DESIGN OF GRILLAGE AND HELICAL PILE FOUNDATION FOR LIMITED ACCESS TRANSMISSION LINE

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ABSTRACT

In the summer of 2016 Xcel Energy experienced a storm event that resulted in the collapse of approximately 8.5 miles of a 345 KV transmission line near Rogers, Minnesota. In design of the new transmission line, Xcel Energy determined that ten tower locations would be replaced with steel H-frame structures supported by helical piles instead of wood H-frame structures supported by driven wooden piles. A steel foundation was proposed for the towers due to time constraints and site conditions unfavorable to large pile driving equipment. Xcel Energy contacted the helical pile manufacturer Hubbell Power Systems, Inc. (HPS) for aid in the design of a complete steel foundation for the structure legs. With the shear, moment, and axial loads provided, the manufacturer used pile group modeling and axial capacity software to design a four helical pile group; and used 3D modeling and finite element software to design a moment resistant grillage to connect to the tower base. The steel grillage utilizes a new moment resistant connection and clamp system to transfer loads from the piles to the grillage. This connection provides a true fixed head condition and reduces lateral deflection issues typical to smaller diameter piles in pinned head connections. The clamp is designed to deform the helical pipe pile shaft and transfer the full axial load of the structure through the mechanical and friction connection. The helical piles and the moment resistant grillage were manufactured with shorter than average lead times and a helical pile installation contractor performed the installation. An expedient plan of install was developed by the contractor that resulted in an average installation rate of one complete set of tower foundations per day. The design of the moment resistant grillage, clamping system, and excellent foundation construction by the contractor provided an expedient and efficient foundation system to be discussed in this paper.

INTRODUCTION:

On July 5, 2016 , during a storm event, existing H-frame structures failed and cause the collapse of 8.5 miles of parallel 345 KV transmission lines. During the design of the replacement towers and foundations, representatives of manufacturer, Hubbell Power Systems contacted Xcel Energy (Xcel) to offer the use of a new steel grillage system being developed through the manufacturer’s research and development team. Xcel contacted the manufacturer’s engineering team and worked in conjunction to create a foundation solution. 10 locations were selected based upon the special existing soil conditions. The soil profile in these locations was a soft cohesive material with high water table, making standard foundation systems extremely difficult to install. The foundation solution would consist of a fixed-head, moment-resistant grillage and four 3 in. schedule 80 helical pipe piles (RS3500.300) connected by a new clamp and grout system to the new H-frame steel structures. Xcel required the foundation system to be a turnkey solution with the installation of the foundations being required as part of the foundation package. A helical pile contactor, Atlas Foundation Systems Co. in Rodgers, MN, partnered with the manufacturer to fulfill Xcel’s requirements. Manufacturing of the first set of piles and grillages finished and shipped on September 22, 2016 and the installation of the foundations began on October 3, 2016. This paper will discuss the design, manufacture, and installation of these foundations.

The locations for installation of the grillages were predominantly unseasonably wet. Due to these wet conditions some of the locations for the towers were saturated and others were submerged by up to 5 feet of water. Access was only attained by floating swamp matting. This resulted in making access for larger equipment extremely difficult due to the low allowable ground pressures on the matting.

Borings provided by Xcel showed 10 to 15 feet of soft clay with cohesion less than 500 psf overlaying sandy stiff clay with cohesion greater than 1200 psf. The depth of the water table was reported at approximately 2 feet below the surface. Actual conditions as stated above were slightly different. The stiff clay at approximate depths of 15 to 20 feet was assumed as the bearing stratum for the helical piles. Figure 1 is typical a representation of the soil profile.

DEPTH (FT)	DESCRIPTION OF MATERIAL	N
0	MUCK, black, soft (PT)	1.5
	CLAYEY SILT, brown and gray	3
	CLAYEY SILT, gray and a little brown, soft (ML)	
5		
	SILTY CLAY, gray, soft to rather stiff, some lenses of clayey silt (CL)	3
		5
10		4
		11
15		9
17	End of Boring	
	Water Table = 2.5 feet	

Fig 1. Typical Soil Profile

FOUNDATION OPTIONS

There were several different options available for the foundations of these towers as well as the piles. Both a concrete cap and grillage were considered for pile caps and Helical Pulldown Micropiles, Round Shaft piles, and Combination piles were considered for the piles. This section will discuss the pros and cons of the options as well as what was chosen for this project.

