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# OPTIMIZATION OF WIND TURBINE FOUNDATIONS FOR POOR SOIL

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**Abstract.** *One of the most important constraints on large-scale civil engineering projects is economic feasibility. All projects are restricted by the cost of construction and materials. A cost analysis of alternative foundation designs for wind turbines is done in this work to aid the choice of design solution. The suitability of different foundation types are compared including a novel solution, with a circular raft surrounded by a water tank for soil with poor properties. In this work cost and behavior comparisons are done for two foundation solutions, namely a piled raft and a circular raft surrounded by a water tank. An observed soil profile found in Gothenburg region, Sweden is used. The soil profile is implemented in the FE software Abaqus to find out the validity of using the different types of foundations on the mentioned type of soil. In terms of settlement and tilting it is shown that there is a good effect of using a water tank surrounding the ordinary circular raft for the actual soil profile in the Gothenburg region. For the cost issue, the analysis was carried out to calculate the whole foundation cost for a circular raft surrounded by a water tank and also for a piled raft. It is shown that using the new foundation system decrease the foundation cost compared to using piled raft with pile length = 28 m and one meter square pile. The effect of dynamic loads was also investigated and the results showed that the complete system, using circular raft surrounded by a water tank as a foundation, successfully avoids resonance through the rotor excitations.*

## 1 INTRODUCTION

The main aim of this study is: (1) reducing the onshore wind turbine foundation costs for poor soil by using a new foundation system instead of piled raft, and (2) checking the dynamic response of the new foundation system.

As expected the overall weight of wind turbine supporting structure components is reduced due to minimizing the costs. Moreover, the wind turbine supporting structure will be more sensitive to dynamic loads. In addition, soft soils have an influence on the dynamic response of the whole structure system. One of the methods that are used to analyze the soil-structure interaction effects is the finite-element method taking the entire system (structure, foundation and soil) into account. A dynamic FE analysis is presented in this study.

Initially, Gothenburg is considered as one of the best areas with good wind speed to build a wind farm in Sweden. Unfortunately, Gothenburg area has soft clay layer from the ground surface down to 40 m. The problem of soil containing deep clay layers is found in many cities around the world. Examples of cities are London in England, Frankfurt in Germany, Port-Said in Egypt and Taipei in Taiwan. The main conclusion from lots of studies is that the classical foundation solution for soil with poor properties is using a piled foundation. It is expected that the foundation cost percentage will increase a lot if the soil has poor geotechnical properties. Therefore, new solutions may be advantageous economically instead of using piled raft.

A study on cost-benefit analysis of wind energy showed that onshore wind turbine foundation without piling make up about 3% of the total costs [11]. Another study showed that onshore wind turbine supporting structures costs approximately 1% to 9% of the total costs [13]. Considering a piled foundation on the other hand an economic evaluation was made in [6] that showed that the major cost was the wind turbine itself 60% and the piled foundation 28.3%.

According to [2] soil-structure interaction had a significant effect for soils which have shear wave velocity lower than 750 m/s and this effect could lead to reduction in response. A study on soil-structure interaction for wind turbine showed that considering soil-structure interaction is very a vital aspect in order to make it possible stay away from entering the resonance range [7]. According to [3] depending on the output power capacity of the wind turbines, the rotational speeds range for blades are from 30 to 60 rpm, which correspond to maximum operational frequencies from 0.5 to 1 Hz. Moreover, these operational frequencies are close to the soil–structure natural frequency range [3].

In this work a parametric study of cost and behavior of two foundation solutions, a circular raft surrounded by a water tank and a piled raft, are performed. The load conditions are based on usual loads for a 2 MW wind turbine considering Gothenburg ground conditions.

## 2 MATERIAL PROPERTIES AND LOADS

The main characteristics of soil and load sets will be illustrated in this section. The geotechnical material model adopted in this study is the Mohr-Coulomb model [9]. The soil parameter values of the soil can be seen in Table 1. The values are from an actual case and Poisson's ratio of the soil equals $\nu_s$ = 0.3 based on [8]. The backfilled soil ($\gamma$ =18 kN/m$^3$) is assumed to be up to natural ground level.

