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The use of micropiled foundations for overhead line construction and energy security

Utilisation de fondations en micropieux pour la construction à ciel ouvert et la sécurité énergétique

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ABSTRACT: Overhead power transmission has been implemented globally across all types of terrain. It is a rare occurrence for a field of view to be free from electricity pylons, even in the most remote locations. Over the last thirty years focus within the UK has been on the refurbishment of existing routes, rather than the construction of new infrastructure. With the change in the UK's power generation strategy, the need for new power transmission and distribution has become a necessity. The foundations of such structures must provide an adequate base whilst also being cost and time efficient, however they are often overlooked. What was effective during the last large scale power infrastructure expansion is not always the optimum solution today. Equipment, engineering techniques and materials, along with attitudes have moved on when considering a sustainable geotechnical solution. A recent overhead line construction project in South West Scotland has involved the installation of a large number of raked micropiled foundations by Cementation Skanska. The three transmission routes, spread across an area of approximately 250 square miles, combined micropiled bases with traditional pad and column foundations. This allowed construction through a wide variety of ground conditions with minimal large scale excavation. During the project tension load tests were carried out to confirm the design assumptions and fibre optic strain measurements where taken. The techniques and tools developed were selected and refined to reduce the risks associated with such a large scale linear infrastructure project in a highly variable geographical and geological location.

RÉSUMÉ : Les lignes à haute tension aériennes ont été construites dans le monde entier sur tout type de sol. Rares sont les horizons dénués de pylônes électriques, même dans les endroits les plus reculés. Ces trente dernières années, le Royaume-Uni a encouragé la rénovation des tracés existants, plutôt que de construire de nouvelles infrastructures. Ce changement de stratégie de production d'électricité du Royaume-Uni a fait naître le besoin de nouveaux systèmes de transmission et de distribution d'énergie. Les fondations de ces structures doivent avoir une base adéquate tout en étant rentables en termes de coût et de temps, mais elles sont souvent négligées. En effet, si l'expansion d'infrastructure énergétiques à grande échelle fonctionnait avant, ce n'est n'est pas toujours la meilleure option qui soit aujourd'hui. L'équipement, les techniques d'ingénierie et les matériaux, de même que les mentalités ont évolué concernant les solutions géotechniques durables. Un récent projet de construction de lignes à haute-tension aériennes dans le sud-ouest de l'Écosse a requis l'installation par Cementation Skanska d'un grand nombre de fondations en micropieux inclinées. Les trois voies de transmission, réparties sur une superficie d'environ 650 km^2, mélangeaient des bases en micropieux avec des fondations et poutres traditionnelles, ce a permis de construire sur beaucoup de types sols différents avec une excavation minimale à grande échelle. En cours de projet, on a réalisé des tests de charge de traction pour confirmer les hypothèses de conception et pris les mesures de déformation en fibre optique. Grâce à cela, les techniques et les outils développés ont été sélectionnés et affinés afin de réduire les risques associés à un projet d'infrastructure linéaire d'une telle envergure dans une zone géographique et géologique extrêmement variable.

Keywords: micropiles; overhead lines; foundations; tension tests; fibre optics

1 INTRODUCTION

The transmission of energy through overhead lines has been widely adopted across the world since the 19th century when electric power was successfully transported for the first time 57km from Munich to Miesbach, Germany in 1882. Electricity pylons were first constructed in the United Kingdom in Edinburgh in the year 1928 as the beginning of the implementation of a national power network.

As a nation the United Kingdom has now entered a period of existing line refurbishment and new overhead line construction due to the majority of power lines being installed over 50 years ago. In recent years this has focused on Scotland largely due to the increasing investment in renewable energy. Scottish Power have constructed three new 132kV overhead power lines in the New Cumnock area of South West Scotland, completed in 2018, named as follows:

- Route B – New Cumnock to Dunhill to Blackhill
- Route C – Blackhill to Glenglass
- Route D – New Cumnock to Margree

(See figure 1 below)

Route D replaces a previous line in this location whereas the other two routes provide connections from the newly built wind farms to the local area and energy network.

