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DESIGN AND CONSTRUCTION OF INTERMEDIATE FOUNDATION® SOLUTIONS FOR WIND TURBINES

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ABSTRACT: The demand for alternative energy sources has sparked significant growth in wind energy. Tower foundation designs consider static bearing and settlement like traditional buildings, but transient pressures from large overturning moments and the need for high foundation stiffness typically control the design. When soft or compressible soils encountered at tower sites do not provide adequate bearing capacity, fuel-intensive overexcavation and replacement, or resource-depleting deep foundations may be used. These solutions are environmentally insensitive. In addition, wind farms are typically located in remote areas, making equipment mobilization and material delivery a costly challenge.

This paper describes the use of Intermediate Foundation® solutions using Rammed Aggregate Pier® (RAP) systems to reinforce poor soils. The process involves constructing high density, stiff RAPs to control settlement and improve allowable bearing pressures and the rotational stiffness. Wind tower support using RAP systems started in Europe and is now more widespread in the United States. This paper details RAP design and construction for wind towers and discusses ancillary environmental benefits associated with this construction method.

1. INTRODUCTION

The demand for alternative energy sources in the United States has sparked significant growth in wind energy development. Wind farm construction continues to grow rapidly throughout the U.S. with a record breaking capacity of 5,249 megawatts constructed in 2007 for a total capacity of 16,824 megawatts (AWEA 2008).

Construction of an equal or greater generating capacity than in 2007 is expected by the end of 2008.

Tower designs mirror the wind industry growth with taller turbines capable of generating even greater energy capacity. The design of turbine foundations must incorporate traditional geotechnical engineering analyses for bearing capacity and settlement for static dead and live loading conditions much like conventional building foundation support. More importantly, though, the designs are often controlled by large transient pressures attributed to significant overturning moments from mean and critical wind characteristics. The design incorporates minimum requirements for foundation stiffness to provide adequate tower serviceability.

The wind industry is touted as a renewable, "green" industry. In addition to the engineering challenges to provide suitable foundation support, designers are often asked to provide sustainable solutions for projects.

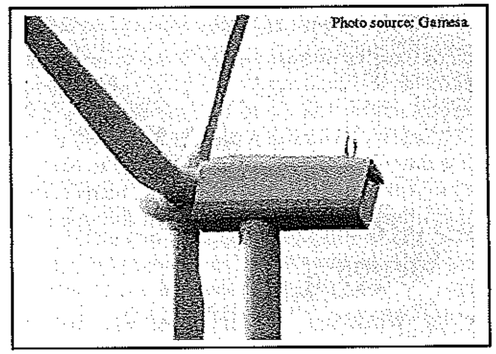

FIG. 1: Gamesa G83 (2MW) Wind Tower

2. WIND TOWER DESIGN CONSIDERATIONS

Wind turbine foundation loading details are often related to the specific turbine manufacturer, make and model and may be a proprietary design detail. In general, tower heights have grown in recent years from early designs on the order of 60 meters (197 ft) to more than 90 meters (295 ft) in height and capable of generating more than 3MW of electricity. These tower heights are expected to grow with the wind industry; towers exceeding 125 meters (410 ft) and 6MW production capability are being unveiled in Europe by companies such as Enercon.

While the vertical loads resulting from dead and live loads for the 1.5 to 2MW towers typically range from only 3,100 to 4,500 kN (700 to 1,000 kips), large overturning moments from the horizontal wind pressures often range from 40,000 to 67,800 kN-m (30,000 to 50,000 ft-kips). The stiffness characteristics of the foundation soils are critical for acceptable tower performance under the wind gust loading conditions. Most manufacturers require minimum horizontal and dynamic (rotational) stiffness criteria specific to the particular tower type be met.

3. FOUNDATION OPTIONS

While deep foundation or pile solutions are an historical option in poor soil conditions, the most cost-effective approach to wind tower foundation design often incorporates the use of a large mat foundation placed on competent soil. Mat foundation design becomes a balancing act tied to foundation sizes and overturning moments. In an effort to minimize the added complexity and cost associated with controlling uplift loads on the foundation, designers often look for the smallest foundation size possible that is yet large enough to preclude uplift pressure at the base. These foundation sizes often result in high foundation edge pressures that may overstress the underlying soil. In poor soil conditions, a low allowable bearing pressure may govern the foundation design unless alternative approaches are utilized.

