Innovative Use of Precast Segmental-Concrete Foundations at a U.S. Government Facility in a Remote Arctic International Location

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ABSTRACT

Several logistical challenges confronted the project team while designing a radar facility (building and radar tower) for the U.S. Government in the remote arctic. Procurement of construction materials in the U.S., delivery to Greenland, limited availability of construction equipment, and a restrictive three-month construction season all contributed to a complex engineering and construction project.

For foundation construction, traditional cast-in-place-concrete construction was not possible given the lack of batch plants near the remote site. Specialty foundation systems were not an option due to the cost of mobilizing specialty equipment and materials. Precast segmental-concrete foundation elements were the solution: a mat foundation for the radar tower and spread footings for an ancillary radar support building. To accelerate the erection schedule, the design engineers engaged a domestic precaster to cast the foundation segments in Massachusetts and truck them to a port in Norfolk, Virginia. From there, the segments were loaded onto a cargo ship that carried supplies to the project area once a year from the United States. The segments had to be small enough to fit into shipping containers, light enough for site cranes to manipulate, and behave as a cohesive foundation system once installed. Using a combination of grouted splice sleeves and post-tensioning techniques, the contractor completed foundation construction within the short summer construction season. This case study shows how the U.S.-based design engineers worked creatively and successfully with a domestic precaster and a foreign contractor to provide a solution that satisfied the project's many technical and logistical challenges.

PROJECT BACKGROUND

The project involved upgrading the airport radar system at Thule Air Base in Pituffik, Greenland. The upgrade included construction of a new, approximately 40-foot-tall, radar tower and a new elevated 2,700 square foot radar facility building. Thule Air Base is located 750 miles inside the Arctic Circle (Figure 1) and 900 miles from the North Pole. The temperature at the base ranges from -40°F to 70°F with a mean annual temperature of approximately 12°F.

Figure 1 – Arctic conditions at project site

The project site is located on the crest of a 500-foot-high escarpment, and the new structures are founded on permafrost with a 6-foot-deep annual thaw zone. The Unified Facilities Criteria (UFC) governed the structural design; the UFC adopts the International Building Code (IBC) for most of its design provisions. According to the UFC, the design wind speed for the base is 135 mph. However, the amplified escarpment-induced wind effects resulted in design pressures that were more than twice the basic design wind pressures.

Project engineers considered several foundation types including deep, intermediate, and shallow foundations; they ultimately selected shallow precast-foundations. The driving forces for this decision stemmed from concerns about: construction on frozen, weather bedrock; sophisticated foundation work in a remote location; construction quality control; and construction schedule. Foundation construction needed to be completed during a three-month window in the summer season between June and August, when temperatures were amenable for construction.

SITE CHALLENGES

High wind speeds and permafrost soils dictated much of the foundation geometry. For example, designers generally sized the foundations to achieve structural stability and to minimize bearing pressures, but issues associated with construction on permafrost further complicated geometric considerations. Figure 2 illustrates some of the following measures that designers used to maintain both structures in a stable and serviceable condition on permafrost:

- over-excavating the frozen, weathered bedrock,
- placing the new foundations on 12 inches of non-frost susceptible fill,
- backfilling the excavation with non-frost susceptible fill,
- installing a 12-inch-thick blanket of rigid insulation throughout the site in the non-frost susceptible fill to locally decrease the annual thaw-depth, and
- elevating the building to allow 3 feet of air space between frozen finished grade and the warm underside of the building floor.