Cementation Skanska Limited (CSL) worked collaboratively with Wood Plc (previously Amec Foster Wheeler) between August 2016 to February 2018 to provide micropiled foundations

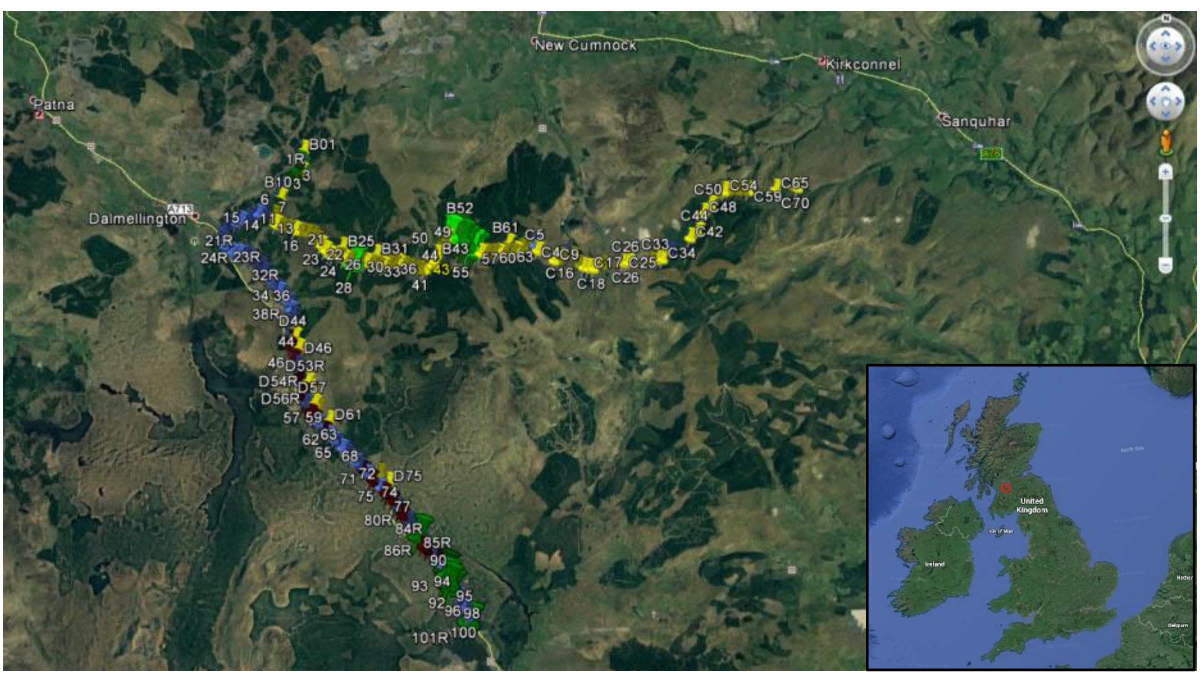

Figure 1. Project location

for the construction of the electricity pylon bases. The project spanned a huge area of land totalling approximately 250 square miles.

2 USE OF MICROPILES FOR OVERHEAD LINE CONSTRUCTION

Various foundation types can be used in the construction of overhead power lines including spread footings, rafts, steel grillage foundations and piles. At the New Cumnock site, a combination of micropiles and spread footings in the form of pad and column foundations were utilised.

The type of foundation required for each electricity tower was dependent on the ground conditions at that specific location. Pad and column foundations were installed where the ground was easily excavated and supported and the founding strata was relatively shallow. Where ground conditions were found to consist of hard rock, extremely soft superficial deposits or high ground water levels micropile groups were adopted instead.

Once the piling rigs were mobilised on site the foundation type could be switched from pad and column to piles with very little notice if required. This was due to CSL developing bespoke design tools to allow quick and easy analysis of new piled solutions. To install the micropiles Cementation employed a percussive overburden drilling system specifically designed to bore through the highly variable superficial deposits. Once bedrock was encountered the drilling system allowed the construction of a rock socket to resist the axial actions. For the majority of the inital works on route's B and D a down the hole hammer method was used to install temporary casings. However, as the project progressed there became a requirement for a permanently cased overburden system to be adopted. This was predominantly due to environmental concerns; the proximity of the Afton Reservoir to route C, the main source of water for the majority of East Ayrshire and the surrounding areas, meant that permanently casing the piles minimised the risk of pollution to the reservoir.