Two sets of loads are given; serviceability limit state (SLS), and ultimate limit state (ULS) loads for Vestas V90-2.0 MW wind turbine. Each set contains a vertical load *N*, a horizontal load *H*, a bending moment *M* and a torsion moment $M_z$. A three-bladed turbine with a blade length of 44 m which gives a rotating diameter of 90 m (wind catching area is of 6362 m2) is used [14]. The wind turbine tower height is 80 m [12]. The load sets is presented in Table 1 based on [12], while the definitions of the loads can be seen in Figure 1. Fatigue is not included in this study.

**Table 1** Material properties and loads

| I. Soil Parameters | | | | | |
|---|---|---|---|---|---|
| Description | depth Z (m) | Unit weight γ (kN/m³) | Young's modulus E (KPa) | Internal friction angle Ǿ (°) | Cohesion c' ( KPa ) |
| Soft clay | 40 | 17 | 5000 | 30 | 1 |

| II. Reinforcement concrete material parameters | | | | | |
|---|---|---|---|---|---|
| Concrete class is C30/37 | | | Reinforcement | | |
| Young's modulus $E_b$ (kN/m²) | Poisson's ratio $v_b$ | Unit weight $\gamma_b$ (kN/m³) | Yield stress $f_{yk}$ (MPa) | Design Yield stress $f_s$ (MPa) | Young's modulus $E_s$ (GPa) |
| $3.3 * 10^7$ | 0.2 | 25 | 500 | 435 | 200 |

| III. Tower loads, characteristic values | | | | | |
|---|---|---|---|---|---|
| Load set | Type of limit state | Load set | | | |
| | | $N$ (kN) | $H$ (kN) | $M$ (kNm) | $M_z$ (kNm) |
| I | SLS | 3510 | 482 | 35108 | 303 |
| II | ULS | 3510 | 797 | 63825 | 1642 |

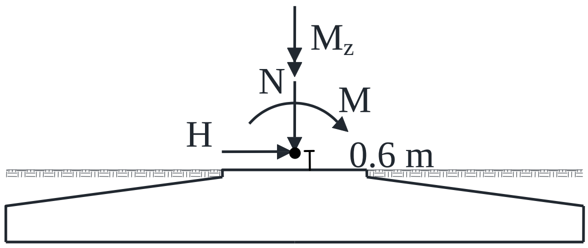


**Figure 1** Definition of load denotations [10]

## 3 FOUNDATION DESCRIPTION

The analysis was carried out for two types of foundation solutions as shown in Figure 2 and Figure 3. It is a piled raft and the new solution is a circular raft surrounded by a water tank. The aim is to check the validity of using a circular raft surrounded by a water tank on a poor soil that contains deep soft clay layer as an alternative to using a piled raft. The new solution is expected to be less expensive in order to pass requirements on settlement and differential settlement.

### 3.1 Piled raft

A piled raft is a raft foundation that has piles to reduce the settlement. The raft foundation and the piles are designed to cooperate to ensure that the settlement does not exceeded the allowable settlement value. The following characteristics were kept constant in all analysis cases: raft diameter $D$ is equal 22.5 m. square piles are placed below the surface foundations, with $a_{pile}$= 1.0 m and pile spacing $s$ = 2.4 m. Piles are located symmetrically along one ring with $D_{ring}$ = 18.5 m. However, the analysis was carried out for variations in one foundation variable, namely pile length $L_p$ = 16, 20, 24 and 28 m. Figure 2 shows the geometry and dimensions of the piled raft.