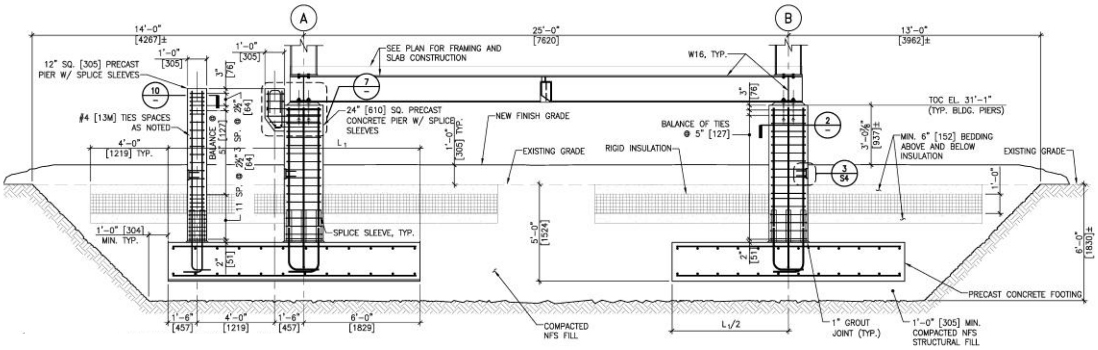

Figure 2 – Section through elevated building foundation and floor system

PRECASTING AND TRANSPORTATION

The limited construction window, the lack of concrete batch plants with quality control measures meeting the project specifications, and concerns about construction on permafrost made traditional cast-in-place-concrete construction impracticable. Project engineers decided to support the building on precast spread footings with tall concrete piers and the tower on a mat foundation. In addition to footings, the elevated building slabs were also precast concrete to expedite building erection. To meet the construction schedule and compensate for the lack of resources, the Massachusetts-based designers had to decide between engaging a domestic precaster (either a precaster near their office, one near the port from which all the precast pieces would ship to Thule), or a foreign precaster (for whom delivery of precast pieces to Thule might be easier). The designers elected to engage a domestic precaster to fabricate the foundations in Massachusetts and transport them by truck nearly 600 miles to the Norfolk, Virginia, Naval Shipyard (Figure 3). Norfolk Naval Shipyard conducts one annual support mission to Thule Air Base in the summer months; the concrete pieces had to be on the June shipment, and there was no tolerance for delays.

(a) Preparing footings in forms (b) Trucking to Virginia

Figure 3 – Precast fabricator

By working with a local precaster, the designers could specify domestic construction materials and practices, work closely with the fabricator to complete design details, and observe the quality of fabrication. The designers, precast fabricator, and material suppliers conferred regularly to determine how best to discretize the foundation pieces into repeatable shapes, how to eliminate the necessity to match-cast adjacent components, and developed details to simplify fabrication and erection. For example, the designer, fabricator, and post-tensioning vendor collaborated to develop details for post-tensioning duct splices in the mat foundation (Figure 4) and grouted splice sleeve details at the pier/footing connections (Figure 5).

Figure 4 – Post-tensioning duct coupler in handhole between mat foundation segments

(a) Splice sleeves in pier form

(b) Placing pier with splice sleeves onto footing dowels

Figure 5 – Grouted splice sleeves for pier/footing connection

As the detailing process unfolded, designers discovered another set of requirements that ended up driving further geometric changes in the foundation designs: shipping and handling. Lifting equipment and transportation methods dictated that each precast foundation element be sized to fit within a shipping container and weigh less than 28,000 lbs. To meet these criteria, the designers discretized the building and tower foundations into modules:

- The spread footings for the elevated building consisted of 7 ft-0 in. by 13 ft-0 in. by 2 ft-0 in.-thick footings weighing 27,300 lbs and 2 ft-0 in. by 2 ft-0 in. by 5 ft-0 in.-long piers weighing 3,000 lbs as shown in Figure 2.

- The mat foundation for the tower consisted of sixteen 7 ft-6 in. by 7 ft-6 in. by 2 ft-6 in.-thick square segments weighing approximately 21,100 lbs each and four 2 ft-0 in.-wide by 2 ft-6 in.-deep border segments weighing approximately 25,500 lbs each as shown in Figure 9.

- The elevated building slab consisted of twenty-eight 6 ft-6 in. by 15 ft-0 in. prestressed panels weighing approximately 7,700 lbs each.