A large benefit of using micropiles was the reduction in programme time compared to pad and column foundations in the case of difficult ground conditions. In addition the micropiling reduced the need for bulk excavation to form deep mass concrete foundations. Hence, in conditions usually considered favourable to pad foundations, micropiled solutions were selected for programme acceleration.

3 GROUND CONDITIONS AND SITE INVESTIGATION

The remote settings and vast areas of overhead line projects bring with them hugely variable ground conditions and logistical challenges for site investigation. On the South West Scotland (SWS) project the ground conditions were as follows.

Superficial Deposits

The superficial deposits encountered on site can be predominantly attributed to the ice age experienced in the Quaternary period approximately 2-3 million years ago. These deposits are composed of glacial till, Hummocky glacial deposits, alluvium and peat. The glacial till and Hummocky glacial deposits consisted of a variety of firm to stiff sandy gravelly clay and dense to very dense clayey sand and gravel. Gravels pose a large challenge to foundation construction and this project was no exception. The significant variability of gravels makes predicting their behaviour difficult and can cause collapse within excavations.

Bedrock Geology

The route of the new power line cut through an extensive number of rock units and strata types; the majority of these were sedimentary in the form of wackes, conglomerates, sandstones, mudstones and siltstones. In addition to this were igneous rocks consisting of basalt and dykes composed of rhyolite and dolerite. The rock formations encountered included; the Western

Midland Valley Sills, the Scottish Lower Coal Measures, the Leadhills Supergoup, the Kirkcolm Formation, the Glenwhargen Formation, the Portpatrick Formation, the Lanark Group Sandstone, the Poltallan Member, the Galdenoch Formation, and the Blackcraig Formation. The area is also known to be heavily faulted according to the British Geological Society maps.

A borehole was undertaken at the centre of each tower location to determine whether spread foundations or piles would be installed. Once this had been determined, the boreholes were used to carry out a bespoke pile design for each pylon. However, as the tower legs could be up to 6m diagonally from the centre of the tower and because the area has been largely impacted by glaciation, the depth to rock head at each leg could vary significantly. Added to this was the complication of regular scheme design changes largely due to the inital route cutting through Forestry Commission land which proved to be steeper or shallower than expected once the dense coniferous woodland was cleared. This led to the relocation of several tower positions, sometimes making boreholes obsolete as they could be up to 100m away from the revised tower location.

Due to the logistical challenges of providing access for site investigation equipment accross land owned by multiple parties, the site investigation scope for such projects is often a function of the equipment that can access the proposed tower position in a single mobilisation. As the site investigation is required as part of the design of any temporary access roads and platforms, equipment often had to be mobilised directly on to the superficial peat. This leads to a reduced scope of geotechnical investigation and a more flexible foundation design philosophy than on a more traditional logistically accessible site.

4 MICROPILE DESIGN

Micropiles for overhead power lines must be designed to resist a complex combination of shear, compressional and tensional forces. In addition to the dead weight loads they must also cater for wind, thermal and ice loading conditions. Lattice tower pylons, as installed at New Cumnock, generally have two of their four legs in net compression and the other two in net tension due to the way that they support the power lines. Overhead line foundation design is particularly special as it is predominantly governed by the tensional forces derived from towers being “pulled over” under certain design conditions.

The design loads for the SWS project provided by Wood Group were based on the guidance in BS EN 50341-1 as modified by the NNA (National Normative Aspects). Generally the factors applied to actions in the UK for geotechnical pile design are in accordance with Design Approach 1 of Eurocode 7 (EC7) as prescribed in the UK National Annex of EC7. The fundamental principle of EC7 remains the same regardless of whether the pile is in compression or tension. The designer must demonstrate that the design satisfies the following condition:

$E_d \leq R_d$ (cl. 2.4.7.3.1 BS 1997-1:2004)

where E_d is the design effect of actions and R_d is the design pile resistance.