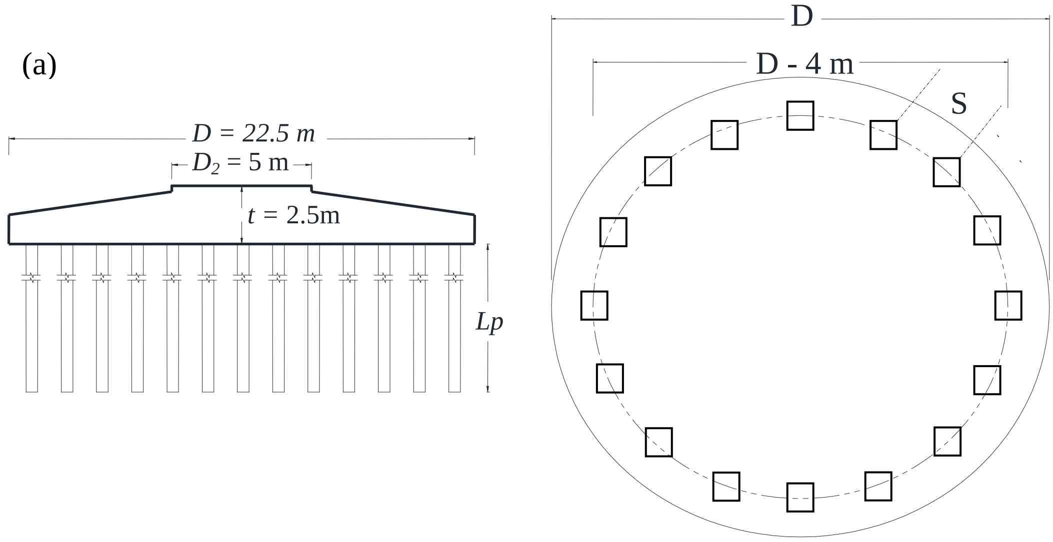


**Figure 2** Piled raft

### 3.2 Circular raft surrounded by a water tank

For a circular raft with a water tank, the idea is to use water as a load to give a stabilizing moment to resist the overturning moment. The reason for using water is the ease of moving water with wind turbine movement. The water tank is divided into four parts and only one or two parts will contain water and all parts are connecting with an active system to move water between parts, see Appendix. To get a big resistant moment with light weight (water load), a big water volume must be used. Figure 3 shows more details of the geometry and dimensions of the circular raft foundation surrounded by a water tank that are used in this study.

The following characteristics were kept constant in all analysis cases: circular raft diameter $D$ equal to 14.5 m, total thickness of the inner part $t$ = 2.50 m and the diameter of upper cylinder equal to $D_2$ = 5 m. Vertical tank wall thickness increase from 0.25 m in the upper part to 0.75 m for $H_{tank}$ = 5.0 m in the lower part, the upper slab thickness is 0.25 m and the lower slab thickness is 0.75 m. However, the analysis was carried out for variations in one foundation variable, namely the tank width $B_{tank}$ = 4.0 and 5.0 m.

