A POST-TENSIONED MICROPILE FOUNDATION SYSTEM WITH GROUTABLE VOID FORMS (GVF)

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ABSTRACT

This is a foundation solution for renewable energy sources such as wind turbine towers, solar collector panels, hydropower and towers for transmission lines. In all cases the focus is to provide the most cost effective, safe, and environmentally friendly solution. For that reason, micropile solutions can be considered as an alternative to mass concrete foundations. Micropile foundation systems are constructible in different ground conditions without the need for changing the equipment or the method of installation.

It is particularly desirable to have a deep foundation with a smaller footprint for wind turbine towers. To resist the imposed overturning moments, the concept of using post-tensioned micropiles (PTMP) in compression and/or tension with groutable void forms (GVFs), relies on the activation of the soil mass under the foundation (Figure 1). This allows for reducing the size and depth of the now pre-tested foundation, which results in savings in reinforcing steel and concrete.

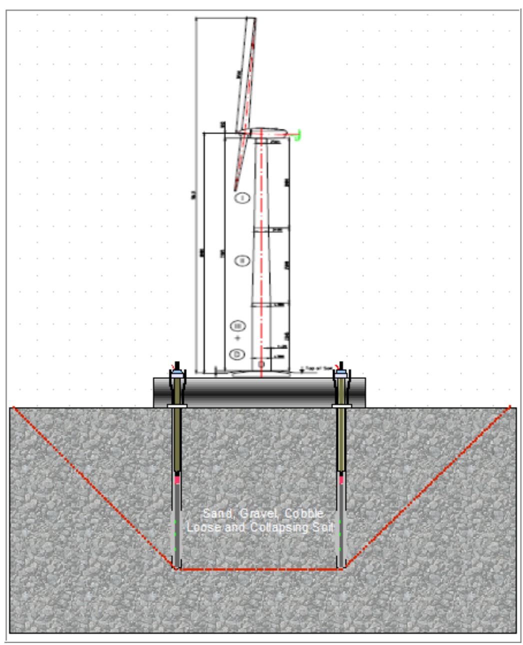

Figure 1. Activation of Soil Mass

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Three possible post-tensioning scenarios for micropile foundations

Case I: No void.

Hard contact between micropile and foundation cap. There is no allowance for micropile movement to mobilize skin friction forces between the micropile grout and soil. The PT force in the pile becomes a compressive stress at the pile to cap interface. No actual pile testing is possible unless each pile is tested before the foundation is placed and locked off later on top of the finished foundation.

Case II: Unfilled compressible void.

Void between micropile and foundation cap for tensioning remains unfilled. It permits unrestrained movement between the top of the pile and the bottom of the cap. Since the void remains unfilled, there is a possibility of long term consolidation and settlement if founded on soil. However; it can be used if founded on rock. In this case it is not a pile but an anchor in tension. The compression loads are supported by the rock.

Case III: Groutable void form (GVF) system.

As it is presented and described in this paper for foundations on soil. The void between micropile and foundation cap is filled with cement grout after tensioning. It permits unrestrained pile movement between the top of the pile and the bottom of the cap during tensioning. After filling the void with cement grout, compressive forces as well as tension forces can be transmitted.

The technical benefits are:

No movements of the foundation and pile can occur unless externally applied forces are larger than the applied PT forces in tension or compression.

INTRODUCTION AND BACKGROUND

Standard Foundations

Foundations for wind turbines normally consist of large reinforced concrete spread footings. If founded on soils, the compression loads are only supported by the soil and the overturning loads are resisted by the counterweight provided by the concrete foundation (Figure 2). The changes in loading from compression to uplift can cause a fatigue problem, which is difficult to predetermine. Consequently, overturning of the wind turbine may result (Figure 3).

Figure 2. Large reinforced concrete spread footing, with 500 to 600 cy of concrete

Figure 3. Overturning failure caused by massive rainstorms

For foundations on soil, an alternative post-tensioned foundation system was developed using micropiles supporting a smaller foundation-pile cap. Not only will this micropile system minimize or eliminate the above mentioned fatigue problem, but it can also provide up to a 75% reduction in foundation area, a 40% reduction in concrete consumption, and a 70% reduction in reinforcing steel, resulting in a total foundation cost savings of about 25%.

