

Design of a Flexible Stiff-Leg Mooring System, Transfer Bridges, and Foundations at McMurdo Station, Antarctica

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ABSTRACT

McMurdo Station is the largest research station in Antarctica and is operated by the National Science Foundation. Climate change has significantly reduced the lifespan of reinforced floating ice piers that the station constructs for annual offload and resupply operations. A more robust replacement solution was required to meet the station's long-term needs. A steel barge-like floating dock moored in position with stiff legs, overwintering in Winter Quarters Bay, was the preferred option. Two steel orthotropic-deck transfer bridges with box girders were designed as access points between the barge and the shore. The stiff-leg mooring system included flexible axial elastomeric elements (load cells) to secure the barge and limit displacements. Precast concrete stiff-leg foundations were designed to be assembled on-site by post-tensioning two pieces. Barge forces are transferred to slurried freeze-back piles installed in 70 ft (21.3 m) of fast ice. Special considerations were given to account for the harsh environment, an extremely remote location, maintenance considerations, limited on-site resources, equipment limitations, environmental contamination, and climate change.

INTRODUCTION

McMurdo Station is the largest research center in Antarctica. Located approximately due south of New Zealand in Winter Quarters Bay (WQB) at approximately 78° south latitude, it is operated under the National Science Foundation's (NSF's) U.S. Antarctic Program (USAP). Since 1972, the station has received most of its annual resupplies from vessels berthing against and mooring beside a man-made, reinforced floating ice pier during the Antarctic summers typically in the months of January and February (see Photo 1).

Access between the ice pier and the shore (fast ice) is achieved using a Bailey Bridge, which is assembled each year. The fast ice, or "ice wharf" as it is commonly referred to, comprises 'land-fast' ice (i.e., old sea ice) and glacial ice resting on vesicular basalt bedrock. The ice layer is typically over 70 ft (21.3m) thick near the shoreline and was interpreted to be static (i.e., not subject to lateral movements) based on historical site observations of the ice warf since the 1960's.

The ice piers' service life has become unacceptably short, with a typical life span of only a couple years, compared to approximately a dozen years in the 1970s and 1980s. As the ice warms, the reinforced ice piers typically fail by cracking into two or more pieces and eroding around the edges, which impedes offload operations. This creates unsafe conditions and costs millions of dollars in incomplete cargo offload and ice pier reconstruction operations.

The purpose of the NSF McMurdo Offload Infrastructure Project is to replace the ice pier and Bailey Bridge with a semi-permanent system that includes a barge-like floating pier (barge), barge mooring system, and two barge-to-shore (fast ice) bridges with a target design life of 40 years.



Photo 1: United States Coast Guard Polar Star moored adjacent to ice-pier in Winter Quarters Bay (Image courtesy of NSF.).

PROJECT CHALLENGES

McMurdo Station is in one of the most remote and harshest locations on the planet. Construction windows and activities are limited to the Antarctic summertime, which effectively begins in November or December when the United States Coast Guard (USCG) Polar Star vessel breaks ice to the station allowing for the first of two annual sealift resupplies in early January. Resupply of the station typically continues until mid-February. The close of the construction season is weather dependent but typically concludes by the end of March when daily sunlight conditions diminish, and the Southern Ocean begins to form sea ice again. Therefore, two short construction windows are available that do not impede cargo unloading operations at the ice wharf, 1) at the beginning of summer in November and December, and 2) at the end of summer from mid-February to the end of March.

Environmental conditions at McMurdo Station are extremely harsh. Temperatures colder than -70°F (-57°C) are common in the winter and temperatures colder than -25°F (-32°C) occur in the summer. The 700-year, 3-second gust wind speed for the site is 264 mph (425 km/hr) in

the winter and 128-mph (203 km/hr) in the summer. The 50-year sustained 1-hour wind speed is 127 mph (204 km/hr) in the winter and 64 mph (102 km/hr) in the summer. The 50-year, 30-second gust wind speed is 168 mph (270 km/hr) in the winter and 84 mph (136 km/hr) in the summer.