PILE CAP OPTIONS

CONCRETE CAP

Piles are installed in the required layout and then encased in concrete and tied together with rebar to ensure fixity of the piles and for load transfer. Generally a new construction cap is utilized to ensure that the concrete can transfer the axial loads of the piles. This is a cost effective option when forming and pouring a concrete pile cap is a viable solution based on existing conditions and location. There are situations when this is not a good option. For example, where water tables are high, reveal is required, or where concrete is not easily accessible. It is typical that if a contractor can form and pour a concrete cap; a drilled shaft then could also be constructed to support the structure.

STEEL GRILLAGE

A steel grillage is a predesigned system to transfer the loads from the structure to the piles through the moment and shear capacity of steel members. It is generally a welded assembly of plates, beams, tubes, etc. that is a good option where concrete caps are not feasible. One main benefit to steel grillages are the ease/speed of installation and the ability to provide reveal heights for the structure carried by the piles instead of an additional member. Steel grillages may be installed with above or below grade connections. For this application it was preferred that the steel grillage be used above grade and the piles be extended as much as five feet above grade to accommodate for the fluctuating water levels around the structures.

HELICAL PILE OPTIONS

HELICAL PULLDOWN® MICROPILE

A Helical PULLDOWN® Micropile is a helical pile that utilizes lead and extension displacement plates to create a column of grout around a central steel shaft. This creates a pile that has both bearing and friction capacity and can be cased to add bending capacity (generally used if lateral loads are applied), or uncased if bending moments are not being applied.

ROUND SHAFT (RS) HELICAL PILE

Type RS helical piles are structural tubing with welded helixes and upset or welded coupling with bolted connections. RS helical piles are used to resist buckling in weaker soils and to carry shear and moment loads imparted by a structure. The large benefit to RS helical piles is that they have the same moment, shear, and torque capacity through the entire length of the shaft.

COMBINATION PILE**:**

A Combination Pile is a pile that utilizes the penetration and installation efficiency of a square shaft and transitions to a round shaft (pipe pile) for buckling and lateral capacity. The torque to capacity ratio (K_t) of the combo pile is greater than its corresponding pipe pile, but lower than square shaft. Generally the K_t is somewhere between 8 and 9.5 depending upon depth, pipe diameter, and soil type for a 1-3/4 in. round corner square helical lead to RS3500.300 extensions that comprise the combination pile. The standard K_t for standard RS3500.300 Helical Round Shaft piles is 7. This means that for the same torque, the combo pile can get higher capacities than a pipe pile.

FOUNDATIONS SYSTEM SELECTION

The options that were chosen for this project were a steel grillage connected to 4-RS3500.300 helical piles.

The grillage option was chosen because of the high water table of the site as well as the soft soil conditions at the surface. Some of the advantages of the grillage for these sites included: The ability to use small machines to install the piles instead of large pile driving equipment required for driving timber piles or heavy concrete trucks required for cast-in-place drilled shafts and pile cap. Another advantage is the installation rate in the field. The standard installation rate was 1 tower (2 grillages) per day. This is something neither of the other two options could accomplish. These installation rates were able to be accomplished in part because of the clamp and grout system discussed later in this paper.
RS3500.300 piles were chosen to keep the torque capacity and section properties of the piles the same throughout. For a combo pile, the torque capacity of the lead is slightly lower than the torque capacity of the pipe. The original design reveal height for the grillages was 2 feet from grade to the bottom of the grillage, but existing conditions and unseasonably wet conditions meant that for installation the reveal height needed to be as high as 5 feet. A 4 in. schedule 80 sleeve was applied to the RS3500.300 shaft for reveal heights greater than 2 feet to in to increase the buckling and bending moment resistance of the shaft.