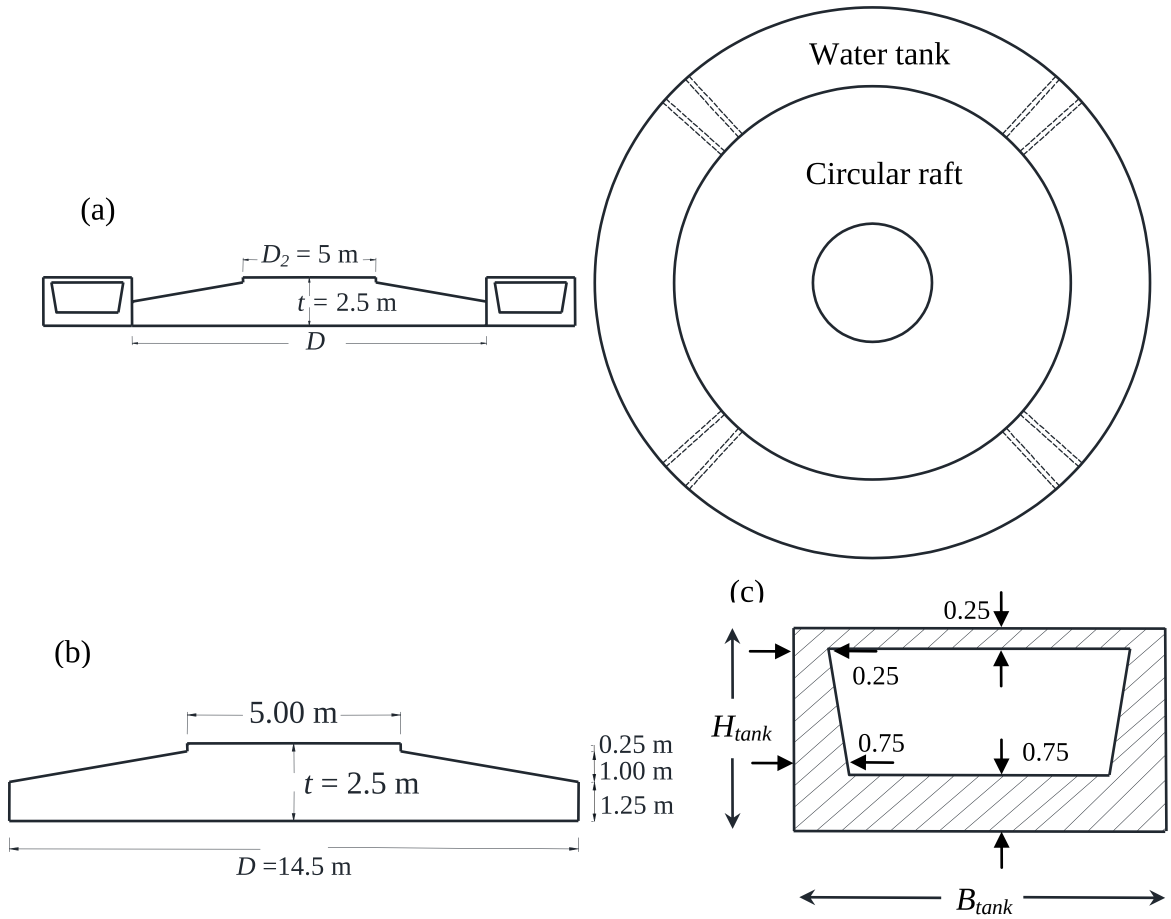


**Figure 3** (a) Circular raft surrounded by a water tank, (b) Vertical section for a circular raft, and (c) Vertical section for a water tank

## 4 FE MODEL

A three dimensional finite element model of the foundation-soil system was created using *ABAQUS* [4]. For the soil model, the computational region chosen is 100*100*50 m where the depth in z direction is 50 m. C3D20R element was selected using a fine grid around the raft and a coarse grid for the far field. The geotechnical material model adopted in this article is the Mohr-Coulomb model [9] with parameters according to Table 1. Full interaction was assumed between the soil and the half of the foundation (the compression side) and surface contact interaction was used between the foundation and the soil in the other half (the tension side) to allow the foundation to elevate without any tension at the interface.

### 4.1 FE verification for the shallow foundation

One case was studied and compared with the results in figure 5.10 on Svensson work [12]. Svensson analyzed a circular raft on moraine soil using 2D FE model in Plaxis and showed that the tilting for a circular raft on moraine soil equal to 1.25 cm, the maximum settlement equal to 1.3 cm and the minimum settlement is 0.05 cm. In this study, 3D FE model is established in Abaqus with the same foundation dimensions and soil properties. For the soil model, the computational region chosen is 100*100*50 m where the depth in z direction is 50 m. The

FE model result is: tilting equal to 1.13 cm with 9.6% deviation, the maximum settlement equal to 1.24 cm and the minimum settlement is 0.11 cm.