When the design was complete, the fabricator had approximately two months to complete shop drawings and then fabricate and ship over 100 precast pieces from Massachusetts to Virginia. Once in Virginia, the precast pieces were placed on flat-rack shipping containers and loaded onto the cargo ship for Thule.

Despite an efficient and timely precast fabrication process, the precast transportation process was not without incident; two of the 2-foot-wide mat foundation border elements cracked on the drive to Virginia (Figure 6). Designers detailed some long beam-like concrete pieces with minimum mild steel reinforcement since there was relatively little in-service demand on them. Minimum reinforcement was adequate for lifting and handling from the pick points. However, when the precast pieces were loaded onto the truck, blocking supported the pieces at the ends, creating a longer span than that evaluated by the designers. As a result, the pieces cracked en route. Fortunately, the precaster responded quickly and repaired the cracks using an epoxy injection system (Figure 6). Although the damaged pieces sustained some permanent deformation that complicated installation, they were repaired with minimal impact on structural performance and durability.

(a) Cracked mat foundation segment (b) Repaired crack

Figure 6 – Mat foundation border segment cracked and repaired during transportation

FOUNDATION CONSTRUCTION

The foundation components arrived at Thule Air Base at the end of June, several weeks into the summer construction season, limiting the available window for installation. Most of the precast pieces arrived either undamaged or with only minor damage (e.g., broken corners and spalled edges). However, during shipping, handling, or storage, one precast elevated floor panel was significantly damaged and required replacement. The contractor worked directly with the precaster to replace the piece and have it delivered to Thule Airbase the following year.

Building Foundation Construction

The design engineers detailed the connections at the top and bottom of the piers to increase alignment flexibility and allow the contractor to accurately position the piers and their cast-in anchor rods. The bottom of the piers contained No. 11 splice sleeves to connect to No. 9 dowels in the building footings and No. 10 dowels in the tower foundation, and the elevated steel floor framing had 5/16 in. oversized anchor rod holes. Together these details provided the contractor with nearly 1-3/8 in. of horizontal foundation adjustment prior to steel erection.

With the end of the construction season approaching, the contractor placed all of the building piers (Figure 7), quickly grouted the piers to the footings, and backfilled. As a result, the contractor did not take full advantage of the adjustability provided by the oversized splice sleeves in the piers, and the piers were slightly misaligned from their as-designed positions.

Figure 7 – Installing a building pier

This resulted in misalignment of most of the 1-1/8 in. anchor rods, some as much as 1 in. away from the holes in the steel floor beams. The contractor enlarged the anchor rod holes in the beams to fit over the as-built anchor rods (Figure 8). Since the designers detailed the framing and anchor rod projection to accommodate a field-welded plate washer, the contractor applied his solution globally with no impact to the structural performance.

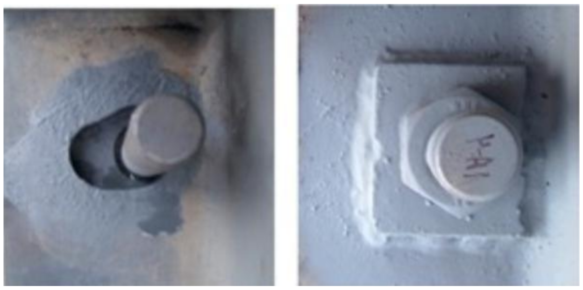

Figure 8 – Modified Anchor Rod Connection

Tower Mat Foundation Construction

Thirty-six 1-1/4 in. diameter post-tensioning bars in two directions clamped the twenty precast mat foundation segments together to create a cohesive 34-ft by 34-ft mat foundation (Figure 9). The overall size of the mat was not only dictated by structural stability and bearing pressures; the designers sized the mat and proportioned the post-tensioning forces to insure that the top and bottom surfaces of the mat stayed in compression under Allowable Stress Design load combinations, considering post-tensioning force losses. Post-tensioning ducts were slightly oversized to improve post-tensioning bar installation. Ducts were spliced with rubber sleeves and screw clamps that could be accessed through blockout hand holes in the top of the mat.