GRILLAGE DESIGN

The grillage designed for this project had to be able to transfer the axial, moment, and shear loads of the H-frame structure used by Xcel. The maximum allowable reactions for each structure provided by Xcel were as follows in TABLE 1.

TABLE 1. Design Groundline Reactions

STRUCTURE	LONG. SHEAR (KIPS)	TRANS SHEAR (KIPS)	LONG MOMENT (FT-KIPS)	TRANS MOMNET (FT-KIPS)	COMPRESSION LOAD (KIPS)	TENSION LOAD (KIPS)
80F	0.77	7.7	58.45	108.42	40.15	18.0
85F	0.74	7.69	63.11	130.15	38.38	17.7
90F	0.8	8.88	73.17	174.36	45.14	21.06
95F	0.75	10.19	76.87	225.95	52.82	24.99

The piles for this project were designed using a mixture of software products including: Ensoft's GROUP® and HeliCAP®v2.0 Helical Capacity Design Software. The manufacturer developed load vs axial deflection plots (T-Z Curves) to allow GROUP to estimate the axial deflection of the pile with a given load and better estimate the passive resistance of the soil. This resulted in a better analysis of the moment, axial, shear, and overall displacement results of the piles. A typical lateral deflection plot from GROUP is shown in Fig. 2. This design required the use of four RS3500.300 piles with a helical configuration of 10 in., 12 in., 14 in., and 14 in. helix bearing plates with larger structures requiring a fifth 14 in. helix plate. This pile group was on a 5 ft. pile circle with piles battered at 15 degrees from vertical. With these results, a grillage could be designed to transfer the loads from the structure to the piles.

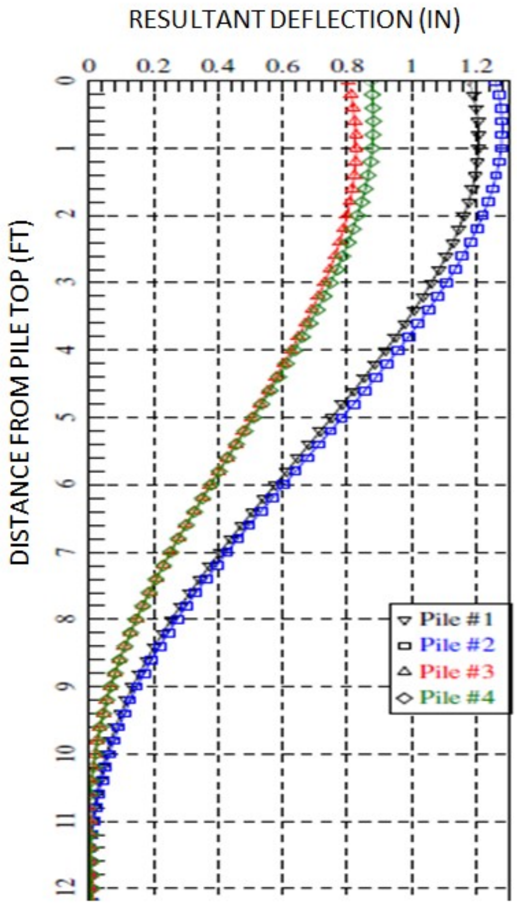

Fig. 2. Typical Lateral Deflection Plot from GROUP Software

The general connection between a steel grillage and helical piles is a pinned head connection. This is mainly because it is generally the easiest and most cost effective means of assembly in the field. A typical grillage connection will look similar to Fig. 3. As can be seen, the pinned head allows for some installation tolerances through slots for bolts. The most common method of having a fixed head condition for a grillage is by welding. This is expensive in the field, so most people prefer to go with the bolted/pinned connection. However, for this grillage, a fixed head condition was required to transfer some of the moment of the structure to the piles and also reduce the lateral deflection of the pile cap to within Xcel requirements.

There are some pros and cons to having a fixed head condition. The positives are that it greatly reduces the lateral deflection of the piles by making the foundation more rigid. However, this does increase the moments in the piles which could be a negative (especially in smaller diameter piles). Another benefit of a fixed connection is that a battered pile design is more efficient and effective than a similar design with a pinned head condition. With the battered piles being fixed in place, there is less vertical deflection from the axial load of the tower because the pile and grillage are working more like a frame rather than two pinned pipes.