### 4.2 FE verification for the deep foundation

One case was studied and compared with the results in Figure 9 and Figure 12 on Abdel Glil work [1] for raft thickness equal to 1.1 m, pile length is 24 m, pile spacing is 2 and pile diameter equal to 0.5 m. Abdel Glil calculates the maximum and differential settlements by using ELPLA software. Abdel Glil calculates the maximum settlement (12.6 cm) and the differential settlement (1.89 cm) [1]. In this study, 3D FE model is established in Abaqus with the same foundation dimensions and soil properties. For the soil model, the computational region chosen is 100*100*50 m where the depth in z direction is 50 m. The FE model result is: deferential settlement equal to 2.13 cm with 11.3% deviation, the maximum settlement equal to 13.36 cm with 5.7 % deviation.

## 5 SETTLEMENT AND DIFFERENTIAL SETTLEMENT

As mentioned above, the maximum settlement and differential settlement ($\Delta S = S_{max} - S_{min}$) for the new system is tested considering specifically the poor ground properties near Gothenburg city, Sweden and compared with a piled raft. Table 2 presents differential settlement and the reduction of differential settlement values for a circular raft surrounded by a water tank and a piled raft. The reduction of differential settlement $H_s$, which is given by:

$$H_s = [1 - (\Delta S_{rwt} / \Delta S_{pr})] \cdot 100 \qquad (2)$$

where $\Delta S_{rwt}$ is the differential settlement of the circular raft with a water tank, and $\Delta S_{pr}$ is the differential settlement of the piled raft. Figure 4 shows maximum and minimum settlements for the circular raft surrounded by a water tank and the piled raft.

**Table 2** Differential settlement (cm) and the reduction of differential settlement

| $B_{tank}$ | | $L_p$ =16 m | | $L_p$ =20 m | | $L_p$ =24 m | | $L_p$ =28 m | |
|---|---|---|---|---|---|---|---|---|---|
| | $\Delta S_{rwt}$ | $\Delta S_{pr}$ | $H_s$ % | $\Delta S_{pr}$ | $H_s$ % | $\Delta S_{pr}$ | $H_s$ % | $\Delta S_{pr}$ | $H_s$ % |
| 4 m | 2.76 | 3.76 | 26.6 | 3.29 | 16.1 | 2.78 | 0.72 | 2.27 | -21.6 |
| 5 m | 1.57 | | 58.2 | | 52.2 | | 43.5 | | 30.8 |

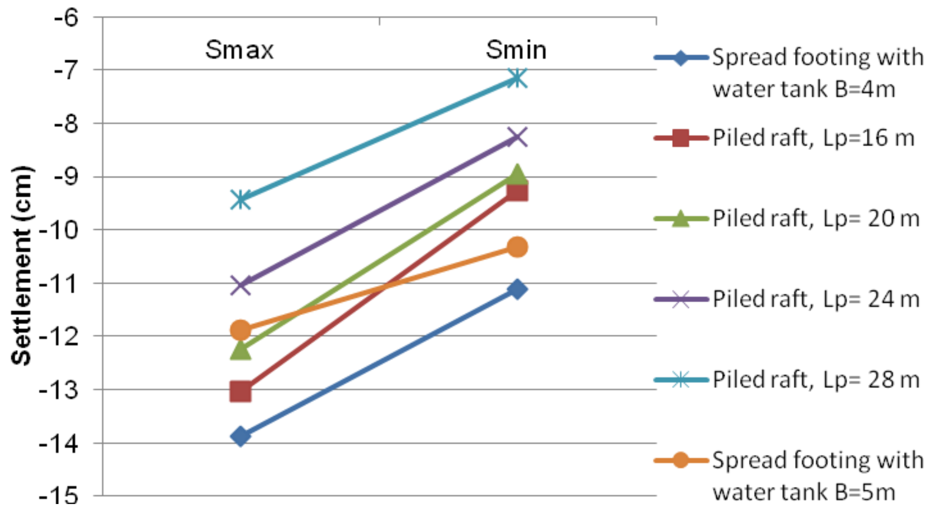


**Figure 4** Maximum and minimum settlement for piled raft and circular raft with a water tank

From Table 2 and Figure 4, it can be concluded that

- Using a water tank surrounding a circular raft decreases the differential settlement compared to a piled raft.
- Using a circular raft surrounded by a water tank with $B_{tank}$ = 5 m decreases the differential settlement by 30% compared to a piled raft with pile length $L_p$ = 28 m.
- Using a circular raft surrounded by a water tank with $B_{tank}$ = 5 m increases the maximum settlement by 26% compared to a piled raft with pile length $L_p$ = 28 m but it is lower than the allowable settlement for shallow foundation.

