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Increasing the Soil Rotational Stiffness using Rammed Aggregate Piers for Wind Turbine Tower Foundations

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SUMMARY: Wind turbine tower foundations must be designed to limit the angular rotation of the tower. Rammed Aggregate Piers (RAPs) are commonly used as a mean for increasing the available soil rotational stiffness by taking advantage of their higher stiffness compared to that of the matrix soil being reinforced. A composite stiffness approach using the elastic dynamic parameters of the soil and the RAP elements is used to develop a solution for increasing the foundation soil available rotational stiffness, thereby meeting the project design requirements. This article presents the technical background and procedures used for developing a solution for increasing the foundation soil rotational stiffness using Rammed Aggregate Piers for support of wind turbine tower foundations. A case history example is also presented at the end to support the technical discussion.

KEYWORDS: Rotational Stiffness, Rammed Aggregate Piers, Wind Turbine Tower Foundations, Ground Improvement, Soil Reinforcement, Settlement

1 INTRODUCTION

Wind turbine foundations must be designed to limit the angular rotation of the tower during service conditions. Wind turbine designers typically specify the required value of available soil rotational stiffness that is then used in combination with the applied overturning moment to estimate angular rotation. The allowable angular rotation for wind turbine foundation applications is typically specified as 0.003 radians, or 3 mm/m.

Rammed Aggregate Piers (RAPs) are commonly used as a mean for increasing the available soil rotational stiffness by taking advantage of their higher stiffness compared to that of the matrix soil being reinforced. A composite stiffness approach using the soil and the RAP elements elastic dynamic parameters, as discussed in Balaam, et.al. (1976) and Kempfert, et.al. (2006), is used to develop a solution for increasing the soil available rotational stiffness, thereby meeting the project design requirements.

2 RAMMED AGGREGATE PIERS

Rammed Aggregate Piers are a ground improvement solution that have been used for more than 20 years to provide soil reinforcement solutions or foundation support in the commercial, industrial, manufacturing and power markets. This ground improvement technology is used to provide improved strength and stiffness of soft or compressible soils.

An example of this system involves drilling a 0.60m to 0.90m diameter cavity, (depending on design requirements), placing thin lifts of aggregate within the cavity and vertically ramming the aggregate using a high energy beveled impact tamper (ICC-ES, 2016).

During construction, the high-frequency energy delivered by the modified hydraulic hammer, combined with the beveled shape of the tamper, not only densifies the aggregate vertically to create a stiff aggregate pier, but also forces aggregate laterally into the sidewall of the hole, resulting in a lateral stress increase in surrounding soil. The lateral stress increase reduces the compressibility of the surrounding soil and promotes positive coupling of the aggregate system element and the soil to create an improved composite, reinforced soil zone.

The RAPs construction procedure using the typical replacement system is illustrated in Figure 1, as discussed in ICC-ES (2016). RAPs displacement systems are also available for soils that are prone to caving-in conditions, as illustrated in Figure 2.

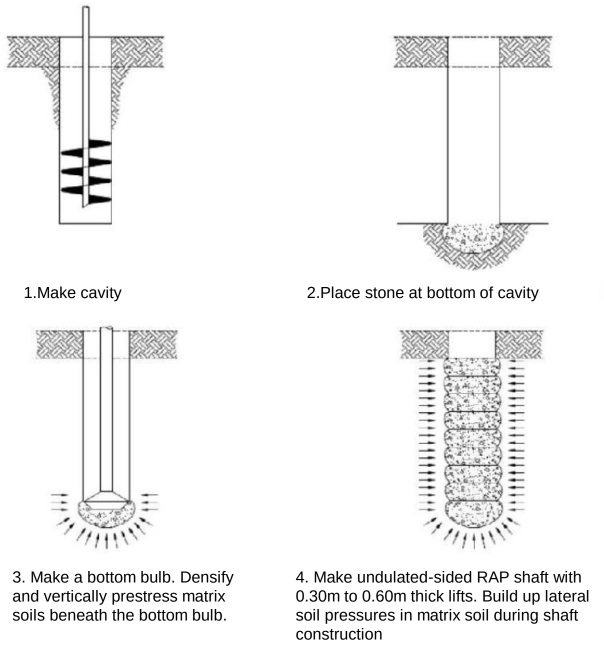

Figure 1. RAP Construction Process Using Replacement Systems (ICC-ES, 2016)

