is calculated as follows:

$$Mub = \alpha_B\, \overline{p}u\, B_B\, D^2_B \qquad (6)$$

Where BB and DB denote the block's width and depth, respectively; pu = soil lateral resistance averaged over the block; and α_B = factor based on the ultimate horizontal pressure distribution with respect to depth (0.25 for a constant pu distribution and 0.2 for a linearly varying pu with depth from zero at the surface). It's worth noting that Eq. (6) for designing raft and pile layout which is rectangular in shape, is presented [1]. However, because the raft considered in this study is circular in shape, it is converted to an equivalent rectangular section in order to use Eq. (6) to compute the block's moment capacity [1].

a) Ultimate Moment Capacity of the Pile Raft: The ultimate moment capacity computed for Case 2 is smaller than that for Case 1, it is determined that the design is regulated by block failure. Using Eq. (7), the FOS for the moment capacity is calculated as 2.2, which is satisfied.

$$FS_M = \frac{\min(Mu-pr\ ,\ Mub)}{M} \qquad (7)$$

C. Design for lateral Load

Broms' solutions for cohesive soil, as detailed in Gudmundsdottir, are used to calculate the lateral pile capacity (1981). The horizontal coefficient of the subgrade reaction is used to compute the ultimate lateral load capacity and lateral deflection of a pile [3]. It was expected that when a lateral load was applied to all of the piles, they would all behave in the same way. As a result, a pile group's ultimate lateral load capacity is calculated as the total of the lateral capacities of all the piles [1]. That is,Vu-PR = n Vu-P. Eq. (8) is used to compute the safety factor for the lateral load:

$$FS_V = \frac{Vupr}{V} \qquad (8)$$

The safety factor is found to be 7.827 which is satisfied.

D. Total Settlement

1) Elastic Settlement: The pile-raft foundation's vertical load against total elastic settlement response is calculated using Poulos' (2001b) methodology in combination with Randolph's approach of determining load sharing between the piles and the raft (1994). The stiffnesses of the raft, piles, and pile raft can be used to predict load sharing between the piles and the raft [1]. The stiffness of the pile raft i.e. Kpr is calculated using Randolph's (1994) Eq.(9) and written as

Kpr = X Kp

$$\text{Where } X = \frac{1+(1-2\alpha rp)Kr/Kp}{1-\alpha rp^2\left(\frac{Kr}{Kp}\right)} \qquad (9)$$

Where Kr = raft's stiffness, Kp = pile group's stiffness, and rp is the raft-pile interaction factor. The raft-pile interaction factor is assumed to be 0.8 because, according to Randolph, as the number of piles in the group grows, the interaction factor grows and tends toward a constant value of 0.8(1994) [1]. The Randolph's approach (1994) is used among the many ways to determine raft stiffness. The method suggested by Poulos (2001b) is utilised to calculate the pile group's stiffness. To begin, the pile raft's desired stiffness is calculated as division between the entire vertical load and the projected permitted settlement. The stiffness of the pile group is then determined using Eq. (9), with the pile raft's stiffness continuing in effect until the pile capacity is totally utilized at load P_A [1]. The axial load versus total settlement correlation is used to calculate the load versus settlement curve for the P-R foundation is obtained using defined by Eq. (10), as follows:

$$\text{For } P \le Pa\ ;\ S = \frac{P}{Kpr}$$

$$\text{For } P > Pa\ ;\ S = \frac{Pa}{Kpr} + \frac{P-Pa}{Kr} \qquad (10)$$

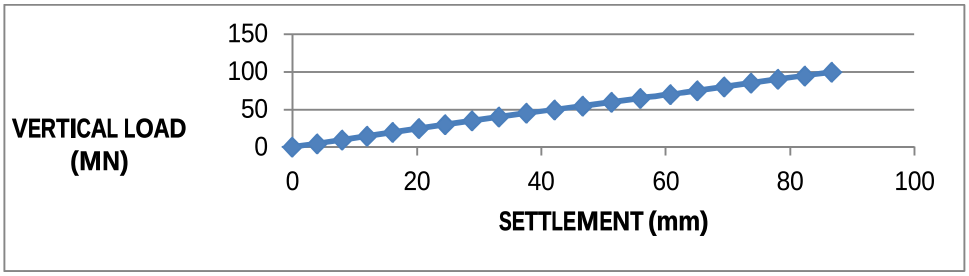

Fig.1. Load versus total settlement curve.

The total settlement of the P-R at a total vertical load of 53.42 MN is found to be 45.25 mm using the load versus total settlement curve.