## 6 COST COMPARISON BETWEEN THE FOUNDATION SYSTEMS

The analysis is carried out to calculate the cost of reinforcement concrete, water system and pilling for spread footing surrounded by water tank and piled raft. For reinforcement in piles, the calculation use 12 bars Ø 16 mm have to provide in a regular pattern and 125 mm for lateral tie spacing. Table 3 shows comparison between the foundation systems. The comparison is depending on estimate cost comparison according to [10] and Peter Alheid (Geo-constructor at Hercules Grundläggning AB).

**Table 3** Cost comparison between raft surrounded by water tank and piled raft

| | Piled raft | Circular raft surrounded by a water tank | Cost in Sweden (USD) |
|---|---|---|---|
| Volume of Rein-forcement concrete ($m^3$) | 670.4 | 1002 | 230/$m^3$ |
| Steel weight (tons) | 48 | 57.5 | 2167/ton |
| Pile (drilling + mate-rial) (m) | 672 | 0 | 893/m |
| Excavation ($m^3$) | 994 | 1945 | 17/$m^3$ |
| Water system | 0 | 8 motors + 12 pipes + 128 electric valves | 208000 |
| Total Cost (USD) | 876546 | 596128 | |

From Table 3, by using the new foundation system in Gothenburg region the foundation cost decreases by 32 % compared to using piled raft with pile length of 28 m and square pile of 1.0 meter square.

## 7 DYNAMIC ANALYSIS

Wind turbine supporting structure systems are sensitive to dynamic loading conditions. Figure 5 shows a summary of the typical forcing frequencies applied to a Vestas V90-2MW wind turbine system [14]: the 1P frequency means the rotational frequency of the turbine, and the 3P frequency means the blade-passing frequency. A summary of the engineering properties of the turbine is presented in Table 4.

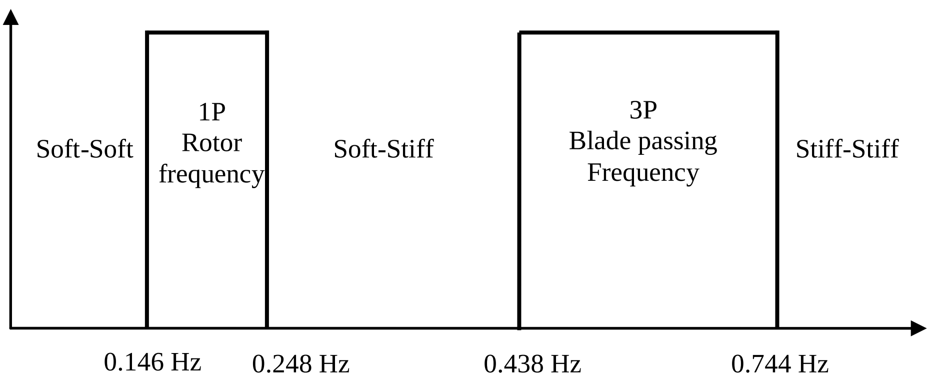


**Figure 5** Forcing frequencies plotted against power spectral density for Vestas V90-2.0 MW wind turbine.

**Table 4** Turbine Properties.

| Property | value |
|---|---|
| Rated power | 2.0 MW |
| Cut-in wind speed | 4 m/sec. |
| Rotor diameter | 90 m |
| Tower height | 80 m |
| Lower section diameter | 4.15 m |
| Top section diameter | 3.15 m |
| Tower wall thickness | 22 mm |
| Tower mass | 156 t |
| Nacelle mass | 68 t |
| Rotor mass | 38 t |

A full 3D finite element model of the tower-foundation-soil system was created using ABAQUS [4]. Initially, the soil, foundation and tower were modeled using quadratic 3D stress elements (C3D20). Infinite element (CIN3D12) was used for soil boundary. Nacelle, rotor and blade masses modeled using mass point, see Figure 6. In this case, steady- state dynamics step, which can be used to analyze linear problems, have been used to calculate the first and the second natural frequency for the whole system by putting harmonic loads in three directions at the top of the tower and seeing the response at many points.