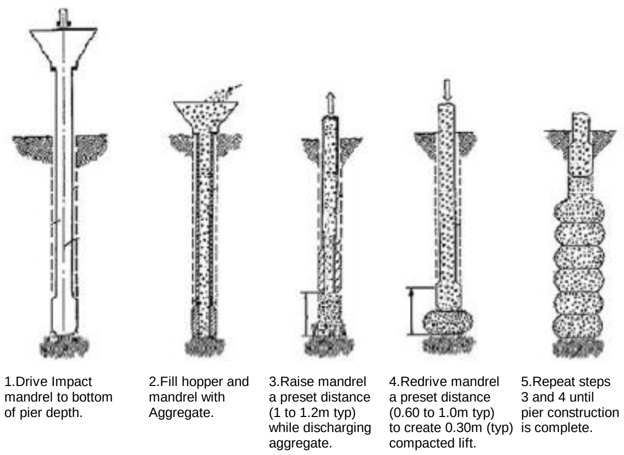

Figure 2. RAP Construction Process Using Displacement Systems (ICC-ES, 2016)

The systems are designed to reinforce the poor foundation soils, which improves the bearing capacity of the reinforced zone beneath tower foundations, controls total and differential settlement (i.e., angular distortion) of the foundations, and improves the rotational and dynamic stiffness values to achieve the desired tower performance. The soil reinforcement designs are developed on a project-specific basis depending on the site and the tower loading conditions.

3 ROTATIONAL STIFFNESS CALCULATION

There are several types of foundation stiffness checks (US Dept. of Defense, 1997) as illustrated in Figure 3. However, rotational (rocking) stiffness is almost always the design controlling stiffness parameter, and is often the overall design controlling parameter for wind turbine foundations. Vertical, horizontal, and torsional stiffness rarely control the design.

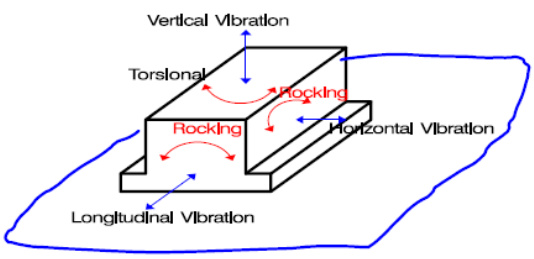

Figure 3. Modes of Machine Vibrations and Various Stiffness Checks (US Dept. of Defense, 1997)

The turbine manufacturer provides a nominal minimum value of available soil rotational stiffness that is required in the foundation design.

The foundation rotational stiffness is defined as the ratio of the applied moment to the foundation angular rotation in radians as shown in equation (1).

$$K_{\phi} = \frac{M}{\theta} \quad (1)$$

Where K_ϕ is the rotational stiffness, M is the applied moment and θ is the angular distortion in radians.

For a rigid circular footing resting on an infinite elastic half-space and subjected to a rocking motion, the general equation for rotational stiffness is provided in equation (2) as described in Richart, et.al. (1970).

$$K_\phi = \frac{8GR^3}{3(1-\nu)} \quad (2)$$

Where G is the soil shear modulus, R is the foundation radius and ν is the soil Poisson's ratio.

Since subsurface conditions are seldom an infinite half-space, the computation for K_ϕ depends on the stiffness and thickness of the subsurface strata.

For a rigid circular footing resting on a two-layer discrete elastic half-space system subject to rocking motion as illustrated in Figure 4, and where $0.75 \leq H/R \leq 2$, and $0 \leq G_1/G_2 \leq 1$, the rotational stiffness is calculated using equation (3) as described in Det Norske Veritas (2002).

$$K_\phi = \frac{8G_1R^3}{3(1-\nu)} \frac{1+\dfrac{R}{6H}}{1+\dfrac{RG_1}{6HG_2}} \quad (3)$$

Where G_1 is the shear modulus at the design cyclic shear strain for the upper soil layer, G_2 is the shear modulus at the design cyclic shear strain for the lower soil layer and H is the thickness of the upper soil layer.

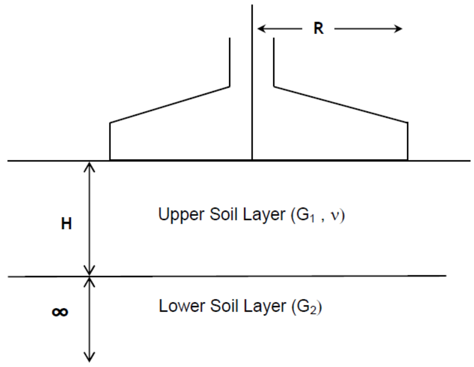

Figure 4. Rigid Circular Footing Resting on a Two-Layer Discrete Elastic Half-Space System (Adapted from Det Norske Veritas (2002))

For a rigid circular footing embedded in a stratum over bedrock (see Figure 5) subject to rocking, and where $D/R < 2$ and $D/H < 0.5$, the rotational stiffness is calculated using equation (4).

$$K_\phi = \frac{8G_1R^3}{3(1-\nu)}\left(1+\frac{R}{6H}\right)\left(1+2\frac{D}{R}\right)\left(1+0.7\frac{D}{H}\right) \quad (4)$$

Where *D* is the depth of embedment of the footing.