Ice thickness data spanning 30 years provided by USCG showed a nominal winter WQB ice thickness of 6 ft to 8 ft (1.8 m to 2.4 m), with a maximum thickness of 14 ft (4.3 m). Total winter ice loads on the shore ice in the bay were largely driven by thermal expansion forces in WQB and were on the order of 10,370 kip (44.34 MN) (ABS, 2023).

The WQB seafloor contains hundreds of pieces of debris, ranging from barrels with hydrocarbons and unidentified contents to pieces of equipment and tracked vehicles (Kvitek, Bretz, & Iampietro, 1998). Environmental constraints prevent this seafloor from being disturbed by construction activities, which includes pile driving and drilling, due to concerns of contamination of unknown type and proportion. The seafloor debris field also limited the use of cross-bay mooring lines with anchors, which may drag across the bay floor disturbing the debris on the seafloor.

Most domestic construction materials and equipment bound for McMurdo are first transported to NSF's homeport, Port Hueneme, and then loaded on carriers before heading to McMurdo Station. Due to the increased travel distance, the costs and schedules for materials departing from the Gulf of Mexico or United States east coast are significantly increased. This extreme remoteness increased the importance of using materials and equipment on site, as well as using precast elements requiring minimal on-site construction time.

Rubber-tired and tracked construction equipment at McMurdo station is generally limited in size and numbers. The largest station crane is an approximately 140-ton (127-tonne) telescopic crawler crane. Other smaller cranes, telescoping handlers, construction vehicles, etc., are also available. Moreover, a collaborative working relationship exists between USAP and the adjacent Antarctica New Zealand (ANZ) Scott Base whereby use of each other's equipment to achieve project goals is frequently practiced; therefore, a larger crane from Scott Base could be available for use during construction of the McMurdo Offshore Infrastructure.

While McMurdo Station regularly produces coarse fill materials from on-site material sources, limited aggregate production exists for one-inch minus applications such as pile freeze-back slurries. Aggregate needs for the project had to be aligned in quantity to meet the station's production capabilities. Additionally, international law prohibits removing continental soils for certain uses, including barge ballast, because this would violate regulations when the barge traveled off-continent for maintenance.

In some areas, the ice wharf is known to be contaminated with pockets of diesel hydrocarbons (Golder Associates, 2017). Diesel can depress the freezing point of ice and weaken its mechanical strength properties, including pile adfreeze strength. Piled foundations using the ice wharf to resist lateral forces must therefore be sufficiently deep to mobilize as much uncontaminated ice as possible. To achieve this, the presence and relative concentration of hydrocarbons is monitored during foundation installation activities and contaminated ice and water are removed.

Data provided by the NSF shows that the shoreline defined in 2021-2023 surveys has receded significantly from shoreline surveys conducted in 2015-2017. A form of niche erosion known as thermal abrasion is the anticipated erosion mechanism at the ice wharf (Michael Baker International, 2015). Warming sea water temperatures and the increased presence of open water in WQB appear to be increasing the rate of thermal abrasion along the ice wharf.

DESIGN DEVELOPMENT

Concept Development

An early concept for the barge came from an alternative analysis commissioned by the Naval Facilities Engineering Command (NAVFAC) that included a barge-like floating dock or a series of floating pontoons connected together, among other options (R&M Consultants, Glosten Inc, 2017). The modular float alternative was also evaluated by NAVFAC, which considered modular barges owned by the DOD as well as other commercially available options (NAVFAC, 2020). The operational costs of having to install and remove the pontoons each year were considered prohibitive by NSF.

NAVFAC later commissioned an analysis of the moored barge-like floating dock with dimensions of 328 ft by 100 ft (100 m by 30.5 m) and also compared it to the modular pontoon option (PCCI, Inc, 2021). It was at this point that sloped sides were added to the barge-like floating dock, which would cause lateral ice forces to raise the barge out of the water and break the ice in flexure. The barge mooring system also advanced in the analysis. Mooring bollards were added on land. Mooring anchors were removed and replaced with long cross-bay mooring lines, which resulted in an unacceptable barge sway displacement of approximately 40 ft (12.2 m) in one direction, and 80 ft (24.4-m) in total. Two permanent pile-supported bridges were proposed for access between the barge and the ice wharf.

