Design and Construction Challenges of Overhead Transmission Line Foundations

Northeast Utilities' Middletown|Norwalk Project

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During the past seven years, Burns & McDonnell has had the opportunity to provide program management and detailed design for Northeast Utilities (NU) subsidiary Connecticut Light and Power (CL&P) on its Middletown|Norwalk 345-kV Transmission Project. The project includes 69 right-of-way miles of 345-kV and 115-kV overhead and underground transmission line. This $1.2 billion project was completed in December 2009.

In order to support to the project locally, Burns & McDonnell established an office near the project site that has been staffed with more than 70 professionals. Under the final design, approximately 45 right-of-way miles of this line were constructed as overhead transmission lines with more than 120 actual miles of overhead line. This will require just over 770 new, single and multiple pole structures to be installed. To accommodate these structures, just under 900 foundations will be required. Given the large scale and conditions of this project, there have been many challenges to overcome regarding these foundations.

Initially, one of the largest challenges was determining the type of foundation best for the rocky terrain. Creating a design process that accommodated the different possibilities was necessary. Geotechnical and environmental questions as well as issues encountered during construction have provided significant challenges. Additionally, the unusually long project timetable created challenges and required a massive coordination effort. This paper will discuss these different challenges and how they were overcome.

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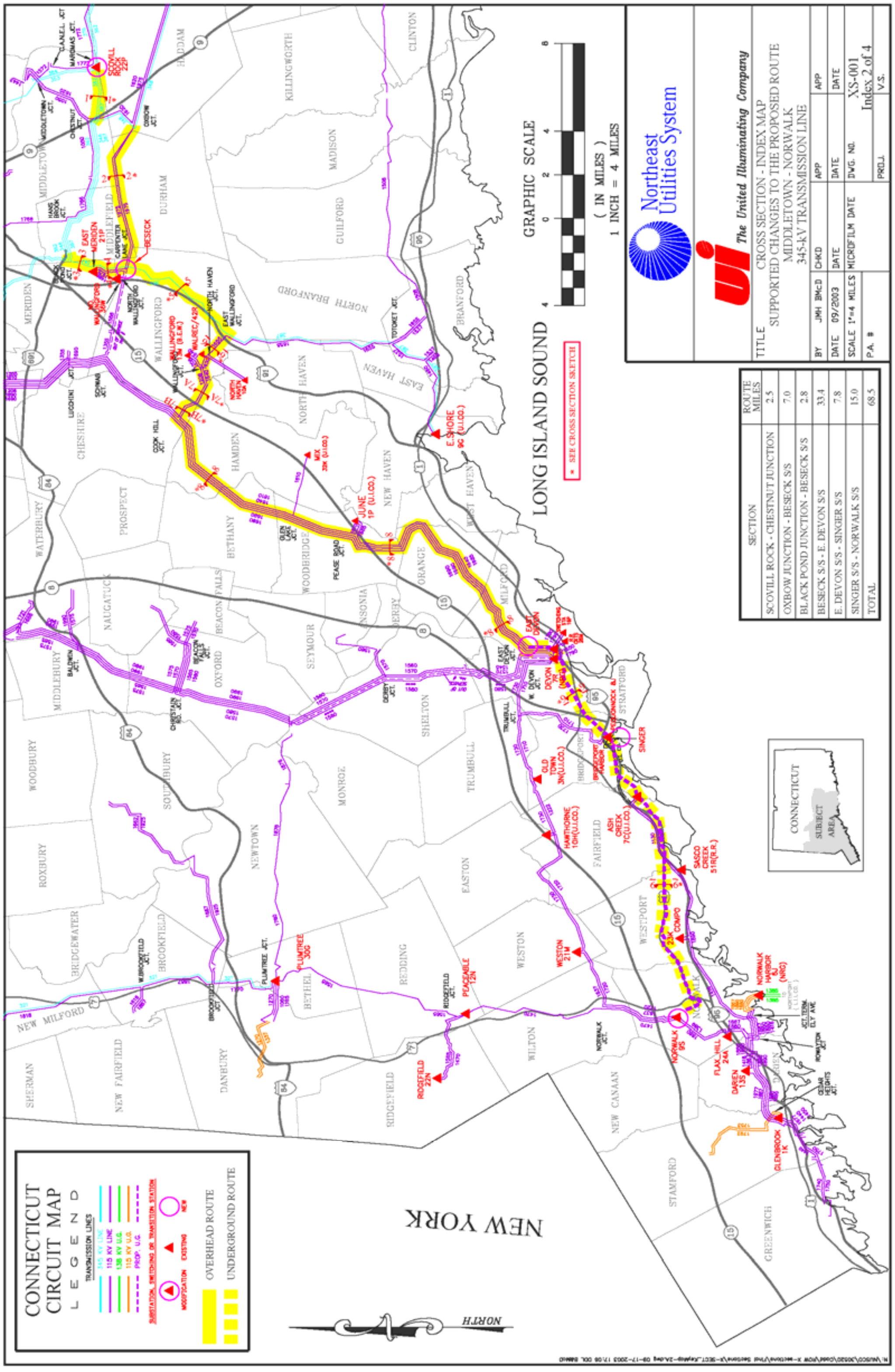
Figure 1: The Middletown|Norwalk line's route through Connecticut.