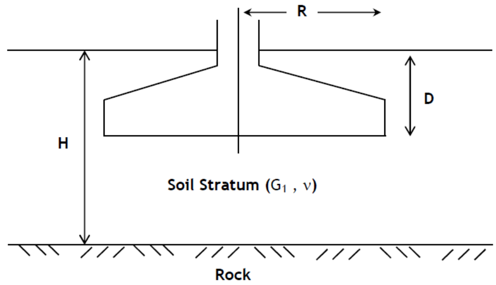

Figure 5. Rigid Circular Footing Embedded in a Soil Stratum over Rock (Adapted from Det Norske Veritas (2002))

From the above discussion, it is shown that there are two soil parameters needed for the calculation of the rotational stiffness: the Poisson's ratio, ν, and the shear modulus, G. The dynamic or maximum shear modulus, G_{max}, can be obtained from its relation to the dynamic or maximum elastic modulus, E_{max}, as in equation (5).

$$G_{\max} = \frac{E_{\max}}{2(1+\nu)} \quad (5)$$

The maximum elastic modulus value is typically estimated in Europe using correlations that relates the static elastic modulus, E_{stat}, to the ratio of the dynamic elastic modulus to the static elastic modulus, E_{dyn}/E_{stat} as illustrated in Figure 6 as presented in Alpan (1970).

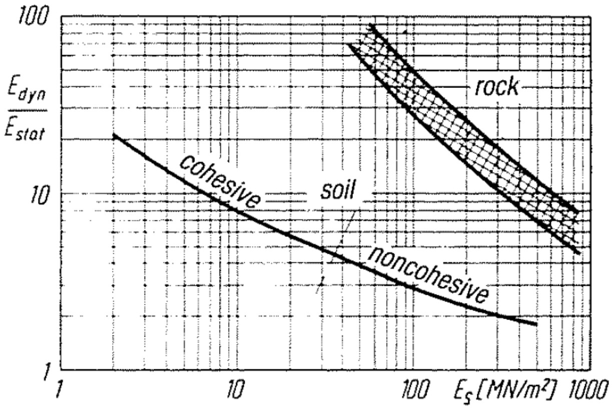

Figure 6. Ratio of Dynamic Elasic Modulus to the Static Elastic Modulus (E_{dyn}/E_{stat}) Based on the Static Elastic Modulus (Alpan, 1970)

The graphical relation illustrated in Figure 6 can be approximated in mathematical form as equation (6).

$$\frac{E_{dyn}}{E_{stat}} = 23.118 * E_{stat}^{\;-0.445}\text{(MPa)} \quad (6)$$

Typical static elastic modulus and Poisson's ratio values are provided in the literature as in Table 1 from AASHTO (1995).

In practice, a maximum *E_{dyn}/E_{stat}* ratio of 10 is desired to avoid overestimating the maximum elastic modulus for soft soils.

Table 1. Typical Elastic Parameter Values for Various Soils (AASHTO, 1995)

Soil	Static Elastic Modulus, E_{stat} (MPa)	Poisson's Ratio, ν
Soft Clay	2 – 15	
Medium-stiff to stiff Clay	15 – 50	0.4 – 0.5
Very stiff Clay	50 -100	
Loess	15 – 60	0.1 – 0.3
Silt	2 – 20	0.3 – 0.35
Loose Fine Sand	8 – 12	
Medium-dense Fine Sand	12 – 20	0.25
Dense Fine Sand	20 – 30	
Loose Sand	10 – 30	0.2 – 0.35
Med-dense Sand	30 – 50	
Dense Sand	50 – 80	0.3 – 0.4
Loose Gravel	30 – 80	0.2 – 0.35
Med-dense Gravel	80 – 100	
Dense Gravel	100 – 200	0.3 – 0.4