Mooring System and Bridge

Design of a reduced-displacement stiff-bridge alternative began in late 2022. The previously calculated 40-ft (12.2-m) sway displacement was identified as infeasible, especially since pile-supported bridges in the water are not permitted in WQB and therefore would have to be anchored to the ice wharf and allowed to move relative to the barge at the other end. Orcaflex was used to verify the prior analyses, and alternative mooring systems were investigated.

The required traffic pattern was outlined from the ice wharf to the barge and back to the ice wharf, resulting in a counterclockwise pattern (see Figure 2). The concept of using two orthotropic-deck box girder bridges was incorporated into a stiff-bridge design arrangement. Use of the transfer bridges oriented perpendicular to the barge to moor the dock was modeled for the design environmental conditions and with fore and aft mooring lines, which showed a significant reduction in sway but still had approximately 10-ft (3.0-m) surge about the center point.

The decision was made to add a stiff-leg mooring system using steel pipe struts to restrain the barge horizontally (Abell, 1995) (Randall, 1995). This eliminated the need to use the bridges in the mooring system and simplified their design. The orthotropic decks were kept to reduce weight. The stiff-leg mooring system yielded acceptable displacements, but resulted in forces between 2,000-kip and 5,300-kip (8.90-MN and 23.58-MN). Therefore, flexible axial connections were incorporated due to their success on other softened offshore systems.

Several strut angle orientations were evaluated to minimize strut loads, while leaving sufficient ice wharf space for cargo operations and existing infrastructure. The optimum layout occurs when the struts are equally skewed relative to the barge and have a common axis of rotation. The final layout was also set back a minimum of 30-ft (9.1-m) from the 2015-2017 shoreline to allow for shoreline recession. This was the greatest setback that could be achieved without inhibiting station operations. The NSF will monitor shoreline erosion going forward. The

final layout is shown in Figure 1, and a vehicle turning diagram for the design vehicle, a WB-62, is shown in Figure 2.