The common similarity between the guidance of Eurocode 7 for pile design and BS EN 50341 for OHL design is that both determine the Ultimate Limit State (ULS). Unlike the majority of structures foundation design is carried out for, the actions which the OHL tower foundations must resist are relatively well known and all the various design situations the tower could be subjected to are modelled with confidence. The partial factors for structural design are therefore relatively low compared to those commonly used for pile design. Rather than the standard for foundation design:

$Ed_{STR}=1.35xG_k + 1.5xQ_k$ (ULS-STR),
the factors are reduced to:

$Ed_{STR}=1.10xG_k + 1.3xQ_k$ (ULS-STR). For exceptional load cases, the factors on permanent (G_k), variable (Q_k) and accidental (A_k) actions are likely to be even lower ($1.0xG_k + 1.0xQ_k + 1.0xA_k$). The design actions for OHL design are derived almost exclusively with structural analysis of the tower in mind.

As pile tests were carried out on the project the lower R4 partial factors for Eurocode design, (i.e. R_s=1.4 for shaft compression, R_s=1.7 for shaft tension and R_b=1.7 for base resistance) were utilised with a high Model Factor (MF) of 1.4.

In essence the ULS is checked using the following:

Combination 1: F+M1+R1

Combination 2: F+M1+R4

Where M denotes Material and refers to factors that are applied to soil strength parameters (M1=1.0). The letter R stands for resitance and it refers to pile resistance factors (R1=1.0 and R4=1.4). F is the design action relevant to OHL design, derived using BS EN 50341-1.

Due to the mismatch in the design standards asociated with overhead line support foundations, it has for the most part resulted in bespoke project design philosophies such as the one shown above being utilised on all recent overhead line foundation projects within the UK. Towards the end of the SWS project the National Grid updated their technical specification for overhead line support foundations (TS 3.4.15). Although the SWS project did not involve National Grid infrastructure, the guidance provided by the revised specification confirmed the general design assumptions made despite the factors used for our bespoke design not being wholly in line with the publication.

On the SWS project the design resulted in two diameters of micropiles being installed; a 220mm diameter micropile with a 165mm rock socket, and a 273mm diameter micropile with a 190mm rock socket. The pile diameter was dependent on a combination of the ground conditions at each pylon location and the size of the electricity tower to be constructed.

The particular type of pylon and hence its loads governed the whole pile design, not just the diameter. In order to reduce the shear loads acting on the piles they were raked at the same angle as the stub of the pylon. This equated to an angle of ~10° for the majority of towers with an increased rake of ~15° for the larger towers, as shown in Figure 2. Pylon loads also dictated the number of micropiles required per tower leg. This ranged from 3, 4 or 6 piles per leg therefore for each pylon location there were 12 to 24 piles installed in total. Reinforcement was in the form of 32mm, 40mm and 50mm high yield threaded bars. A single bar was installed in the centre of the pile to its full length using lantern spacers to retain a central position, this was especially important considering that the piles were raked.

Figure 2: Micropiles installed at a rake of ~15°

As a result of the range of ground conditions the pile design was primarily based on a rock socket taking no capacity from the glacial till above due to the inherent variability of the strata and the limited geotechnical investigation. For this rock socket design Ultimate End Bearing (UEB) of the founding strata was modelled as up to 20 MPa in the case of strong sandstone and igneous rocks. The Ultimate Shaft Friction (USF) was taken as a maximum of 1 MPa. On occasion rock was not encountered at the depth predicted by the site investigation; in these instances capacity was taken from the glacial till and a design precluding the need for a rock socket was produced.