It is important to note that the maximum shear modulus, G_{max}, is typically associated to a shear strain value on the order of 0.0001 % (0.000001). Since the wind turbine foundations are subjected to greater shear strains than those associated to the maximum shear modulus, G_{max}, the industry guidelines for the design of wind turbines (Det Norske Veritas, 2002) have selected a shear strain value of 0.1 % (0.001) as the typical design shear strain level. Therefore, the soil design shear modulus, $G_{s'}$, can be calculated as in equation (7) applying a degradation reduction factor, G_s/G_{max}, to account for the shear strain level. The degradation reduction factor is selected based on the soil type as generally illustrated in Figure 7 from Vucetic, et.al. (1991).

$$G_s^{\,'} = G_{\max} \frac{G}{G_{\max}} \quad (7)$$

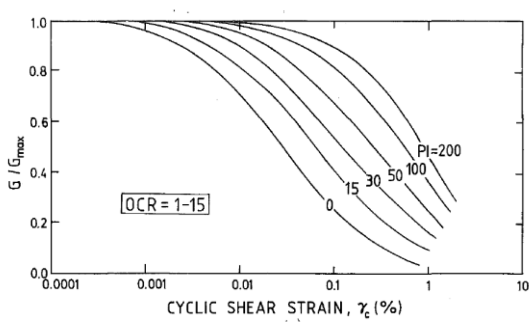

Figure 7. Shear Modulus Reduction Factor, *G/Gmax*, versus Cyclic Shear Strain for Various Soil Types (Vucetic, et.al. 1991)

4 INCREASING THE ROTATIONAL STIFFNESS USING RAPs

The RAPs design approach, for foundation soil rotational stiffness increase, is to reinforce the upper soil layer as in Figure 4 or 5 to meet the wind turbine manufacturer required foundation soil rotational stiffness value. The RAPs design solution is schematically illustrated in Figure 8.

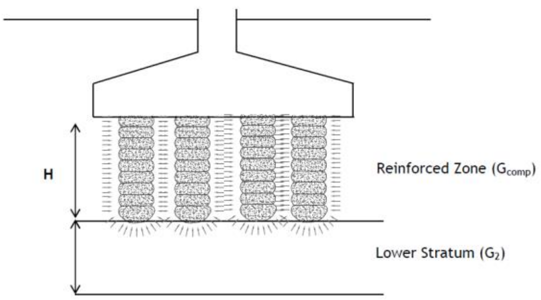

Figure 8. RAPs Concept for Increase in Foundation Soil Rotational Stiffness

The Composite Shear Modulus, G_{comp}, of the reinforced zone is calculated using equation (8).

$$G_{comp} = R_a G_g' + (1 - R_a) G_s' \qquad (8)$$

Where R_a is the area replacement ratio, defined as the ratio of the total area of the RAP elements within the reinforced zone to the total area of the reinforced zone, $G_{g'}$ is the shear modulus of the RAP element aggregate at 0.1 % cyclic shear strain, and $G_{s'}$ is the shear modulus of the matrix soil at 0.1 % cyclic shear strain.

The RAP design shear modulus is also determined from equation (7), but using a $G_{g,max}$ value of about 280 MPa, as determined by the in-situ measurements in RAPs made by Iowa State University (White, 2004).

If only the upper soil layer is considered for calculating the available rotational stiffness of the foundation soil as in equation (2), the expression provided in equation (8) can be re-arranged to obtain the minimum area replacement ratio, R_a, required to achieve the composite or required shear modulus value (making G_{comp} equal to G_{req}) to meet the project design requirements as in equation (9).

$$R_a = \frac{\left(G_{req} - G_s'\right)}{\left(G_g' - G_s'\right)} \qquad (9)$$

5 CASE HISTORY

A wind farm project was designed in Chile, South America, where the foundations for the wind turbine towers had a diameter of 21 m, and the required rotational stiffness value was 44 GN-m/radian. The soil conditions to a depth of 6 to 9 meters consist generally of soft to medium-stiff silt with a static elastic modulus value, E_{stat} = 2.4 MPa. The soil Poisson's ratio was assumed as 0.4.

Based on the soil conditions and the proposed foundation diameter, the required composite design shear modulus can be determined from equation (2) to meet the minimum soil rotational stiffness value as follows.

$$G_{req} = \frac{3K_\phi(1-\nu)}{8R^3} = \frac{3(44GN - m/rad)(1-0.4)}{8(10.5m)^3}$$

$$G_{req} = 8.6Mpa$$

The project design team asked for a design solution using RAPs to increase the soil rotational stiffness value to at least the minimum required value.