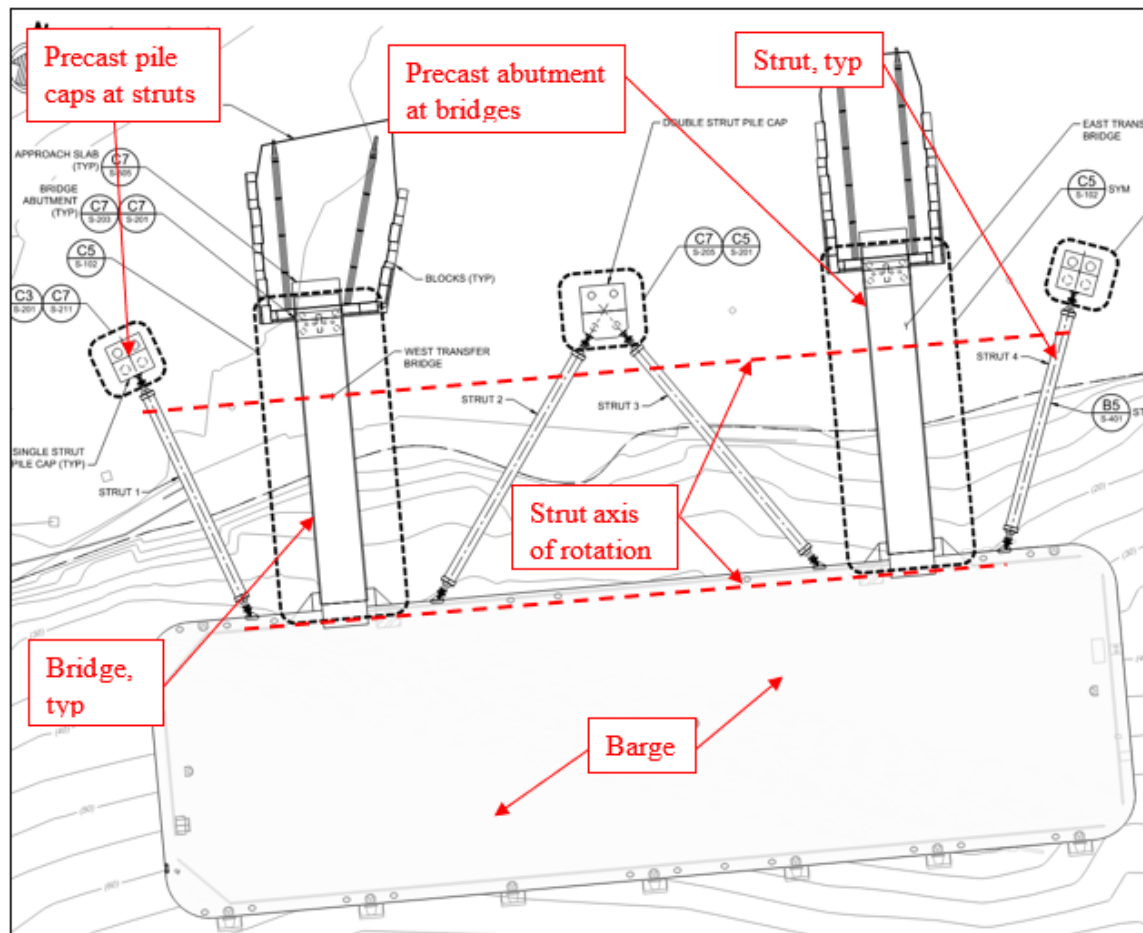


Figure 1: Bridge and foundation layout plan.

The chosen stiff-leg solution came from “load cells” used in the offshore industry which shear rubber to soften reactions and dissipate energy. They are shown schematically in Figure 3. The product uses two concentric pipes with pressure fitted and bonded rubber rings in the annulus. This bond gives the element resilience to axial movements and temperature changes. Stop plates are included to limit the range of motion and prevent overstress in the rubber. A shroud made of Dacron sail cloth is installed over the moving end to prevent water, snow, and debris intrusion into the load cell. The resulting load cells reduced the compression demand to 636 kip (2.83-MN) and the tension demand to 430 kip (1.91-MN) (Glosten, Inc, 2023).

The struts significantly reduced the barge and bridge displacements to a manageable 51 in (130-cm) total, or about 25-in (64-cm) about center. To accommodate this, a corbel was added to the barge to support the bridge without limiting the barge’s working area. A sleeve was added to the corbel, which would receive a pipe with 1 1/4-in (31.8-mm) wall thickness forming a pinned connection to the barge. A slot was cast into the abutment and filled with a pourable silicone to prevent water intrusion and would receive another 1 1/4-in (31.8-mm) pipe to form a roller connection.