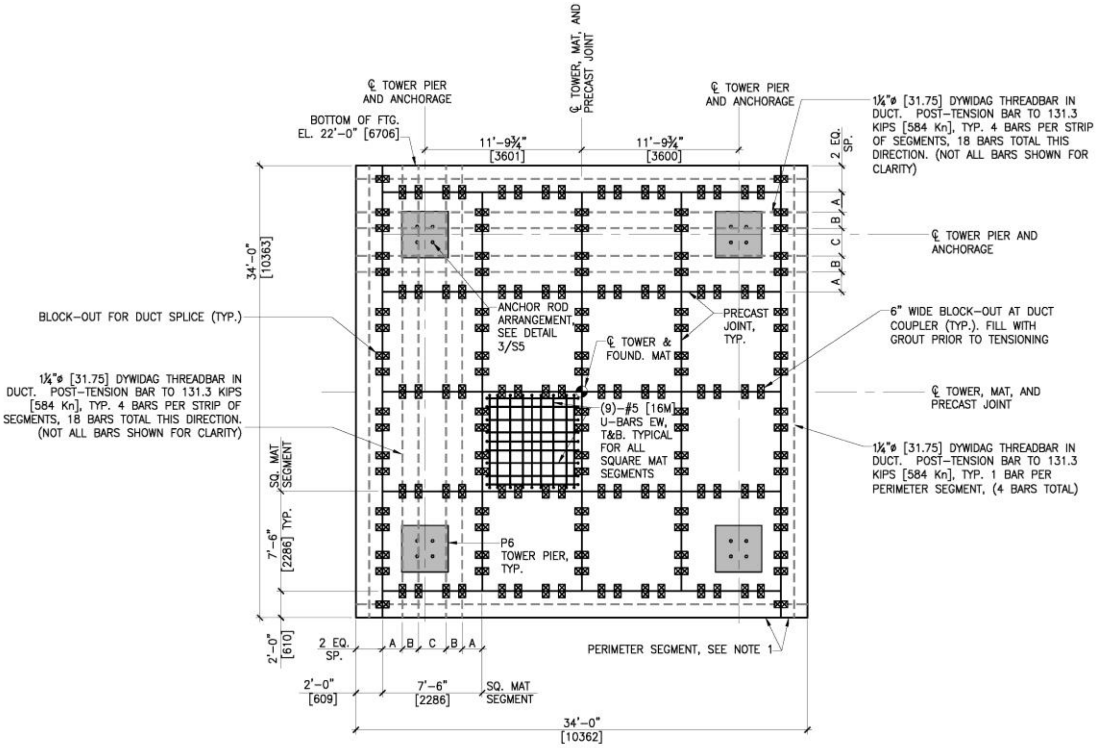

Figure 9 – Plan of radar tower mat foundation

Figure 10 – Foundation placement

This mat foundation construction technique has its inherent challenges (Figure 10). Specifically, while tensioning the bars, it was difficult for engineers to differentiate between gap closure and actual post-tensioning bar elongation when measuring the apparent bar elongations. When the contractor tensioned a bar, the precast segments shifted slightly as the gaps between segments closed; this relieved tension in other bars. To work around this, engineers required the contractor to stage stress and tension the bars in the sequence indicated by Figure 11. The contractor sequentially applied load to the post-tensioning bars in increments of 5% of final stress and closed the gaps between adjacent precast pieces. By incrementally applying load to the post-tensioning bars and tensioning in the sequence illustrated by Figure 11, the designers could observe gap closure, control bar tensioning and tension relief due to gap closure, and confirm permanent tensioning. This systematic method of post-tensioning proved to be very effective; the radar tower fit perfectly onto the foundation anchor bolts with no modification.