Alternatives such as massive overexcavation of the poor soil and replacement with high strength backfill or Rammed Aggregate Pier® reinforcement may be used in these cases to support higher allowable bearing pressures and optimize the mat foundation size. Typical mat foundation designs for the 80 to 90 meter (260 to 295 ft) towers range in width (diameter) from 14 to 19 m (45 to 65 ft), resulting in bearing pressures from 144 to 215 kPa (3,000 to 4,500 psf) in many cases. The best solution must then reflect performance, cost-effectiveness and construction schedule.

4. PROJECT DESCRIPTION

Construction of the Winnebago 1 Wind Farm was distributed over 10 sites throughout Winnebago County, Iowa. The project incorporated 78 meter Gamesa® G83 2.0 MW wind turbines with static vertical loads of 2,936 kN (660 kips), horizontal base shear of 676 kN (152 kips) and overturning moments of 50,335 kN-m (37,120 ft-kips). A photograph of the turbines used is shown in Figure 1. Preliminary foundation designs involved "inverted tee" octagonal foundations with diameters ranging from 45 to 60 feet depending on the soil conditions. The foundations were designed to bear 2.75 m (9 ft) below grade.

5. SOIL CONDITIONS

The soil conditions across the ten different sites were explored by the project geotechnical engineer using a combination of Cone Penetration Tests (CPTs) and soil borings and Standard Penetration Tests (SPTs). Testing was performed up to depths of 50 feet at the tower locations. Additionally, shear wave velocity measurements were made at 4 turbine locations using a multi-channel geophone array.

The results of the explorations indicated the soils across the sites generally consisted of a mixture of clay, silt, sand and gravel representing glacial drift, alluvial and colluvial soils extending to depths ranging from 4 to 15 m (13 to 50 ft). In many areas, these soils were underlain by glacial outwash sand and gravel. The upper soils consisted of soft to stiff silty clay with varying amounts of sand to depths of 4 to 5.5 m (13 to 18 ft) underlain by stiff to very stiff sandy lean clay. Groundwater was present at the site at depths of 1.8 to 7.3 m (6 to 24 ft) below existing grade. Moisture contents for the upper soils ranged from 14 to 41%. Undrained shear strengths from unconfined compression tests ranged from 42 to 135 kPa (870 to 2815 psf). Shear wave velocities at the sites increased with depth from approximately 183 to 229 mps (600 to 750 fps) near the bottom of footing elevation and extending to depths of about 7.5 m (25 ft) to 243 to 396 mps (800 to 1300 fps) at depths of 7.6 to 21 m (25 to 70 ft).

6. FOUNDATION RECOMMENDATIONS

As a result of the low shear strength material encountered near the bearing elevation, the allowable bearing pressure for these sites was limited to 120 kPa (2,500 psf) to control settlement and provide sufficient support As an alternate to over-sized foundations using 120 kPa bearing pressures, the design-build contractor utilized the Geopier® system (a type of Rammed Aggregate Pier® system) to improve the composite allowable bearing pressure, control settlement, improve the rotational stiffness all while providing cost savings by reducing the foundation sizes.

The wind tower contractor considered a variety of foundation sizes. The largest was designed to bear on native soils with a width of 20 m (65.5 ft), area of 330 m^2 (3554 ft^2) and resulting maximum bearing pressure of 120 kPa (2,500 psf). With the option of increasing the allowable bearing pressure to 215 kPa (4,500 psf), the contractor finalized plans to use a smaller 229 m^2 (2,460 ft^2) octagonal foundation with a maximum width of 16.6 m (54.5 ft). The design conditions and requirements for the specific foundation are shown in Table 1. The decision was related to cost savings in the concrete and steal for the foundations.