Foundation Design Objectives

To provide a post-tensioned micro pile foundation system, such as for wind turbine foundations, the following design objectives should be achieved:

- Design and construct post-tensioned micropiles to achieve a design load in compression and/or tension with the required factor of safety.
- Provide a rigid foundation to resist extreme overturning moments while limiting the pile cap size.
- Improve rotational stiffness and reduce / eliminate movement of the foundation through post-tensioning.
- Reduce excavation and backfill required for the pile cap/tower foundation.
- Reduce consumption of concrete and steel reinforcing to optimize foundation efficiency and performance.
- Provide a cost effective post-tensioned deep foundation system on micropiles

In order to test and post-tension these foundations, a groutable void form (GVF) has been developed. The GVF temporarily separates the pile from the pile cap during stressing and testing, to a load higher than the design load in compression and tension, while also allowing for some range of pile movement. After post-tensioning the GVF is filled with cement grout in order to also transfer compression loads to the pile (Figure 4).

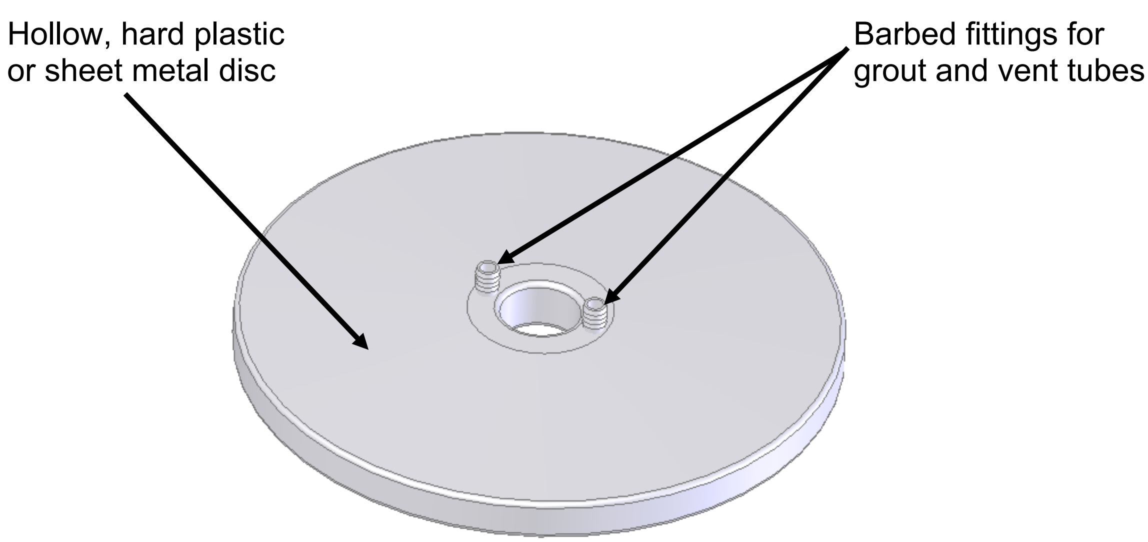


Figure 4. Groutable Void Form, (patented).

Prime Advantages

The post-tensioning procedure using GVFs with micropiles offers the following advantages:

1. Controls foundation settlement and prevents overloading the soil (bearing capacity failure) with a prescribed sequence of post-tensioning.
2. Post-tensioning in balanced anchor groups permits gradual load transfer into the piles without overstressing the soil.
3. Settlement of the foundation cap is minimized as the piles take over the compression load from the cap.
4. Fatigue failures can be eliminated since the post-tensioned tension and compression loads are higher than the design loads and as such minimize or eliminate movements during load changes (Figure 5).
5. With the reduction of concrete and steel, reduced environmental impact is also achieved.