ROUTE DESCRIPTION

The Middletown|Norwalk Project traverses the state of Connecticut from near the center (Middletown area) to the southwest corner (Norwalk area). See Figure 1. Between Middletown and Norwalk, the project passes though 18 municipalities, with the overhead portion of the transmission line extending from Middletown to the town of Milford. The entire line winds though rural, suburban and urban areas. With the exception of small portions of the line, the route follows existing corridors of 115-kV and 345-kV lines. By making use of several pole configurations and by replacing and upgrading large portions of the existing lines, the final route minimized the disturbance and additional right-of-way required. In some instances small bypasses were constructed to accommodate residential developments that have been constructed along the corridors. With expanding development in the area, right-of-way access and expansion became a large coordinated effort. As with many transmission line projects, construction access also became an issue.

TERRAIN AND SOIL CONDITIONS

The first item to consider in foundation design is the condition of the soil in which the foundation is to be placed. With a project of this size traversing 45 miles of right-of-way (ROW), the soil conditions vary greatly. The second issue is the size of the foundations required. Burns & McDonnell subcontracted Haley and Aldrich, a geotechnical engineering firm with offices in Connecticut, to perform soil borings at each proposed structure location. These locations were based on the initial line designs. As we will discuss, changes to these initial locations provided some of our greatest challenges. Various all-terrain drilling rigs were used to perform the necessary borings and collect soil and rock samples. Where required, small track-mounted rigs were used to gain access to areas of steep terrain and heavy vegetation. Laboratory tests including grain-size analysis, moisture content, unconfined compressive strength of soil and rock, split tensile strength of rock and soil chemistry analysis were performed to provide pertinent design information. Using the information gathered from these soil borings, Burns & McDonnell was able to conceptualize the types of foundation designs that might be feasible. There was now significant evidence that most of the foundations would have to be placed in rock. However, given the rolling and sometimes mountainous terrain, the depth of the different types of soil and rock sometimes changed between adjacent soil borings, let alone the change that occurred between miles of line.

As a generalization, testing showed bedrock at slightly higher subsurface elevations in Segment 1 of the project. Segment 1 comprised everything north and east of the Beseck Substation (seen in Figure 1). Bedrock in this area consisted mainly of schist, gneiss and amphibolite. Topsoil in this area was typically less than 1 foot thick, with thin layers of subsoil and colluvium beneath it at maximum thicknesses of 3.5 feet and 3 feet, respectively. Soil in this area consisted of sandy silt to silty sand with increasing amounts of gravel in the subsoil and beneath. Glacial till consisting of much denser silty sand and gravel containing large cobbles and boulders was found below this. Bedrock in the remainder of the project was slightly less shallow and was composed of sedimentary and volcanic rock. In these areas various amounts of fill material was encountered at a maximum depth of 23 feet. Topsoil in the area was generally less than 5 feet thick with subsoil up to 5 feet in thick as well. In some areas, wind-blown deposits of loose to medium dense silty sand and sandy silt up to 2 feet thick was found beneath the subsoil. Beneath the subsoil and wind deposits more of the same glacial till was encountered.