The manufacturer had been working to develop a new clamping system for RS3500.300 pipe piles to transfer both compression and tension loads. With the addition of a tube and grout, the connection could be considered fixed. This connection allows for installation tolerances similar to a bolted connection with the fixity of a welded connection. The basic idea behind this clamp and can connection is that a tube can be welded to the grillage and battered at the angle the pile is to be installed at. These tubes can be round or square and are generally between 6 and 10 in. diameter/side length. This generally will result in about 2-4 inches of installation tolerance on the pile location depending upon the size of the tube. The pile is cut off within an inch of the top of the tube and the tube is filled with grout. This grout is what provides the fixity of the connection. Plates are used on both sides of the grillage to hold the grout in place as well as transfer the axial load to the clamps. The clamp is placed under these plates and tightened under the grillage to resist the compressive load. Before the clamp is tightened, a small round puck that is slightly smaller than the inner diameter of the pipe and connected to a threaded bar is pushed below the area of the pipe to be crimped by the clamp. After the clamp is tightened, this puck is then pulled up tight again the area of pipe crimped by the clamp and tightened on the plates on top of the tube providing the tension capacity. Once the grout has hardened, this connection has the ultimate capacity of the RS3500.300 in tension and compression as well as the ability to transfer the full moment capacity without welding or drilling holes.

With this connection, pile locations, and pile loadings determined. The grillage itself could be designed. The basic design for the grillage included an 18-in-diameter tube in the middle with thick enough wall to carry the loads from the baseplate of the grillage to the spreading beams. It was determined that four beams would be required to transfer the load from this central tube to the clamp and can connection. The resulting design of the grillage can be seen in Fig. 3 and Fig. 4. These beams were originally sized using allowable stress calculations and then were checked using the finite element analysis (FEA) software ANSYS seen in Fig. 5. To aid the load transference amount the four beams, two circular washer plates were sleeved over the central tubing and welded to the top and bottom of the beams. This reduced the moment load on the central shaft and removed the need for a coped beam that fit the radius of the central shaft improving manufacturability.