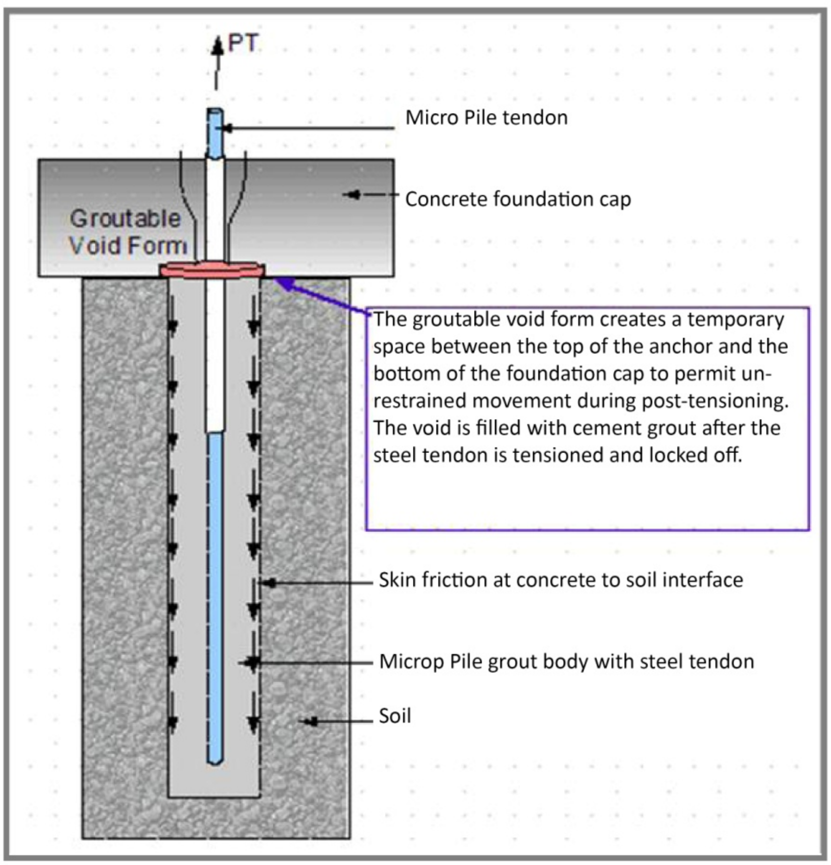


Figure 5. Load transfer diagram

Two CONSTRUCTION METHODS

1. Micropiles are installed prior to placing the concrete foundation cap.
2. Micropiles are installed after placing the concrete foundation cap. (i.e. Micropiles drilled through pre-installed sleeves inside the pile cap).

   The advantage with the first method is that a larger drill hole diameter can be achieved using the open or cased hole drilling method and that the GVF can be wet set into the upper cement grout body of the pile (Figure 6). Three types of post-tensioning steel tendons may be used: (1) 7 wire, 270 ksi low relaxation strand, (2) solid, 150 ksi high strength bars, or (3) injection bored hollow bars. Strand and solid bars are used primarily for micropiles drilled through soil into rock, or for foundations on soil when a larger drill hole is required and the micropiles are pre-drilled.