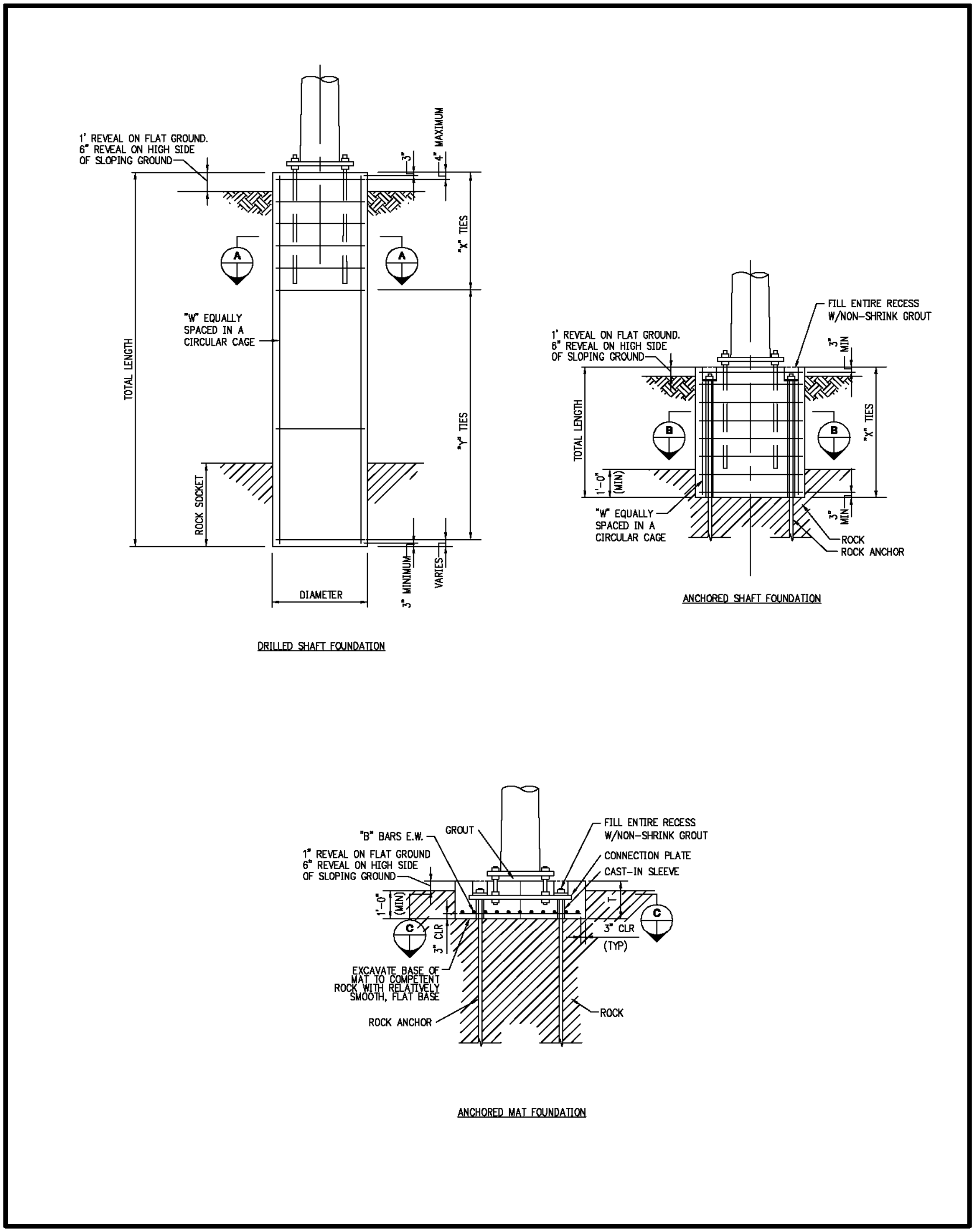
FOUNDATION OPTIONS

Numerous structure configurations support single and double circuit conductors on structures of moderate to extremely tall heights. Additionally, various required conductor tensions produced structures with a variety of loading conditions. The loads that resulted from some of these structures necessitated extremely large foundations. Drilled shafts are a commonly used foundation for tubular steel transmission structures. Because of their design, drilled shafts tend to have the most capacity for resisting large overturning moments from transmission line structures. In many designs, the drilled shafts make use of rock sockets near the base of the foundation to provide the required capacity. In the case of Middletown|Norwalk, there initially was significant concern expressed about the extremely hard and very shallow rock that existed in some areas. With compressive strengths greater than 30,000 psi, there was a concern that the rock could not be drilled with conventional drill rigs. The designers and the construction contractors both believed there could be problems drilling to the required depths for drilled shaft foundations through considerable solid rock. Blasting was considered but was ruled out because of proximity to businesses and residences in some areas, as well as the potential for damage to the remaining rock required to support the foundation. In an attempt to decrease foundation depth, two additional foundation types were considered. In instances where extremely hard rock was deep or nonexistent, conventional drilled shafts would be used; however, when extremely hard rock was relatively shallow, one of the other two designs would be considered, depending on the specific depth of rock. Where more moderate strength rock was encountered, even at shallow depth, conventional rock socketed drilled shafts were still considered most economical.

The first of the alternate foundations was an anchored mat design. This foundation is similar to a spread footing or mat. Instead of installing full length anchor bolts into a thick mat or pedestal, a steel plate placed in the mat transfers the loads from the pole to grouted rock anchors attached to the foundations. These anchors extend from the bottom of the mat and anchor the foundation to solid rock below. This keeps the size of the mat to a minimum while resisting the overturning moments. These types of foundations were intended to be used when very hard rock was extremely shallow, or within a few feet of the ground surface. See Figure 2.