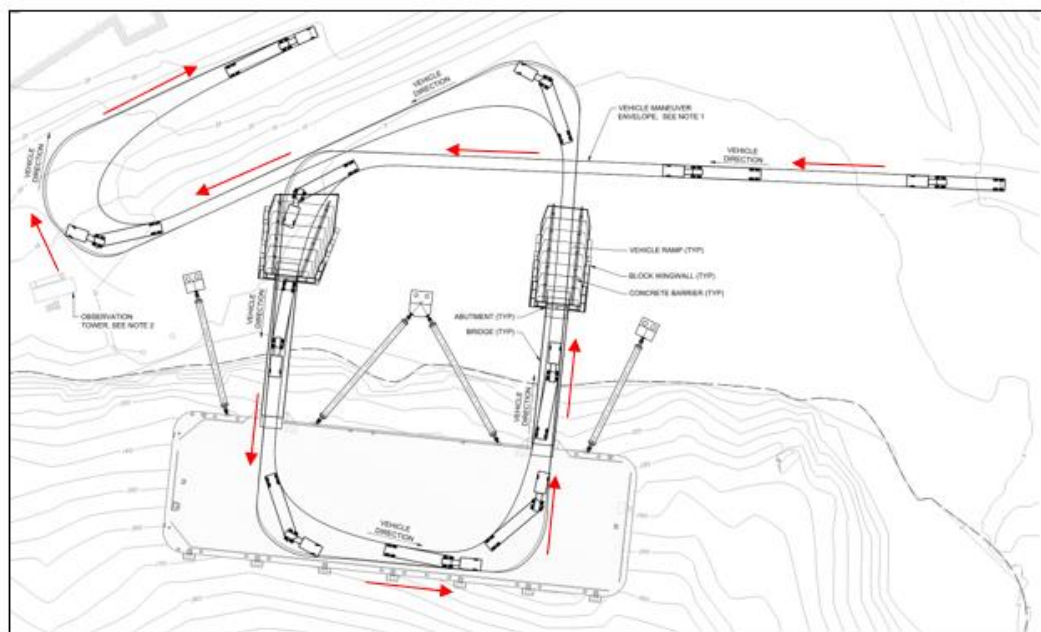


Figure 2: Vehicle turning diagram for a WB-62. Arrows denote vehicle travel direction.

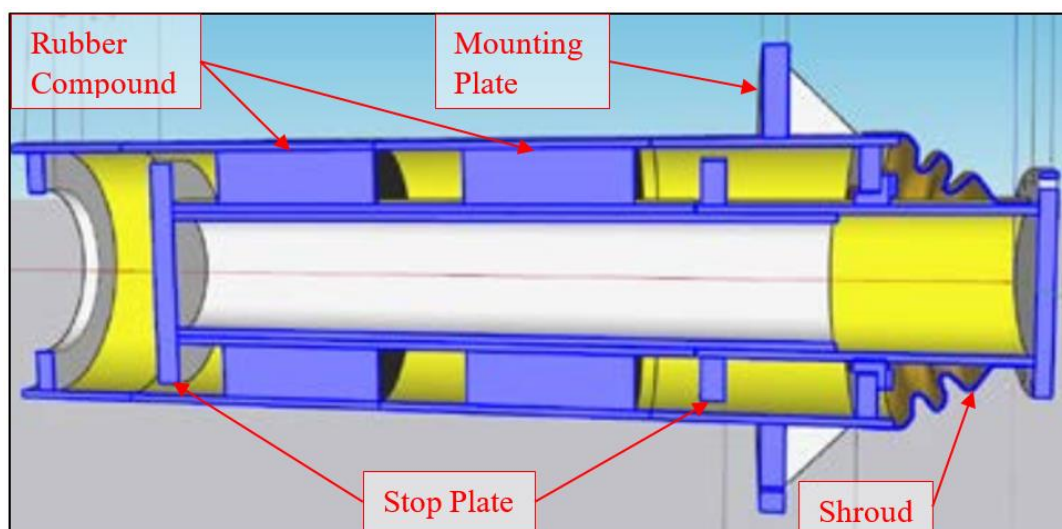


Figure 3: Load cell schematic. (Image courtesy of AIMS Composites, Inc.).

The shoreside bridge displacements and harsh environments created challenges for the bearings. Pot bearings were considered for their low cost and availability. However, their maintenance requirements, including susceptibility to water intrusion and freeze-thaw performance, made them infeasible. Disc bearings were selected due to their ability to accommodate large motions and demonstrated limited vulnerability to freeze-thaw conditions. Both ends of the bridge have removeable Dacron sail cloth encapsulating the bearings and the sliding surfaces to limit the amount of snow, water, and ice that can inhibit the bridges' range of motion. The bridge-to-barge, abutment pin, and sleeve connections are shown in Figure 4.