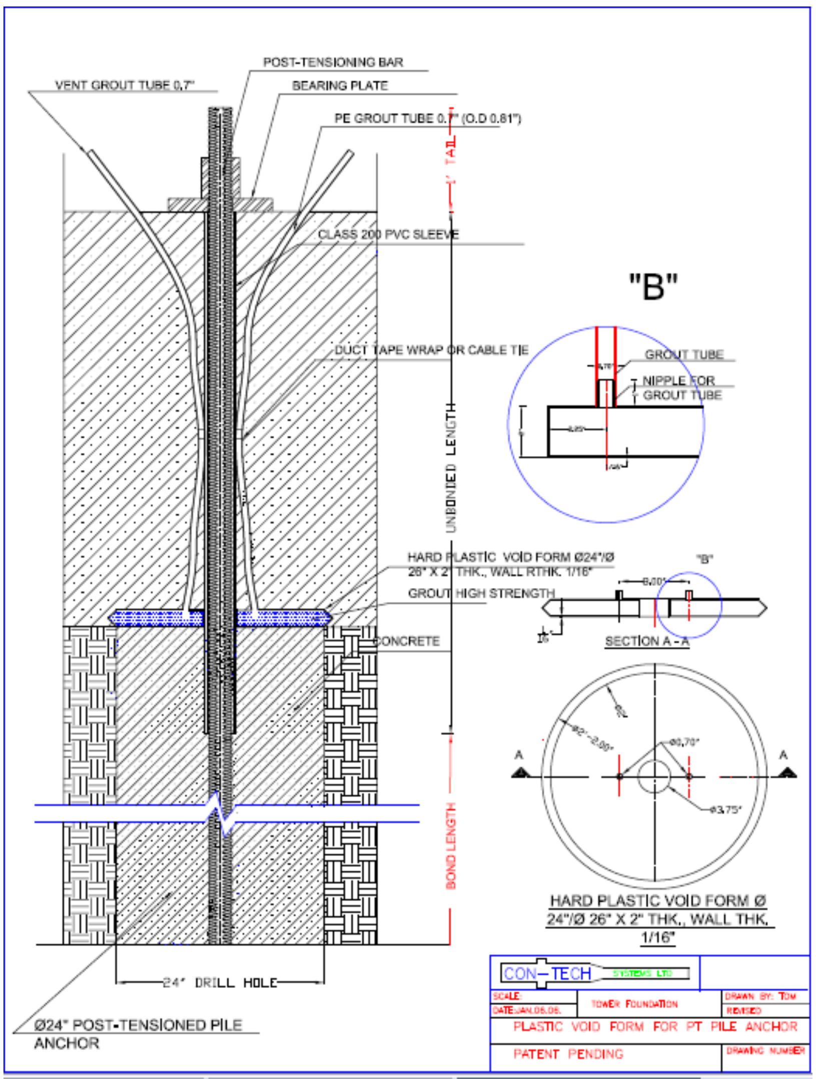
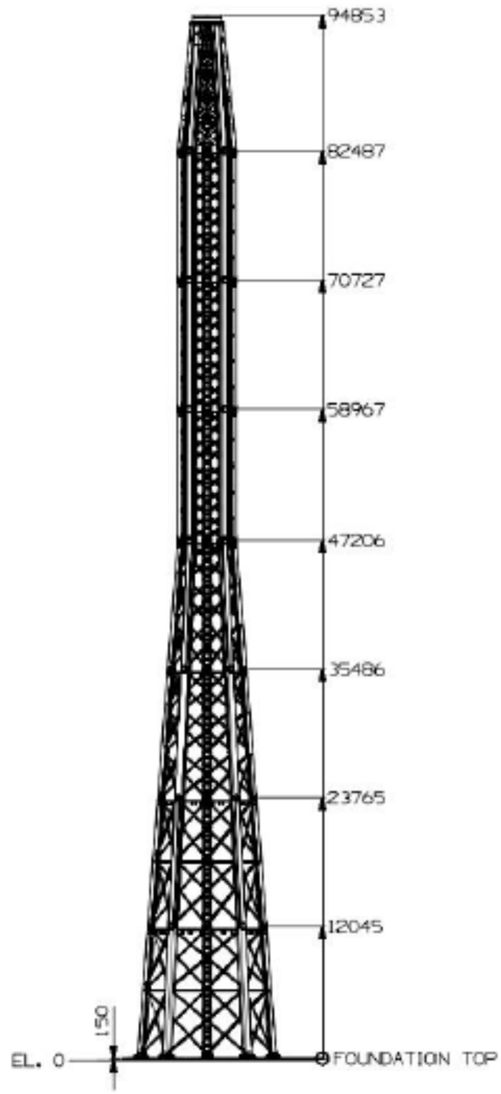


Figure 6. Location of the GVF with grout tubes

Method 1

A foundation for a 1.6 MW wind turbine was constructed in Tehachapi, California, using 300 mm diameter pre-drilled post-tensioned micropiles and GVFs. The 100 m tall lattice tower was founded on five individual pile caps, each supported by 4 micro piles.