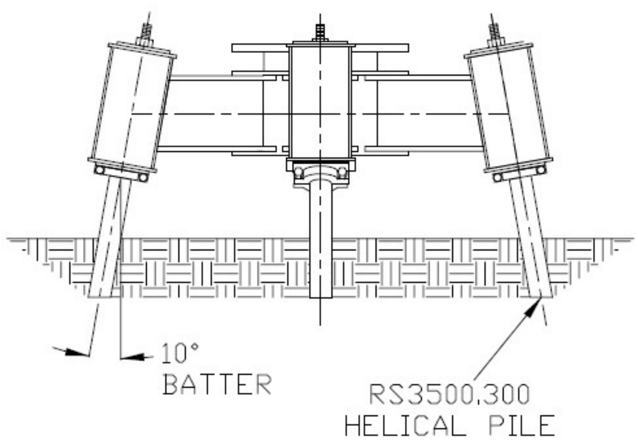

Fig. 3. Elevation View of Grillage

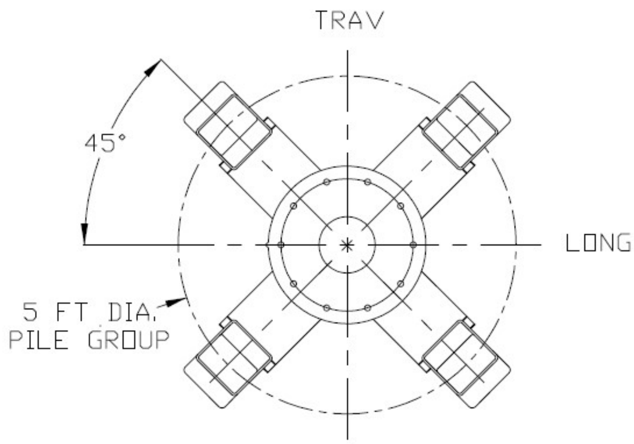

Fig. 4. Profile View of Grillage

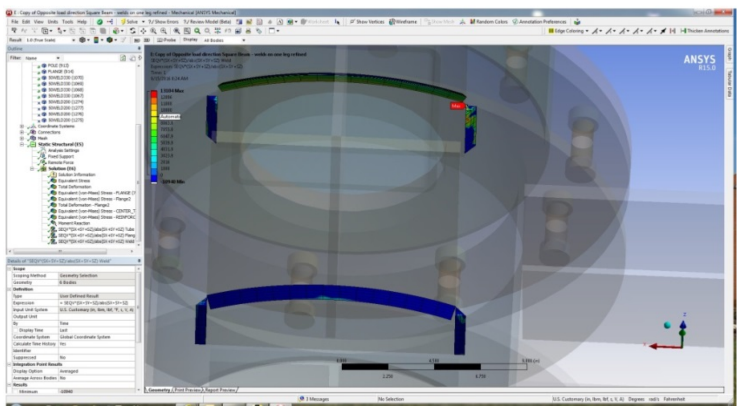

Fig. 5. Weld Analysis using Finite Element Software ANSYS

INSTALLATION

Installation began on October 3, 2016. The helical pile contractor was contracted to install the piles and the grillages. Prior to installation, the helical pile contractor designed a system to install the grillages that would hold the grillage temporarily above the saturated (swampy) soils while using the grillage itself as a template to locate the piles. The center of the tower legs were marked by survey crews provided by Xcel and an RS3500.300 helical pile was installed at the center of the tower leg. A 48 in. square cap was placed over the central helical pile and the grillages of both legs were lowered into place on top of the cap to set elevation and location. A steel square tube was connected between the two grillages to set the lateral spacing between the structures legs. Wooden boxes were inserted into the square tubing grout reservoirs on the ends of the grillage. These wooden boxes were sized such that they would fit the I.D. of the square tubing and had cap boards on the top and bottom of the box with a centered hole large enough to stick a wooden dowel through. The wooden dowel was placed through the box and driven into the soil. After the wooden boxes and the grillages were removed, the four wooden dowels marked the location and angle for installation of each pile. During installation, the alignment and angle of batter of the piles was checked regularly. The piles were installed to the minimum torque requirements for each structure. The torque and allowable axial pile loads requirements for each structure were as follows in TABLE-2 based on GROUP software analysis:

Table 2. Torque and Axial Capacity Required

STRUCTURE	**EFFECTIVE TORQUE (FT-LBS)**	**ALLOWABLE AXIAL PILE LOADS (KIPS)**
80F	7,900	55.3
85F	7,900	55.3
90F	11,600	81.2
95F	11,600	81.2

The grillage was lowered back onto the piles and the required cut elevation was marked on the piles. The cut-off height is 1 to 3 inches below the top of the grillage. The grillage was removed and piles were cut with a portable band saw. The lower pipe clamps were installed with the bolts tightened to finger tight. Void fill material was placed in the pipe a minimum 6 inches below the clamp. This is to insure that the threadbar and grout within the pipe can be installed properly without material falling down the shaft of the pile. A foam sponge was used as void fill material and expanding foam was placed on top of the sponge to seal the void. Once the material was expanded the threadbar with the puck was lowered into the shaft with the puck below the clamp. The large washers were placed over the piles and then the grillage was placed on top of the washers. When the grillage was positioned in the correct location and level in all directions, the bolts below the grillage were tightened to 450 ft-lb. The majority of the tightening was done with an impact wrench with the final torque completed with at torque wrench.
Tape was wrapped around the pile washer to seal the connection between the large washers and the grillage pipe so that grout was contained. A non-shrink grout with a minimum 4,000 psi rating was then used to fill the void around the piles and the square tubing. The pipe is also filled with grout from the void fill material to the point of cut off. This provides a fixed end condition for the helical pile. With the voids and rectangular tubing filled with grout, the top washers and nuts were installed. The nut was tightened until all slack is taken out of the connection. When all components came to bear the nut was tightened a minimum ¼ turn past snug. No structural connections were allowed for the first 7 days so that the grout had time to setup within the square tubing and voids.