5 LOAD TESTING

In order to validate the piles CSL and Wood proposed the following testing regime: "Pile test requirements are to be a minimum of 1% of all piles and one per solid deposit (bedrock) type or drift deposit if these are considered for pile resistance. Additional testing should boreholes highlight a significant variation in ground conditions from anticipated". This meant that a significant number of sacrificial piles, 21 in total, were tested and the results provided an opportunity to better understand the performance of such piles. Although the working piles were installed as raked the test piles were drilled vertically. First of all this was the safest way to conduct the test and secondly testing a sacrificial vertical pile allowed the piles to be subjected to much higher loads. A summary of the test results can be seen in the below table. Piles were tension tested using a 1.5 Mega newton test beam which was designed and fabricated specifically for this project by CSL. The piles were tested to the maximum load that the central reinforcement bar could withstand which was often 200-300% of the design actions using a cyclic test schedule. Four transducers measured and recorded the pile movement in real time throughout the duration of the test. Rather than installing additional piles, reaction to the test loadings were provided by specifically designed test pads fabricated by Cementation. These were two circular steel pads filled with concrete to provide the reaction beam with a level surface to test from, as seen in Figure

Table 1. A summary of the 21 test piles installed

Tower	**Design Verification Load (DVL)** kN	**Movement at DVL** mm	**Maximum test load** kN	% of DVL	**Movement at maximum test load** mm	**Central bar diameter** mm	**Pile Length** m	**Founding Strata**
B1	337	7	506	150	11.8	40	13.5	Mudstone
B2	283	4.7	509	180	7.9	40	15.5	Clay
B10	175	5.1	333	190	12.7	32	12	Clay
B25	248	12	521	210	28.2	40	10.3	Sandstone
B53	175	4.8	333	190	11.2	32	7.6	Clay
B61	170	6.3	525	300	23.8	40	13.5	Clay
D17	283	3.6	481	170	6.9	40	13	Sandstone
D26	283	6.6	481	170	11.6	40	11.7	Chert
D43	175	2.1	333	190	4.5	32	4.5	Siltstone/ mudstone
D44	289	1.3	549	190	3.1	32	7.5	Sandstone
D54	110	1.8	250	275	5.1	32	7.5	Siltstone
D73	110	1.7	330	300	6.3	32	8	Dolerite
D75	110	2.9	275	250	10	32	17	Sandstone
D77	289	3.8	520	180	7.8	40	8	Gravel
D83	170	2.7	425	250	7.6	40	10	Mudstone
C4	158	4.7	300	190	11.5	32	7.5	Sandstone
C11	283	1.3	481	170	1.7	40	9	Sandstone
C26	108	1.6	335	310	8.5	32	17	Sand/ Gravel
C36	158	3.5	332	210	9.5	32	7.5	Sandstone
C44	283	4.5	481	170	9.9	40	12.75	Sandstone
C58	170	3.5	527	310	8.8	40	5.5	Sandstone

Figure 3: Pile test beam set-up

3. These pads saved time, costs and materials and did not damage the piling platform.

Over the course of the project two of the test piles, one on route B at tower location B61 and one on route C at tower location C26, were tested with the addition of sophisticated fibre optic strain and temperature sensors. This allowed a continuous strain profile within the pile to be measured providing increased understanding of how the applied load dissipated with depth. Figure 4 shows the microstrain versus depth relationship within one of the micropile tests at Tower B61. The two lines on the graph represent both legs of the fibre optic loop installed within the pile. Tower B61 was constructed using temporary casing through the glacial tills to a depth of 10.5m below piling platform level with a 3m long rock socket constructed below to resist the axial actions. Due to the limited geotechnical investigation, the superficial glacial till had been ignored when calculating the geotechnical axial resistance of the pile. However, during the static loading of the test pile, the additional continuous strain measurements highlighted that the actions applied at the head of the pile were being resisted, for the most part, within the glacial till. This gave confidence in the geotechnical design parameters selected and allowed the design to evolve along the course of the project to become more efficient.

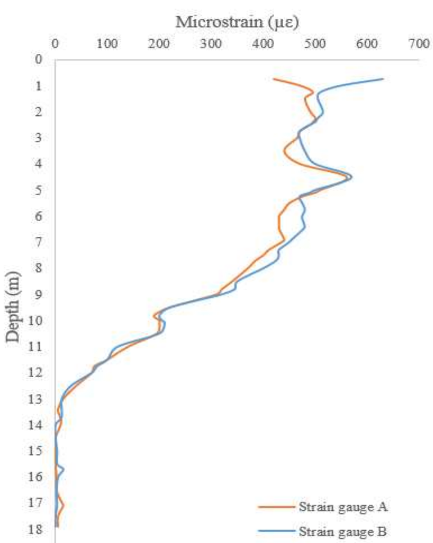

Figure 4: Plot of microstrain versus depth using fibre optic strain measurement at tower location B61