The post-tensioned micropile/GVF system was load tested to provide assurance that the construction cost and long-term maintenance of the micropile system could be reduced.



Photographs of the drilling for the solid bar, double corrosion protected (DCP) micropiles are shown in Figures 7 and 8. These larger diameter holes were formed prior to the construction of the pile cap. The GVFs were wet set into the top of the micropile grout in the levelling pad with pipe sleeves and grout tubes (Figure 9) placing the rebar cages and forming pile caps (Figure 10). All pile caps are cast with a total of 20 micropiles (Figure 11). Micropiles are stressed in sequence after placing the bearing plates and nuts (Figures 12 and 13).

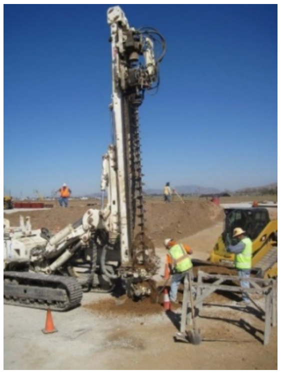


Figure 7. Drilling lager hole


Figure 8. Placing bar and grouting


Figure 9. Wet set GVF


Figure 10. Placing rebar and forms


Figure11. Ready for post-tensioning


Figure 12. Bearing plate with grout tubes


Figure 13. Stressing of solid bar tendon


Figure 14. Finished grouting the GVF

Grout is pumped through one tube and vented out of the other to ensure 100% filling of the GVF by the grout (Figure 14). Thereafter, the micropiles are able to transfer the applied loading into the ground.

METHOD 2

The advantage of the second method is that the micropiles are drilled through pre-formed sleeved holes in the foundation cap fitted with a pre-installed GVF under the foundation cap. (Figure 15).

The disadvantage is that the drill hole size is determined by the smaller sleeve, inside the foundation slab, which does not, therefore, provide sufficient cement grout body under the GVF. The smaller sleeve size is dictated by the size of the bearing plate for the micropile.

However, the issue with the grout under the GVF is not present when using the grout injection bored method with hollow bars (Figure 16). In this case the cement grout is injected simultaneously during the drilling operation. The drill bit has small diameter side holes through which the grout will exit under high pressure, similar to that during jet grouting. This will flush and create a larger size drill hole than the drill bit size under the GFV (Figure 17), as such creating a sufficient cement grout body underneath the GVF. This method also greatly improves the condition of the ground around the micro pile and, therefore, creates a very favourable higher skin friction capacity.

Figure 15. Pre-set sleeves in footing

Figure 16. Drilling of a hollow bar

Figure17.Grout injection

Stressing of the micropiles simultaneously in pairs, (Figure 18) will pre-stress the piles and post-tension the foundation before the GVF is filled with cement grout.

The amount of anchors stressed in pairs is dictated by the compression load capacity of the soil. When this load is reached, the GVFs are grouted. After the grout has reached sufficient strength, the stressing procedure can continue.

Figure 18. Stressing Arrangement

The typical stressing stages for a foundation system with 20 micropiles is shown in Figures 19 through 21.