2) *Differential Settlement and Rotation:* There is no precise approach for determining the differential settling of a P-R foundation system subjected to a moment. The differential settlement of a P-R foundation is calculated using a new method provided in this paper. The percentages of bending moments borne by the raft and piles are modified in this approach until the differential settlements of both are equal, which is referred to as the pile-raft foundation differential settlement [1]. In practice, the piles are fixed to the raft's bottom, and the piles' and raft's rotations are identical[1]. The concept of modifying the weights until the rotations are same is similar to the condition on field.

a) *Differential Settlement of the Raft:* To compute this settlement, Grünberg and Göhlmann (2013) used Eq. (11) to calculate the raft's rotation, θ_{RAFT} from the wind load:

$$\theta_{RAFT} = \frac{Mraft}{Cs\ Iraft};\quad Cs = \frac{Es}{f'\sqrt{Araft}} \qquad (11)$$

Where M_{Raft} is the fixed-end moment at the soil-structure interface; c_s is the foundation modulus; I_{Raft} is the second moment of inertia; Es is the modulus of elasticity of soil; f' is the shape factor for overturning (0.25); and A_{Raft} is the area of the foundation. After computing θ_{RAFT}, the differential settlement of the raft is calculated using a simple relationship that the raft rotates about its centerline [1].

b) *Differential Settlement of Piles:* Pile group's differential settlement is calculated using the Fellenius approach, which is published in Coduto, based on the single pile-settlement profile due to the resultant vertical load caused by the moment borne by the piles (2001) [1]. The difference or sum of the loads due to the dead load and the vertical load caused by the moment is used to compute the resultant vertical loads operating on each pile [2]. The differential settlement of the piles is then defined as the difference in pile settlement of the piles lying in the outer periphery in the direction of the moment[1].

c) *Differential Settlement of the Pile Raft:* The MRaft and MPiles values are modified until the raft and pile difference settlements are equal. The differential settlement is judged to be the differential settlement of the P-R foundation, with the associated final values being the moment sustained by the piles and the raft. This exercise produced a differential settlement of 17.04 mm and a θ of 0.00095 radian which is within the range.

III. DESIGN OUTCOME

The end result is a raft with a radius of 8.0 metre, a thickness of 1.0 metre, and a depth of 1.5 metre. The raft is supported by 36 precast concrete piles with a width of 0.6 m and a length of 15 m, evenly spaced within 5.8 m and 7.2 m inner and outer circumferences. Figure depicts the final design.

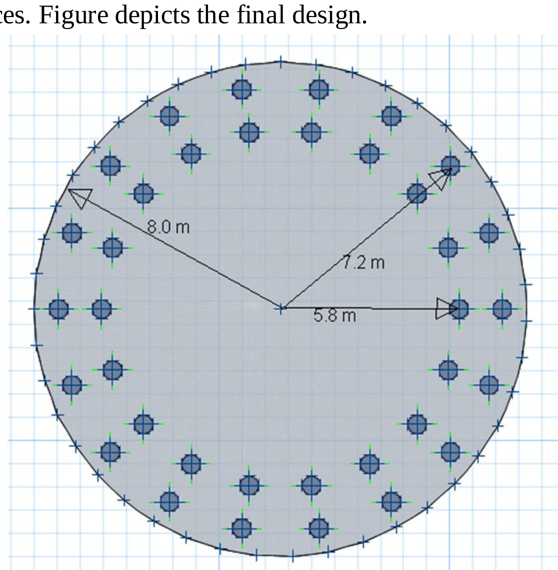

Fig. 2. Plan of Pile raft foundation

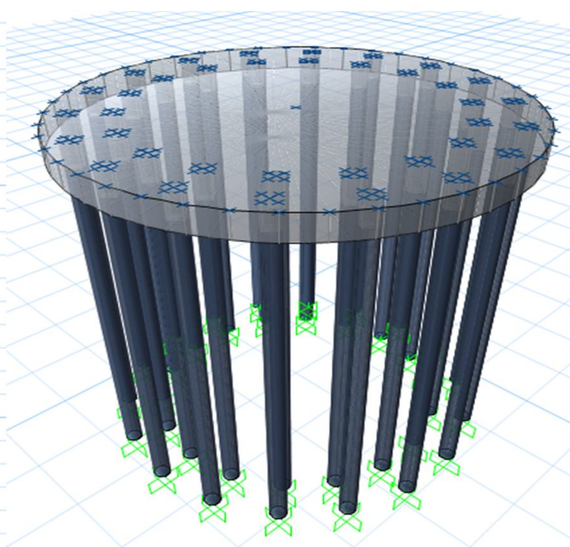

Fig. 3. 3D View of Pile raft foundation

IV. RESULTS AND DISCUSSION

A. FOS for Vertical load is calculated as 4.08 i.e. >2 hence it is satisfied.

B. Pile Raft's Ultimate Moment Capacity by Considering Individual Capacity is 789864.8 KNm, Pile Raft's Ultimate Moment Capacity by considering as a Single Block is 759375.0 KNm and FOS for moment capacity is 2.2 i.e. >2 hence it is satisfied.