TABLE NO.1: Wind Tower Foundation Design Criteria

Design Parameter	Criteria
Total Settlement	50 mm (2 in)
Differential Settlement	3 mm/m (0.036 in/ft)
Rotational Stiffness	3×10^7 kN-m/rad (2.21×10^7 k-ft/rad)

7. GEOPIER® CONSTRUCTION

Construction of a Rammed Aggregate Pier (RAP) system using the *Geopier* approach is well-described in the literature (Lawton and Fox 1994, Wissmann et al. 2000). As depicted in Figure 2, RAP elements are installed by drilling 610 mm (24 inch) to 915 mm (36 inch) diameter holes to depths ranging between 2 m and 8 m (7 feet and 26 feet) below working grade elevations, placing controlled 0.3 m (1 ft) thick lifts of stone within the cavities, and compacting the aggregate using a specially designed high-energy beveled impact tamper. During densification, the beveled shape of the tamper forces stone laterally into the sidewall of the excavated cavity. This action increases the lateral stress in the matrix soil thus providing additional stiffening and increased normal stress perpendicular to the perimeter shearing surface. RAP elements are installed to reinforce weak and compressible soils offering improvements in the composite shear strength and the composite compression characteristics of the reinforced deposit, thereby controlling settlement and improving bearing pressures.

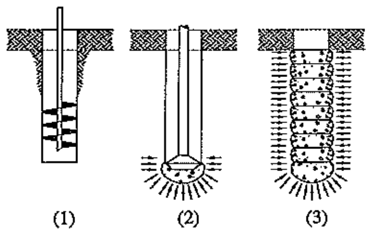

FIG 2: Rammed aggregate pier installation using the Geopier System

The Geopier system provides sustainable construction benefits in addition to increasing the foundation bearing capacity. The system uses locally-available natural aggregate or recycled concrete for construction of the piers. The volume of material utilized for Geopier elements beneath the foundation is typically only 10 to 20 percent of the material required for massive overexcavation and replacement. These factors limit excessive fossil fuel required for material delivery and disposal as compared to other solutions. Additionally, the equipment utilized for the pier installation consists of only 2 to 3 small excavators, thereby further limiting fossil fuel consumption and dramatically reducing the carbon footprint of the foundation construction activities.

8. GEOPIER DESIGN APPROACH

8.1 Settlement control and bearing capacity

In the case of the wind tower foundations, multiple loading scenarios are evaluated. These loading cases include the 1) static pressure only, 2) mean production pressure, and the 3) abnormal extreme pressure. The pier design is performed for the full range of pressures (Cases 1 – 3) to provide sufficient bearing capacity (strength) and maintain acceptable pier stress levels. Often, only the cases of static pressure and the mean production pressure are used for settlement estimates though. This is because the case of the abnormal extreme pressure is not anticipated to result in settlement particularly because of the short-term duration of loading. The pressures provided for a 215 kPa (4,500 psf) foundation are shown in Table 2.

TABLE NO.2: Wind Tower Foundation Design Pressures

Loading Condition	Maximum Edge Pressure
Static Pressure	71 kPa (1487 psf)
Mean Production Pressure	104 kPa (2180 psf)
Abnormal Extreme Pressure	199 kPa (4160 psf)

Allowable bearing pressures for RAP-supported foundations are developed based on classical limit equilibrium analyses and depend on the soil and pier characteristics. Allowable bearing pressures for RAP-supported foundations are often increased over unreinforced conditions by a factor of 2 or 3 because of the improved composite strength characteristics in the reinforced soil. Construction of the Rammed Aggregate Pier elements affords angles of internal friction on the order of 50 degrees which provides substantial improvement in the composite bearing support.

From a settlement perspective, the deflection of the RAP-reinforced zone supporting the foundation is estimated as the ratio of the top-of-pier stress (q_g) and the pier stiffness (k_g). The pier stiffness modulus is assumed as described in the literature (Lawton and Fox, 1994) based on known pier properties and the properties of the surrounding soil, and is then confirmed with a site specific modulus test. The top-of-pier stress is calculated as

$$q_g = q\left(\frac{R_s}{R_s R_a - R_a + 1}\right) \quad (1)$$

where q_g is the top-of-pier stress, R_s is the ratio of pier stiffness to matrix soil stiffness, R_a is the ratio of pier area to the total foundation area and q is the applied foundation stress. For support of transient loading conditions, it's important to evaluate the pier stress for both sustained static pressures as well as the dynamic maximum pressures to be sure the performance of the pier will be acceptable. Typical stiffness ratios for foundations supported by Geopier elements range from 6 to 40.

The settlement of the soils at depths below the reinforced zone is estimated using conventional consolidation or elastic geotechnical approaches. The change in pressure at the center of a compressible layer may be evaluated using a variety of different stress influence factors (i.e. Westergaard, Bousinesq, 2:1 distribution). Based on this estimated change in stress and the soil compressibility, the additional lower zone settlement is added to the reinforced-zone settlement to arrive at the total settlement.