Route C of the SWS project required all the piles to be permanently fully cased to rock head to reduce the risk of grout loss into the peat and an adjacent reserviour. Tower C26 lay in a valley containing deeper superficial deposits than its surroundings therefore the rock at this location was not encountered by the site investigation or during the pile installation. Thus a pile test was conducted. Generally the shaft friction of a fully cased pile installed by an overburden system and down the hole hammer is not relied upon. This is because the drilling system creates an oversized annulus around the casing to aid installation. To mobilise the shaft friction the ground therefore needs to relax and "grab" the casing.

The performance of the test pile at location C26 exceeded expectations. A maximum movement of 1.6mm was recorded at the DVL of 108 kN, recovering to 0.5mm once the load was removed. At the maximum test load of 334.8kN (DVL + 210%) the micropile moved 8.5mm recovering to 4.0mm, as shown in Figure 5. Settlement of this pile was predicted to be

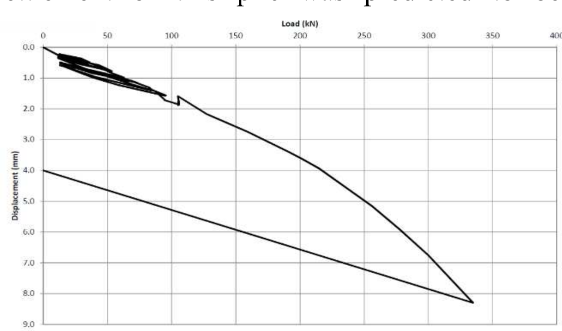

Figure 5: Load displacement graph for the test pile at tower location C26

roughly 1.0mm at DVL and 34.5mm at DVL + 210% indicating that the design parameters may have been slightly conservative and the ability of the soil to "grab" the casing was greater than expected. Back calculations on the data have suggested a likely USF of 350kN in in the sand of the Kirkcolm Formation rather than the 320kN used for design purposes. Hence, the angle of internal friction (φ') of the gravelly sand that the pile founded in may have been slightly underestimated. Our calculations suggest a φ' of 30° represents the ground in this case as opposed to the φ' of 27° used in design. This value was used in conjunction with a shaft friction coefficient (k_s) of 1.0 and a skin fiction (q_s) value of 90kN/m^2. The fibre optic strain measurements taken from this load test allowed the magnitude of the bond formed to be calculated and the design of the foundations to be validated. The fibre optics within the pile demonstrated that along the 17m length, the applied load had dissipated by 13m depth, verifying the foundation design and aligning with the theory that the parameters were slightly conservative.

6 OPERATIONAL AND TECHNICAL CHALLENGES

Across the project a number of non-conformances were encountered due to piles being installed out of position in plan or installed out of rake. Several possible reasons for this were proposed, primarily boulders within the glacial till or tree roots within the peat causing the piles to move out of position during the drilling process. However, as time went on investigations began to suggest that the majority of out of position piles could be due to the nature of the piling platforms. The platforms were built "floating" upon peat making them highly susceptible to movement during the drilling process. Whilst no single cause was identified a possible mitigation measure for future projects could be to increase the allowance for pile plan tolerance.

7 CONCLUSIONS

Cementation have worked closely with Wood Group to successfully develop a bespoke foundation solution to a large new build overhead powerline in the south west of scotland. Throughout the project the design and construction process has been optimised and validated using new inhouse design solutions in conjunction with state of the art fibre optic strain monitoring.

8 ACKNOWLEDGEMENTS

We thank all those on site throughout the project duration working hard to achieve successful completion regardless of the weather conditions. This includes; the pre-construction, design, testing, operations, commerical, procurement and plant teams from CSL, all those from Wood Plc involved in the piling aspect of the project, and Scottish Power Energy Network. We would also like to thank all those associated with the project for their collaboration and support.

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