Fig. 6. Connection Prior to Grout

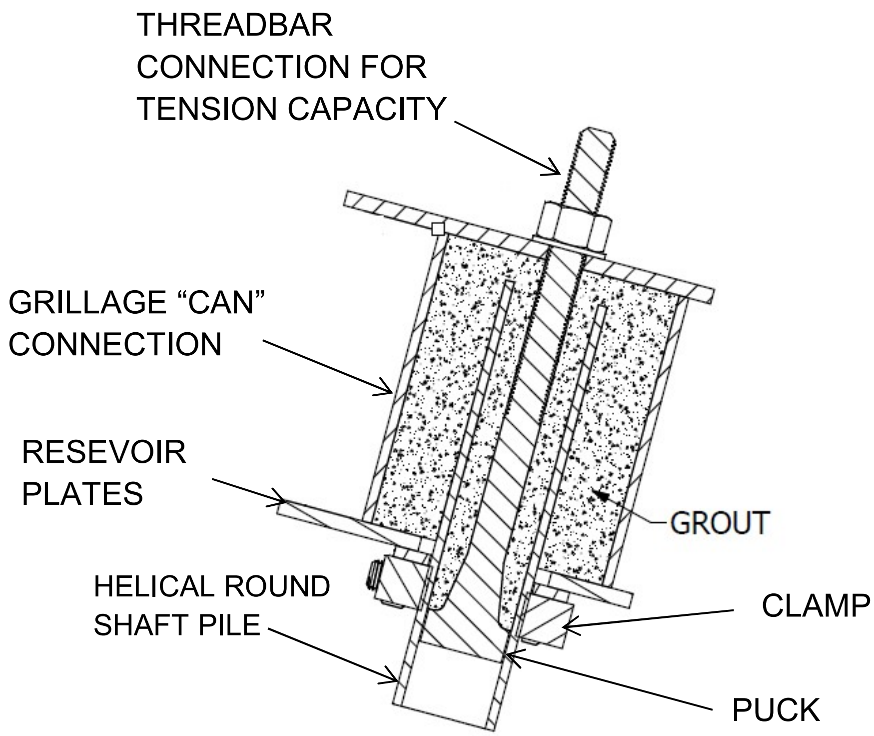

Fig.7. Section of Pile Connection

Fig. 8. Complete Grillage

Conclusion:

This paper discussed the reconstruction of a 345 KV H-Frame transmission line in Rodgers, MN for Xcel Energy. The lines required reconstruction after a storm toppled 10 miles of parallel H-frame structures. The site in question had limited access because of the seasonably wet conditions. Since some of the locations were underwater five feet, floating mats and small equipment were required for the installation of the piles. The piles were designed using both GROUP and Helicap software to model the behavior of the piles in the soils. The boring showed about 10-15 feet of soft clay underlain by a layer of stiff clay that the helices were to bear in. With the results from HeliCAP (axial loading software for helical piles), a model of how the piles work together in the soil can be created using GROUP (an Ensoft product). This GROUP model assisted in the design of both the piles and the grillage.

Because of the requirements of the site: high water table, small equipment access, and requirement for substantial reveal, a fixed-head condition grillage was designed that utilized four RS3500.300 helical piles. These RS3500.300 piles were sleeved with a 4 in. schedule 80 sleeve on some piles to increase the acceptable bending moment and thus allow for greater reveal than was originally planned. These piles were connected to the structure by a new clamp and grout system designed by Hubbell Power Systems that removes the necessity of a welded connection to get a fixed-head condition on a grillage. The clamp crimps the pipe creating a mechanical and friction connection to transfer both tension and compression loads to the pile. The grouted tube fixes the top of the pile in place and transfers both the moment and the shear into the pile. This system also allows for 2-3 inches of installation tolerance on the piles.

The installation began on October 3, 2016. The helical pile contractor designed a system that was very effective in ensuring the grillages and piles were in the correct location and oriented correctly. The grillages were installed at the rate of 2 grillages (one structure) per day. That includes installing the piles, tightening the clamps, placing the grillages, and grouting both grillages.

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