The second alternate foundation was an anchored drilled shaft design. In instances where hard rock was shallow enough to require a rock socket but not shallow enough to necessitate an anchored mat foundation, an anchored shaft could be used. The concept of these foundations was that a standard drilled shaft foundation could be designed to the depth of rock. In order to prevent excessive drilling into rock, the foundation would be anchored to the rock with grouted rock anchors that protruded from the base of the foundation. The rock anchors would span the height of the drilled shaft portion of the foundation before extending though the bottom and into the rock. The anchors were assumed to be prestressed to limit shaft deflection and rotation. See Figure 2.

Figure 2: Various foundation designs.



FINAL DECISIONS

At this point a framework had been established regarding design concepts. With this framework in place, preliminary design was performed to establish bid quantities. As usual a large majority of the foundation designs incorporated the standard drilled shaft approach. This left around 20% of the foundations, which fell within the parameters initially lending themselves to one of the two alternate designs. Areas where rock was present within a few feet of the groundline used mat foundation designs. The remaining areas of concern used the anchored shaft design.

Even though the alternate foundations would ideally save time and money required for the drilling of large quantities of very hard rock, several problems with these foundations were discovered through the bid process. Testing was the first issue. It became obvious that large-scale testing of the rock anchors would be required at each structure site. The problem with on-site testing is that the consequences of a test failing would typically render the foundation useless. If one of the rock anchors did not hold its required capacity and pulled out of the rock below, that foundation would no longer be sitting in a viable location. In turn, this would require moving the structure's location and creating another foundation. Another issue dealt with materials. The materials needed to construct the alternative foundations tend to have long lead times. This was especially true of the large metal plates needed for the mat anchor foundations. Each plate was several inches thick to resist the bending moments with unique hole locations placed in each mat. Because final designs were being completed as the installations of previously designed foundations were in progress, this caused procurement concerns. Discussions with bidders also revealed that the alternate foundations required considerably more labor due the more complex construction. The plates were heavy and would be difficult to handle in the field, and the grouted rock anchors turned out to be a more expensive option than initially considered.