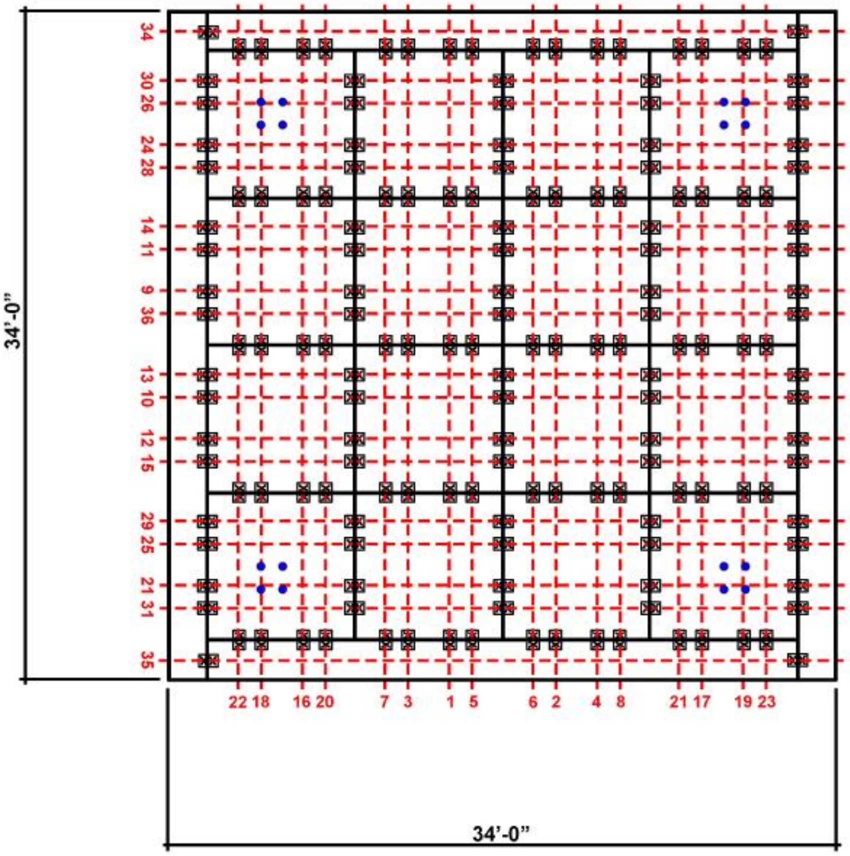

Figure 11 – Bar stressing sequence. The red dashed lines represent post-tensioning bars and the red numbers indicate the order in which the contractor stressed the post-tensioning bars.

Figure 12 shows the measured, apparent bar elongation as a function of jacking force for Bars 1, 3, 5, and 7. The theoretical line in this chart represents the elongation an isolated 36-ft-long piece of post-tensioning bar when subjected to the jacking forces. The plots for Bars 1, 3, 5, and 7 are not linear for the first 30-percent of the jacking force. This occurred because the jacking force applied to the ends of the bars initially serves to close the gaps between the adjacent concrete pieces rather than to actually tension the bars. Once the concrete pieces are drawn together, the load elongation plots for the four bars becomes linear and parallel with the theoretical line, indicating that the bars are actually undergoing elastic deformation and taking load.