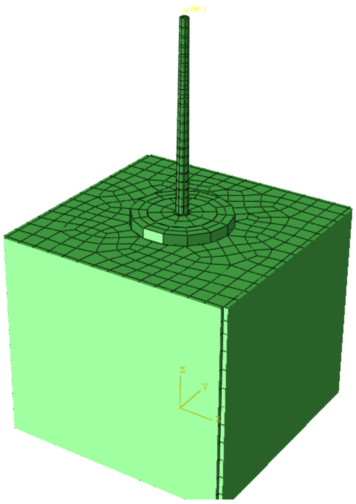

**Figure 6** Meshed 3D model using Infinite elements as a boundary condition

Table 5 presents the frequencies for the first and second mode of vibration obtained from the dynamic analysis for a circular raft surrounded by a water tank, and a piled raft with $L_p$ = 28 m. The results show that the structure-foundation-soil system, using the new foundation system, successfully avoids resonance during the rotor excitations.

**Table 5** Frequencies and periods of vibration

| Mode of vibration | Frequency (Hz) | Frequency +10% (Hz) | Frequency -10% (Hz) | Period of vibration (s) | Rotor frequency (Hz) | Blade passing frequency (Hz) |
|---|---|---|---|---|---|---|
| For a circular raft with a water tank | | | | | | |
| 1 | 0.3 | 0.33 | 0.27 | 3.33 | 0.146-0.248 | 0.438-0.744 |
| 2 | 1.08 | 1.188 | 0.972 | 0.93 | | |
| For a piled raft with $L_p$ = 28 m | | | | | | |
| 1 | 0.38 | 0.418 | 0.342 | 2.63 | 0.146-0.248 | 0.438-0.744 |
| 2 | 1.23 | 1.353 | 1.107 | 0.81 | | |

## 8 CONCLUSIONS

In this work, a new solution is developed to decrease the cost of wind turbine foundations for poor soils. Using a water tank surrounding the raft decreases the cost and differential settlement problems compared to using a piled raft. Considering specifically the poor ground properties near Gothenburg city, the whole foundation cost for a circular raft surrounded by a water tank was compared to an ordinary piled raft. In this analysis actual costs were determined considering local Swedish construction cost levels. The results revealed that using the new foundation system in Gothenburg city region can decrease the foundation cost by 32% compared to using a piled raft with pile length of 28 m and square piles of 1.0 m side. Differential settlement problem is one of the biggest challenges for designing wind turbine foundations for poor soils. Using a circular raft surrounding by a water tank with $B_{tank}$ = 5 m decreases the differential settlement by 30% compared to a piled raft with pile length $L_p$ = 28 m. However, the settlement increases by 26% compared to a piled raft with pile length $L_p$ = 28 m but is still lower than the allowable settlement value for a shallow foundation. Secondly, the effect of dynamic loads was also investigated and the results showed that the structure-foundation-soil system, using a circular raft surrounded by a water tank, successfully avoids resonance during the rotor excitations.

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## Appendix

### Water movement system

The water system depends on 8 motors and 15 pipes (10 inches) with electric valves buried in the tank lower slab, the system is designed with 7 working motors and one motor is for safety to move the half volume of water and pipes will move the other half, see Figure 7. According to [5] required motor horsepower is calculated from the following equation:

$$\text{Motor HP} = \rho\ g\ Q\ H / \mu$$

where: $\rho$ is water density (Kg/m$^3$), $Q$ is water discharge (m$^3$/s), $H$ is the total head (m), $g$ is the acceleration due to gravity (m/s$^2$) and $\mu$ is motor efficiency ($\mu$ = 0.8).