Once construction began, it became apparent that the contractor was not having as much trouble drilling through the hard rock as had initially been expected. With this in mind, the decision was made to redesign all of the alternate foundations so that, if at all possible, drilled shafts could be used. If the rock were to pose serious problems, the original alternate foundation design could still be recalled and put into place. Even though it sometimes required an extended timeframe to drill the newly designed rock sockets in hard rock, it proved to be a more efficient method of foundation placement. Ultimately, there were no structures requiring alternative foundations.

GEOTECHNICAL CONSIDERATIONS

Burns & McDonnell's structural department was faced with determining the reactions at each of the roughly 900 foundation locations for drilled shaft design. Through discussions with NU, parameters for foundation deflection and rotation were determined to be 3 inches and 1.5 degrees respectfully for the entire project. These parameters were used as the basis for the foundation designs. The inconsistent rock depths and varying soil conditions made this a complicated task.

While the presence of shallow rock resulted in shallower drilled shafts for some structures, the internal shear stresses built up in the rock sockets required very tight shear ring spacing for the more heavily loaded drilled shafts.

There were a small number of structures that were placed in areas with very loose soils with shallow groundwater and no rock to provide stability. Providing the required foundation capacities and maintaining the required deflection and rotation criteria in these locations required quite deep foundations. The resulting foundation designs required some of the largest volumes of concrete in the entire project.

Due to the quantity of structures, organizing the boring logs and keeping them coordinated with the foundation designs became critical. Troubles along the way included changes in the structure numbering during design that caused the boring log numbers to be mismatched with the structure numbering scheme. This was overcome by a coordinated effort in organization. As indicated some individual structure locations changed following the completion of the soil borings. These changes made it necessary to make engineering judgments regarding the actual soil profiles and depth to rock in these new locations.

ENVIRONMENTAL CONSIDERATIONS/PERMITTING

As with any project, particularly one of this magnitude, environmental considerations always need to be considered. Burns & McDonnell employs environmental scientists to do exactly that. As usual it was necessary to establish relations with all permitting agencies. For Middletown|Norwalk, the span of the project included a range of permitting agencies. When it came to foundations, there was an increasing concern for the amount of earth that would be displaced during construction. However, the most important environmental issue was the affect the construction would have on wetlands. In order to decrease wetland disturbances, substantial effort was made to keep as many of the new structures out of existing wetlands as possible. Once the structures' final locations were determined, the overall changes and specific structure locations were compiled so that the overall displacement could be provided to all permitting agencies as needed. As the project progressed, the final displacement information was continuously updated with all interested parties.

Overall, more than 250 documents were submitted to different permitting agencies, municipalities and the siting council for review and approval. Permits ranged from items such as road and railroad crossings for the Connecticut Department of Transportation to Tidal Wetlands Permits for the Office of Long Island Sound Program. The U.S. Army Corps of Engineers was involved with wetland protection, while the U.S. Fish and Wildlife Service, National Marine Fisheries Service and the Connecticut Department of Environmental Preservation were all involved in overseeing environmental and wildlife concerns. As stated, the Middletown|Norwalk Project passes through 18 municipalities. Each of these had various concerned parties ranging from tree wardens to planning and zoning commissions. Additionally, approval from the Federal Energy Regulatory Commission and the New England Regional ISO was essential for the technical and monetary authorization of the project. Lastly, a large majority of the required submittals consisted of Development and Management Plans requested by the Connecticut Siting Council. Design changes, extended work hour requests and contractor location information were submitted through these plans.

CONSTRUCTION

Once the Middletown|Norwalk Project moved into the construction phase, a whole new set of challenges presented themselves. Hard-to-reach locations caused mobilization issues, the quantity of foundations caused headaches in procurement, and the variable depth to rock over short distances forced many redesigns for structures that were moved even slightly during construction. Actual site conditions caused significant field changes. Timing and coordination between the owner, contractors, designers and field representatives became critical. Time required to drill rock sockets determined the pace of foundation placement. Other field changes had to be coordinated with drilling schedules so that the affect on the overall timeline could be minimized.