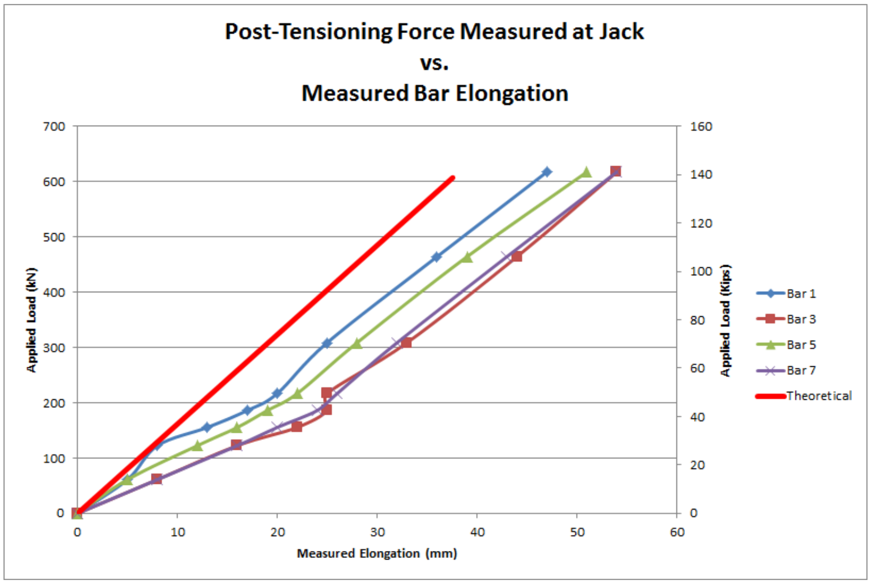

Figure 12 – Measured bar elongation vs. theoretical bar elongation

Of the thirty-six post-tensioning bars shipped to the site, one bar in the shipment was nearly 3 feet shorter than the rest. As a result, it was too short to lock off and tension. The post-tensioning supplier, through expedited air shipment, sent a short length of post-tensioning bar and a bar coupler to the job site. Fortunately, the oversized post-tensioning ducts and rubber duct splice sleeves were large enough to accommodate the bar splicer, and the hand holes in the mat provided enough room to allow the splicer to move during bar tensioning (Figure 13).

(a) Post-tensioning bar stub

(b) Post-tensioning bar splicer

Figure 13 – Post-tensioning bar splice for short bar

Despite this incremental-tensioning approach, not all of the joints fully closed. To complete the mat installation, engineers specified a sealant for the joints between precast pieces, and a cementitious waterproofing product for the entire top of the mat and the four edges.

With the late start of construction, grouting of the post-tensioning ducts had to wait until the following summer. The mat spent the winter wrapped in tarps and plastic, protected from high winds and drifting snow. When spring arrived, the contractor performed lift-off tests to verify bar tension and completed the installation of the post-tensioning system. The contractor was then able to position the tower piers on the mat, align and grout the piers, and erect the radar tower without any issues.

SUPERSTRUCTURE ERECTION

The contractor requested a change in the source for the steel superstructure and building-envelope materials since a cargo ship visits the project area from Europe earlier in the summer months than the U.S. ship. Importing European building materials helped accelerate construction and provided a larger buffer against poor weather or other construction complications. The early end to the first construction season prompted the contractor to request a change in source for the steel superstructure and building-envelope materials. The contractor wanted to switch from the American-specified and manufactured steel and envelope materials to European materials, which could be readily procured and transported to the job site.

With the designers’ assistance, the contractor was able to erect and enclose the building with European construction materials during the second construction season, and allow work to continue inside the building until the next winter (Figure 14).

Figure 14 – Contractor installing roofing material at the end of the construction season

CONCLUSIONS AND RECOMMENDATIONS

This project illustrates the creative use of precast concrete to satisfy unique technical and logistical demands. These unique demands included a harsh arctic environment, significant transportation considerations including limitations on size and weight of structural components, and a limited construction season. The owner, designers, fabricators, and material suppliers worked closely during the design and procurement phase to meet very tight delivery deadlines.

The use of heavy or specialized construction equipment limited the contractor; however, the team worked together to maximize the use of available tools and materials to erect and enclose the structures for the winter. While construction was not without incident, the owner, designers, and contractor regularly communicated to resolve technical or construction challenges in a timely fashion as they arose.

Based on challenges associated with this project, we recommend the following improvements for other projects with similar circumstances:

- Specify and purchase extra accessories (bolts, nuts, plate washers, post-tensioning components) since material availability and transport is a significant obstacle.

- Provide details that maximize adjustability for field-connected components, particularly anchor rod connections.

- Match-cast precast components whenever possible for a better fit and tighter joints. Otherwise, ensure adequate adjustability in connections.

- Think critically about precast pieces with minimum reinforcement and how they will be handled.

- Minimize handling pieces (and potential damage) by loading pieces into shipping containers at precaster, or as early as possible.

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