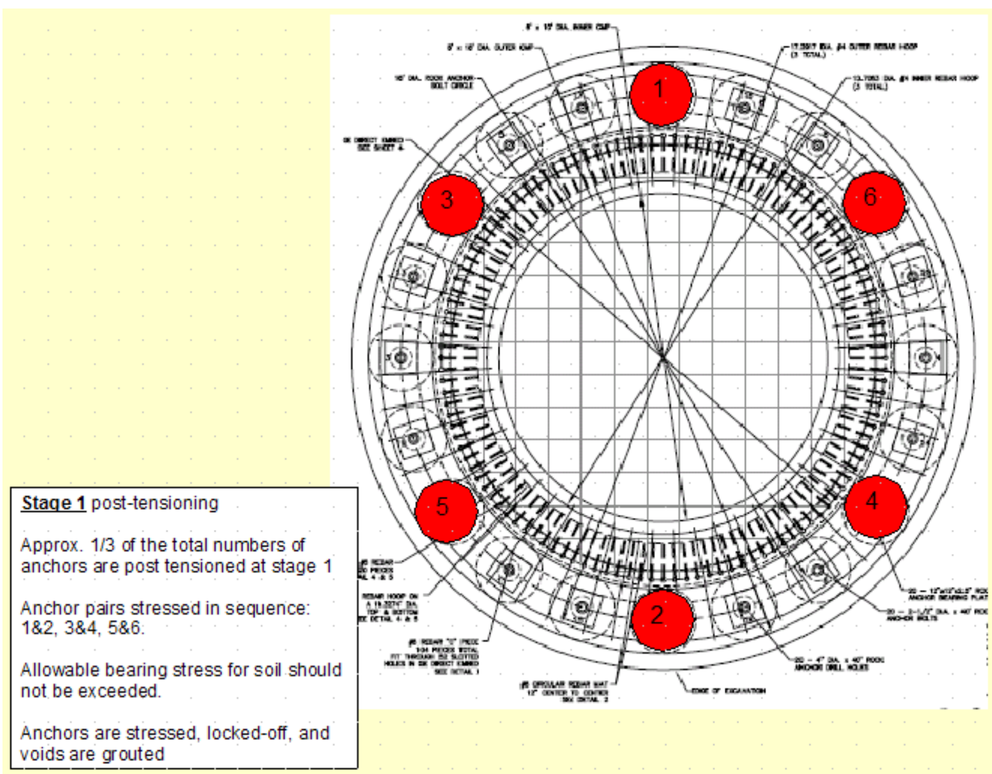


Figure 19. Stage 1 stressing

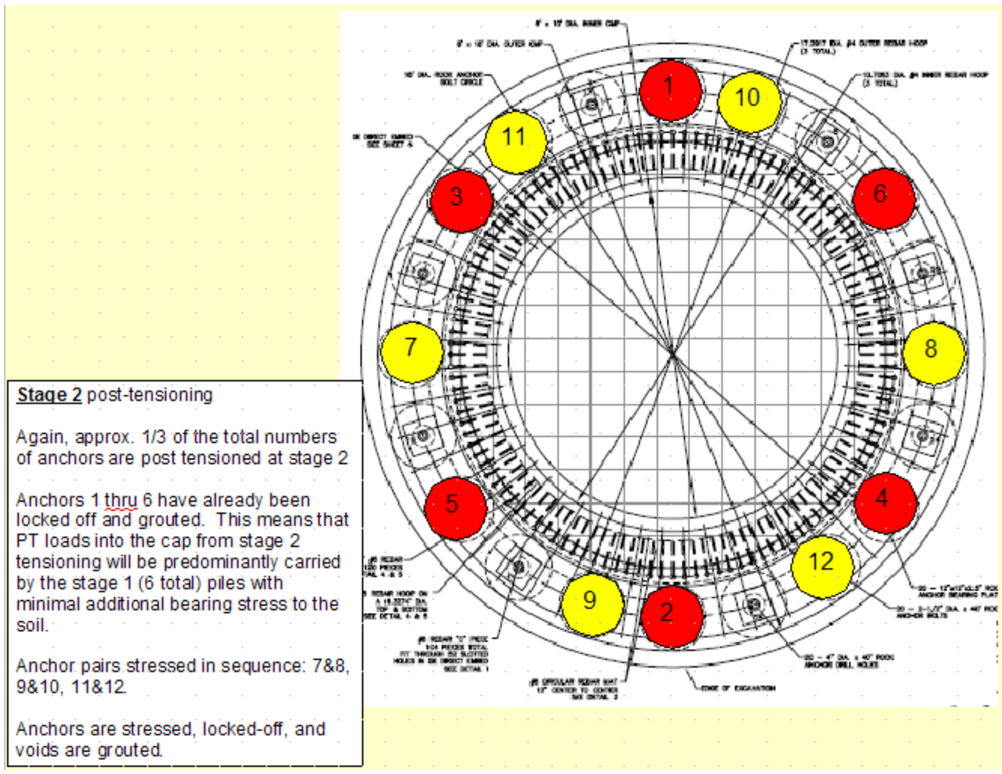


Figure 20. Stage 2 stressing

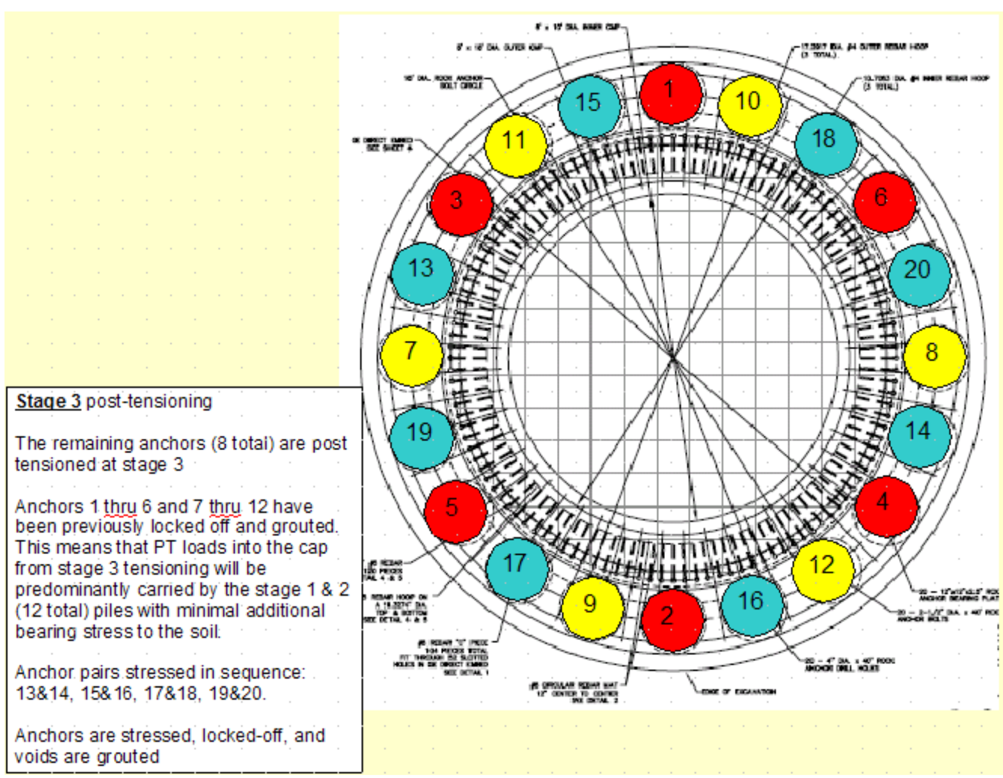


Figure 21. Stage 3 stressing

Conclusions and Summary

Photographs of the completed post-tensioned micropile foundation are shown in (Figures 22 and 23).
Compared to a large diameter mass concrete foundation, the following observations were noted for the micropile/GVF foundation system:

- More than a 75% reduction in foundation area
- More than a 40% reduction in concrete consumption
- More than a 70% reduction in reinforcing steel consumption
- Preliminary estimated total foundation cost reduction of 20% to 30%

Figure 22. Typical post-tensioned micropile wind turbine foundation with hollow bars

Figure 23. Typical post-tensioned wind turbine foundation with strands

As a result of the findings in this paper, it can be stated that the safety of wind turbine foundations composed of post-tensioned micropiles with GVFs is improved and the cost greatly reduced. Therefore; the micropile/GVF system provides a competitive alternative to large diameter reinforced concrete spread foundations and to foundations on soil, if constructed with post-tensioned tie down anchors.