C. FOS for lateral load is is calculated as 7.82 i.e. >2 hence it is satisfied.

D. The total settlement of the P-R at a load of 53.42 MN is found to be 45.25 mm using the load versus total settlement curve. It is less than 50mm, hence it is satisfied.

E. Differential Settlement of the Pile Raft is determined as 17.04 mm.

F. Rotation of the Pile Raft is determined as 0.00095 radians.

V. CONCLUSION

This study examines the analysis and geotechnical design of pile raft foundations. In this study the parameters such as total settlement, differential settlement and rotation are found out. By considering results, it is found that pile raft is effective foundation system to carry heavy load due to wind turbine.

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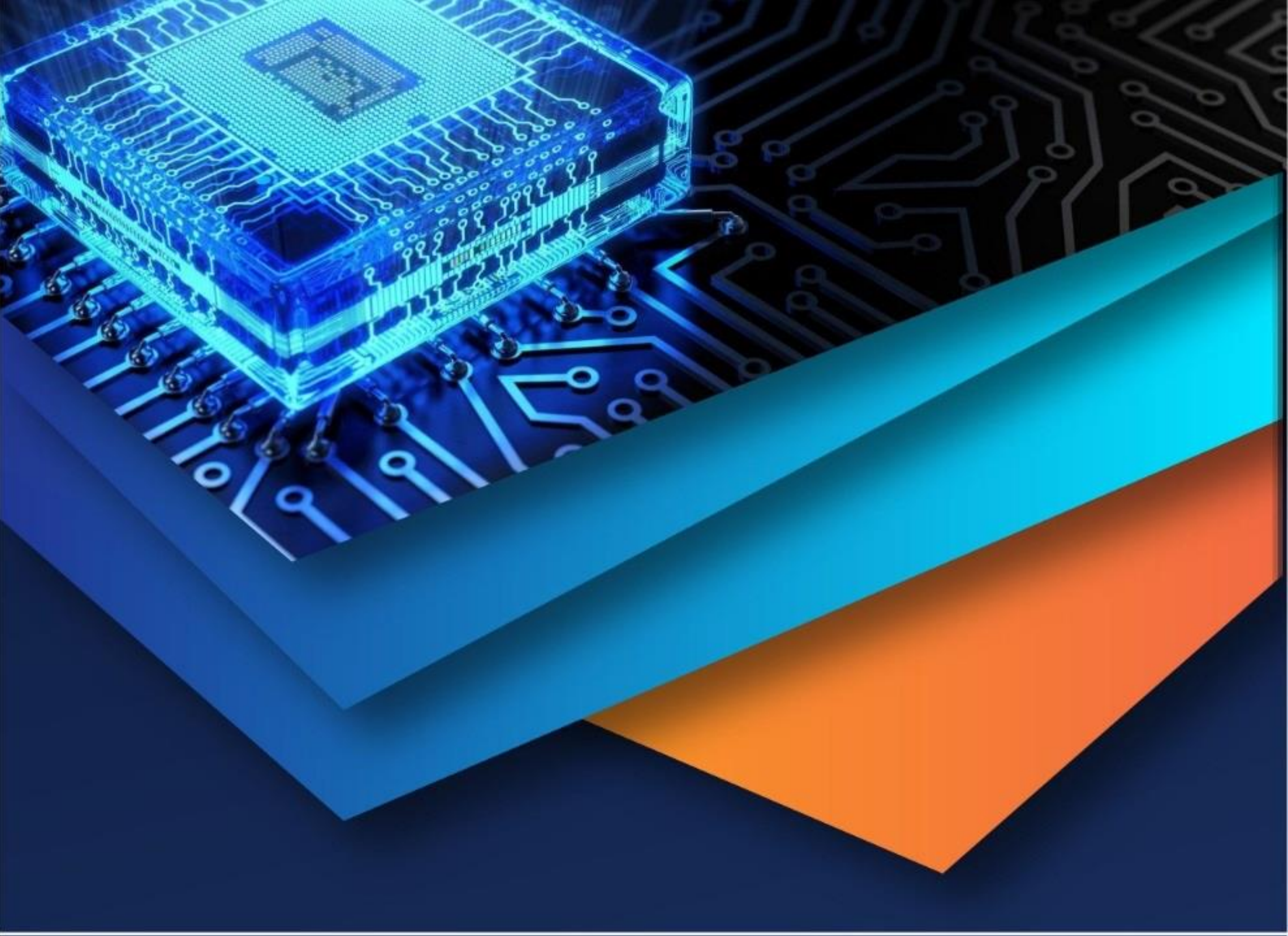

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