8.2 Rotational Stiffness

Rotational stiffness calculations for wind tower foundations are evaluated using the following approach described in NAVFAC DM7.3 (1983):

$$k_\varphi = \frac{8Gr_o^3}{3(1-\nu)} \quad (2)$$

where G is the shear modulus value, υ is Poisson's ratio and r_o^3 is the foundation radius. For the Geopier-reinforced zone, the shear modulus value, which is proportional to shear wave velocity, may be evaluated using a composite approach as described by the following:

$$G_{comp} = G_g(R_a) + G_s(1-R_a) \quad (3)$$

where R_a is the Geopier element area ratio beneath the foundation, G_s is the shear modulus of the soil within the reinforced zone, and G_g is the shear modulus of the Geopier element (Miller et al. 2005). Research has shown that the shear modulus values of Rammed Aggregate Pier elements are on the order of 287 to 335 MPa (6,000 ksf to 7,000 ksf) (Sulieman et al. 2006). Depending on the levels of strain anticipated from the loading conditions (sustained or transient), degradation factors (G/G_{max}) may be applied to the values for the shear modulus of the soil and the pier. These degradation factors are determined based on soil type and strain level, which can be conservatively estimated based on deflection of the reinforced-zone.

9. PROJECT CONSTRUCTION AND TESTING

A total of 64 Geopier elements were installed prior to foundation excavation at each of the ten tower sites. Pier lengths extended 2.4 to 4.6 m (8 to 15 ft) below the bottom of the foundations. The piers were concentrated near the outer edges of the foundation to provide the improved bearing pressure where the overturning moments resulted in pressures exceeding the bearing capacity of the soil. Figure 3 shows a typical layout of the piers beneath one of the tower foundations. The piers were typically installed at each site within one to two days.

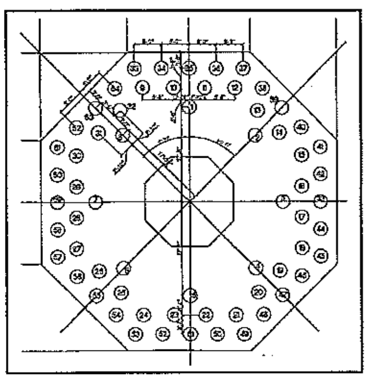

FIG. 3. Typical RAP Layout

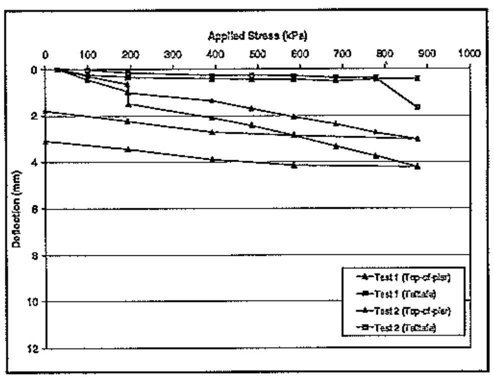

FIG. 4: RAP modulus test results

The performance of the system was evaluated at the project sites by performing modulus tests to evaluate the behavior of the pier under applied stress. The modulus test is performed in general accordance with a pile load test and is described in Shields et al. (2004). The results of two modulus tests are shown in Figure 4. The test results indicate a pier deflection of less than 4.3 mm (0.17 inches) at a stress level of 878 kPa (18.3 ksf) resulting in a pier stiffness of at least 204 MN/m^3 (750 pci). This value exceeded the design value of 48 MN/m^3 (175 pci) by a factor of 4.

10. CONCLUSIONS

This paper describes the use of Rammed Aggregate Pier® (RAP) solutions to reinforce soft to stiff clay soils at the site of ten towers. RAP reinforcement has been shown to be a cost-effective alternative to overexcavation and replacement or deep foundation for support of the towers. The Intermediate Foundation approach provides a more environmentally-conscious and sustainable solution for the wind industry. The RAP approach allows for a tailored solution to foundation support to provide improved allowable bearing pressures particularly where the applied pressures exceed the bearing capacity for the unreinforced soil. The piers also provide a significant improvement to settlement control and dynamic stiffness.

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