Rocky soil conditions were found to pose less of a problem to drilling than they did to engineering. The upper limits of this decision have been tested and have proved to hold true. Some of our largest rock sockets extended up to 15 feet in depth. Using large, crane mounted drilling equipment the contractor has been able to drill though the largest rock sockets in less than a week. For most rock sockets rock augers and core barrels were used to drill a series of smaller diameter holes to the full length of the rock socket. By drilling a series of smaller holes, the full diameter of the foundation could be reached by breaking up and removing the remaining rock to the appropriate diameter. The exact amount of time it takes to drill these sockets depends, of course, on the size of the drill rig in use and the actual strength and depth of the rock in question. In the worst cases, it was not a large enough loss of time to make the material lead time and additional construction cost required for the alternate foundation designs worthwhile.

One scheduling issue was the difference between what could be considered competent rock for design purposes and what was considered rock for payment to the contractor for drilling. The competent rock that is assumed to provide the needed rock socket for support of the foundation designs often lay beneath layers of weathered or less competent rock. Unfortunately, the drilling contractors assumed that any material not specifically called out as rock would be much easier to drill though. In reality the less competent rock still required significant effort to excavate. The contractor's drilling rates for rock were uniform. Any soil that drilled like rock was charged as rock. Once this was realized, the required drilling could be estimated more effectively. This allowed for a much more accurate construction schedule.

In several locations, loose, sandy soils below the water table were encountered during drilling that required installation of temporary casing. In a few instances, the casing was not properly sealed and the sands were found to flow into the shaft during excavation, resulting in relatively large areas of subsidence surrounding the foundations. In areas of subsidence, the soils were assumed to have become very loose. Pressure grouting was needed to stabilize the soils surrounding foundations and re-establish the anticipated soil strength required to support the foundation. Detailed grouting plans and specifications were prepared to accomplish this work.

Like all projects, field changes had to be dealt with as construction progressed. For foundations, the most significant changes occurred due to the actual depth of competent rock. Initial soil borings were taken for every structure in the initial design of the project. However, issues arose for foundations where borings were taken for a structure that was relocated or where borings were used for structures that were in close proximity but not at the exact location. As the foundation installation took place, it was monitored by the contractor as well as on-site representatives for the geotechnical consultant and Burns & McDonnell to ensure that the conditions were as anticipated. In the event that the conditions failed to conform to expectations, a new foundation design could be generated for the existing conditions. As noted, the most common cause for a foundation redesign was a significant difference in the depth of competent rock.

When a foundation redesign was required, Burns & McDonnell's on-site construction superintendents relayed the information to the design engineers in Kansas City, Mo., where they had a brief period to return a new foundation design that would support the revised subsurface conditions. This communication need brings up the most important challenge faced on the Middletown|Norwalk Project. Without good communication and timing between all parties, significant delays and cost increases could have been experienced. Burns & McDonnell's on-site construction superintendents proved to be the vital link between the field and the design engineers. They coordinated the transfer of all pertinent information from the on-site geotechnical engineers, who provide the required expert opinion of the existing soil conditions. They also coordinated the needs of the construction contractors so that they were able to efficiently use their time and equipment. In addition to coordinating with the field, the design engineers also had to maintain coordination with the pole supplier, Thomas and Betts. In the case of foundation design, all parameters were based on the loads and dimensions that each specific pole originally required. Through cooperation with pole manufactures, delivery of pole designs was coordinated to meet the timing needs of the field for foundation construction. Last, but not least, coordination with NU was critical, not only so that it could stay informed of progress, but so that its engineers could review and comment on multiple aspects of the project.

CONCLUSION

Overall, NU's Middletown|Norwalk 345-kV Transmission Project has been a great success. The overhead line design was completed six months ahead of schedule and under budget. It has shown again the benefits of teamwork within Burns & McDonnell and also within the industry. The foundations in transmission and distribution projects are sometimes overlooked due to the more impressive nature of the project's other aspects, but as engineers we know these foundations offer the hidden support the project requires. Overall, the most important lesson learned from Middletown|Norwalk has been that an engineer can never be too organized, whether the project in question requires a hundred miles of line or just a few. Being able to offer answers during construction, instead of asking additional questions, has proven worthwhile. It provides a perfect example of the need to prepare for all foreseeable situations in design so that construction can proceed as scheduled.