LESSONS LEARNED

problems and solutions encountered by practicing structural engineers

Exploring the Deep

Innovation in Wind-Turbine Foundation Design

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The Casselman Wind Power Project in Pennsylvania sits atop parts of former coal mines – unsuitable sites for conventional wind-turbine foundations (*Figure 1*). To enable Iberdrola Renewables to construct wind turbines on these mine spoils, a team of engineers from Barr Engineering Co. designed a wind-turbine foundation that uses micropiles to reach the bedrock located 50 to 100 feet below ground.

Figure 1: A string of wind turbines along the ridge.

The Project Begins

Wind whips over western Pennsylvania's coal-rich Allegheny Ridge, making it an ideal location for wind turbines. In 2006, Iberdrola Renewables began planning the region's newest wind farm, which would include a complete geotechnical investigation of 23 prospective wind-turbine locations, the design of wind-turbine foundations, and the observation of the foundations' construction.

Unstable Soils

Field investigations, which included soil boring and rock coring, revealed the types of soils and rock present at the 23 proposed turbine sites. The subsurface conditions varied, and natural soils consisting of sand, silty sand, silt, silty gravel, and gravel with both low- and high-plasticity clay were found near the surface. Bedrock was found anywhere from half a foot to nearly 100 feet below the surface. The investigation also discovered that, like much of southwestern Pennsylvania, this site was formerly used for coal mining. Rocks and soil generated during mining excavations – the spoils – were dumped in massive, hill-like piles, becoming the region's dominant characteristic and rising up to 96 feet above the bedrock. Beginning as loose piles of rubble and stone, these piles became overgrown with vegetation to resemble a natural landscape. The geotechnical behavior of mine spoils is difficult to predict, and there is a major risk that structures built on such spoils will be exposed to ground subsidence and uncontrolled settlement. The geotechnical investigation found that 8 of the 23 wind-turbine sites were on these unstable and risk-prone mine spoils.

An Engineering Challenge

Most buildings are not designed for significant dynamic loads. Wind turbines, by contrast, are designed as machines to catch and harness wind energy and produce electricity. At times, wind force – a combination of aerodynamic and mechanical forces – can be extreme and unpredictable, and the machine forces are widely varied and highly repetitive. A wind-turbine tower structure and its foundation receive a wide spectrum of millions upon millions of fatigue load cycles during the turbine's 20-year expected life span. The wind's aerodynamic and mechanical forces concentrated at the top of the tower create a huge overturning moment at the tower base, and the wind-turbine foundation must be able to resist this large, concentrated force.

More than 90 percent of the thousands of wind-turbine foundations that Barr has engineered are spread-footing foundations made of reinforced concrete, with typical plan dimensions ranging from 40 to 70 feet in diameter and depths of embedment 5 to 10 feet below the surface. A spread footing transfers the large overturning moment to soils by bearing downward on the soil at its base. Spread footings are relatively simple to construct and are the foundation of choice for most wind projects. However, they require stable soils 50 to 100 feet deep. At some sites with poor soils, spread footings can be used, but require modification of the underlying soils. Excavating and removing poor soils, and replacing and re-compacting the site with engineered fill is one method, but this is feasible only to depths of 15 feet. At the eight project sites, mine spoils were too thick – in some places, nearly 100 feet thick – for this technique to work. Dynamic compaction is another option, in which a large, heavy weight is dropped from a fixed height to impact, compress, and densify the loose soil. Again, this method was infeasible because the mine spoils contained too much clay and water, rendering dynamic compaction ineffective. Because the mine spoils could not be modified using these lesser expensive methods, a different approach was needed.

The Foundation Solution

The foundation engineers determined that the most viable option for Casselman would be deep-pile foundations. Each of the eight wind-turbine foundations would be supported by piles that extended through the mine spoils to carry the load from the

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Figure 2: 24 micropiles installed and ready for the pile cap.


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foundation to the competent bedrock beneath. The main problem was how to get these piles through the mine spoils. Large boulders found in the spoils could deflect the piles during driving; augered piles would have similar problems and be even further limited to installation depths of 40 feet. To overcomes these issues, the engineers selected micropiles – small piles only 8.5 inches in diameter that are often used when working in tight quarters or for underpinning structures, such as the subway tunnels around the World Trade Center re-construction. This would be the first time that micropiles would be used to support wind-turbine foundations.

The micropile installation method proved to be innovative. A rotary drill rig and pneumatic hammer were used to install the outer steel shell of the micropile, which then served as the outer casing for the rotary drill bit. The bit drilled through the mine spoils' soil, rocks, and boulders. High pressure air injected at the bit removed the cuttings by blowing them up the casing to the surface. The pneumatic hammer advanced the casing with the drill bit as it removed material. As the drill bit and outer casing advanced through the mine spoils, additional lengths of micropile casing were attached through threaded connections. Drilling continued until bedrock was reached, and the casing was socketed an additional 15 feet into the bedrock (*Figure 2*).

The foundation design used 24 micropiles for each turbine. And each micropile was installed with an outward inclination of 15 degrees, causing the spoils to press down on the piles to increase stability and better handle the large overturning moment. Loads from the wind-turbine tower were transferred to the piles by a six-foot-thick reinforced-concrete pile cap. The pile cap was heavily reinforced so that it could transfer the highly concentrated moment from the tower into large axial loads through the micropiles. Although small, each micropile has a 450,000-pound capacity when filled with concrete and reinforcing steel. The micropiles installed at the Casselman turbine sites were expected to be subjected to a maximum load of 180,000 pounds under the most extreme conditions. Because the wind turbine was expected to subject the micropiles to countless repetitive load cycles, the design needed to consider stiffness and fatigue, which is unusual for conventional structures.

Successful Construction

Preliminary micropile foundation engineering began in October 2006 and the micropile foundations' construction was completed in December 2007 – in time to meet Iberdrola's critical schedule for delivery and installation of the wind-turbine towers and machinery. The total construction budget for the eight micropile foundations was approximately $4 million, but final construction costs came in under budget at approximately $3.2 million. Construction at the mine spoil sites enabled Iberdrola to meet significant financial and power-supply commitments made for the project.

Conclusion

The deep-foundation design advances the state of the practice by making possible the safe construction of wind turbines in otherwise unsuitable soils. The design is transferable to other sites, and has been used successfully at similar projects in Pennsylvania and West Virginia.

What might have remained an unusable tract of land is now the Casselman Wind Power Project, which generates enough electricity to power 10,000 homes a year. The economic benefits to the region, which has suffered job losses due to the decline of the coal industry, are notable. The project is expected to generate $375,000 annually for the local economy through taxes, easement payments, and landowner revenue. Permanent jobs will be created, and local people will help run and maintain the facility. In addition, the project will help Pennsylvania meet its 2021 target that 18 percent of all energy generated in the State come from alternative or renewable energy sources.■