Solution: First, the maximum or dynamic soil elastic modulus value is determined using Figure 6 or equation (6) as follows.

$$E_{dyn} = E_{stat} * 23.118 * E_{stat}^{-0.445} (\text{MPa})$$

$$E_{dyn} = 2.4Mpa * 23.118 * (2.4MPa)^{-0.445}$$

$$E_{dyn} = 37.6MPa > 10(2.4\,\text{MPa}) = 24\,\text{MPa}$$

Since the maximum or dynamic elastic modulus value determined from figure 6 and equation (6) is greater than 10 times the static elastic modulus value, a maximum or dynamic soil elastic modulus value of 24 MPa is selected. The corresponding soil maximum shear modulus, $G_{s,max}$, is determined using equation (5).

$$G_{s,\max} = \frac{24MPa}{2(1+0.4)} = 8.6MPa$$

The design soil shear modulus value is obtained by applying the corresponding degradation factor based on the soil type and plasticity index. A degradation factor of G_s/G_{max} = 0.35 was selected for design based on the soil index properties. The degraded design soil shear modulus value is $G_{s'}$ = 8.6MPa * 0.35 = 3MPa. This value is compared to the required shear modulus value of 8.6 MPa and the need for ground improvement is confirmed.

The known RAPs maximum shear modulus value of 280 MPa is used to obtain the design RAP shear modulus by applying a degradation factor of G_g/G_o = 0.3, which is considered a reasonable value for the dense compacted aggregate. The design RAPs shear-strain-degraded shear modulus value is $G_{g'}$ = 280MPa * 0.3 = 84MPa.

Using equation (9) we have:

$$R_a = \frac{(8.6-3)}{(84-3)} = 0.069$$

Therefore, the required area replacement ratio is 0.069, that is, at least 6.9% of the total foundation soil area needs to be occupied by RAPs. For this project, the selected RAPs diameter was 0.76 m and the RAPs area is 0.45 m^2 each, therefore, a total of 54 RAPs could have been selected to provide an area replacement ratio of 7%, meeting the project minimum area replacement ratio. Based on additional design checks, and because client desired to provide RAPs coverage for the entire foundation footprint, a schematic layout as in Figure 9 was selected for construction. This layout resulted in 79 RAPs, providing an area replacement ratio, Ra, of 0.104 (10.4%). Note that the RAPs are located closely spaced along the edges of the footing plan in order to provide increased stiffness along the areas where the foundation pressure is higher, while providing a wider spacing towards the center of the footing, where foundation pressure is smaller.

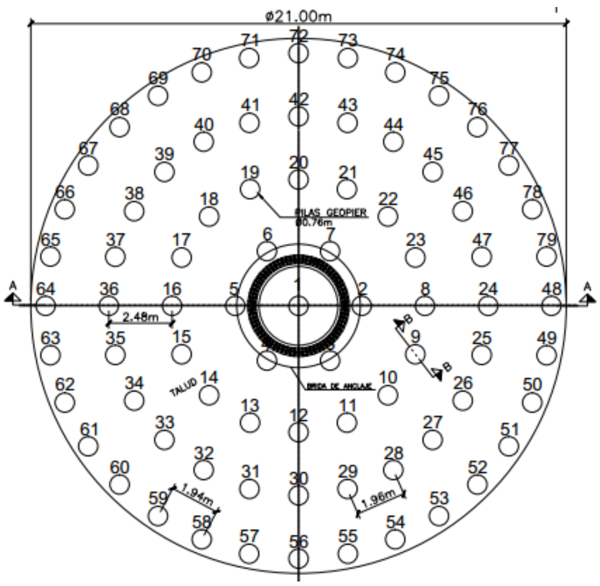

Figure 9. Schematic of the RAPs Solution Provided for Case History Example

6 CONCLUSIONS

This article provided technical analysis on the use of Rammed Aggregate Piers (RAPs) as a mean for increasing the available soil rotational stiffness for wind turbine foundations applications by taking advantage of their higher stiffness compared to that of the matrix soil being reinforced. The increase in soil rotational stiffness is achieved by using a composite stiffness approach resulting from a weighted average of the stiffness of the RAP elements and that of the matrix soil being reinforced.

The special case of machine vibrations involved in the wind turbine foundations requires that dynamic elastic parameters be used in the formulation of a solution. The criteria used for selecting soil and RAPs design parameter values were explained. A case history of a real designed project was provided to demonstrate the steps for developing a solution using RAPs for increasing the foundation soil rotational stiffness.

The use of RAPs as an alternative foundation support solution is commonly used because it is an economic alternative compared to massive over-excavation replacement and deep foundations. The cost savings of using RAPs typically range in the order of 20 to 30% compared to massive over-excavation replacement and deep foundations alternatives.

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