Water system design is carried out for some constant values such as tank width $B_{tank}$ = 5.0 m, tank depth $D_{tank}$ = 5 m and water volume = 275 m$^3$. Between all parts there are two pipes to move air from the part which is intended to be filled to the other part which is intended to be emptied. Water movement will depend on rotor hub position which depends on wind direction in Gothenburg city. Figure 8 shows the reference line and angles which used to move water from one part to the other parts. Table 6 presents the location of the water according to the rotor hub position. Control system for the water movement system deals with wind direction and wind speed sensors that used in yaw system in wind turbines. This system needs 7 motors (with flow rate equal 0.33 m$^3$/s) to move half of the water volume in one minute from one part to the other parts.

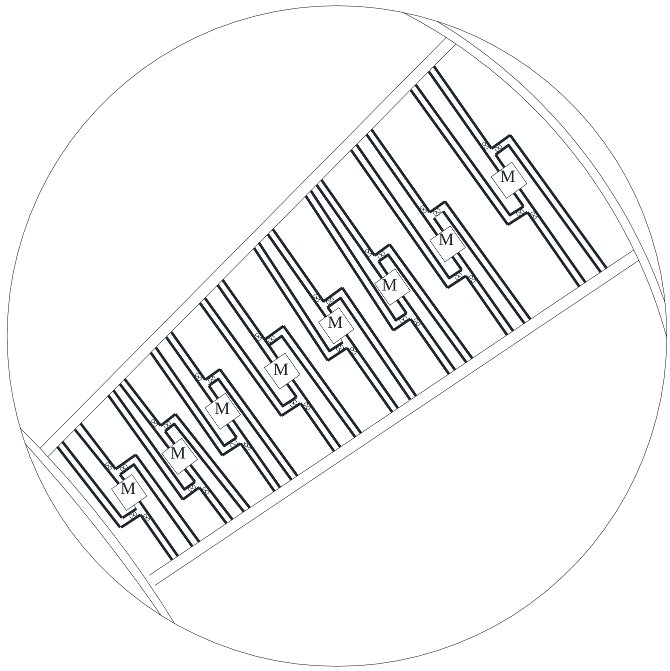


**Figure 7** Water movement system between water tank parts

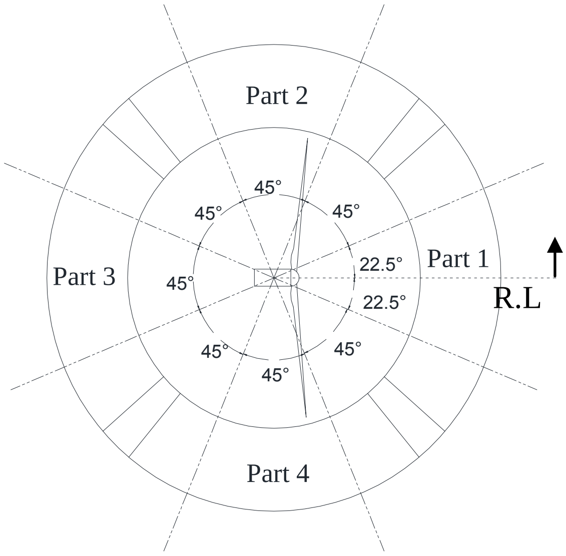


**Figure 8** Reference line and angles used to move water from one part to the other parts

**Table 6** Location of the water according to rotor hub angle with the R.L.

| Rotor hub angle with the R.L. | Water position |
|---|---|
| 0.00 to 22.5 & 337.5 to 360 | Part 1 |
| 22.5 to 67.5 | Part 1 + Part 2 |
| 67.5 to 112.5 | Part 2 |
| 112.5 to 157.5 | Part 2 + Part 3 |
| 157.5 to 202.5 | Part 3 |
| 202.5 to 247.5 | Part 3 + Part 4 |
| 247.5 to 292.5 | Part 4 |
| 292.5 to 337.5 | Part 4 + Part 1 |