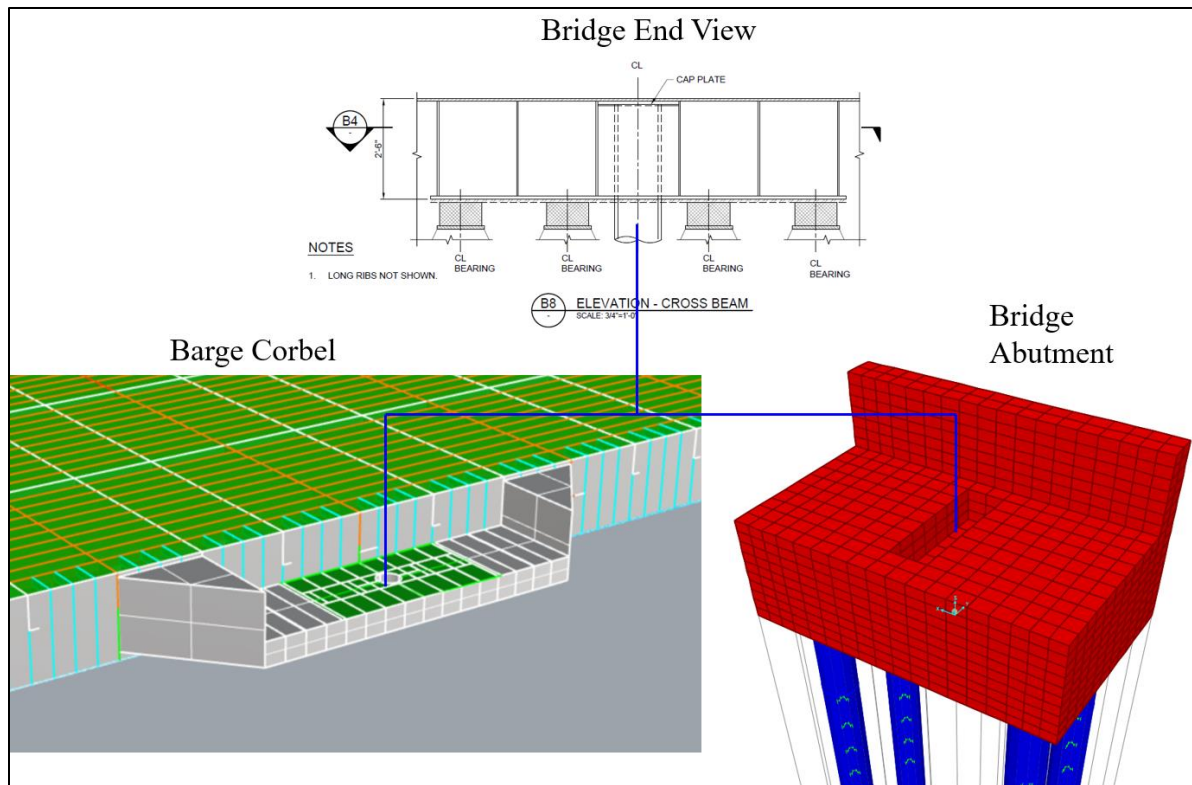


Figure 4: Bridge-to-barge and abutment connections.

Foundations

Precast pile cap foundations were selected to minimize the amount of site work required. Bridge abutments were able to be cast in one piece. Strut pile caps were cast in two pieces, which were then post-tensioned together and are shown in Figure 5. Forces from the barge pass to the struts and through a series of two gimbal hinges and into a mounting plate in the upper block. Concrete tensile breakout capacity was insufficient and required hairpin reinforcing. Force from the top block was transferred to the lower block through a series of post-tensioning rods and shear keys into the lower block. The force then travels into a cast-in steel pipe sleeve via shear lugs, then travels through fins welded to both the cast in sleeve and the pile. Shear lugs welded to the pile ensure bond between the pile and grout. The piles are set in oversized drilled holes and the annulus is filled with a gravel, sand, and water slurry. As the slurry goes through freeze-back, it bonds to the pile.

Piles are installed in fast ice to depths of 70 feet (21.3 m). This depth provides adequate compressive, tensile, and lateral capacity for the precast pile cap foundations. It also avoided the need for rock socketed piles, which would have added another season to the construction schedule. Further, the required foundation setback from the shoreline to reach more shallow bedrock for lateral loads would have made the stiff legs too long, and they would have impeded by cargo operations. Slurry freeze-back piles were selected due to their frequency of use and efficiency in cold regions. The drill hole diameter for pile installations was selected based in part on the available equipment, which was being supplied by a contractor in New Zealand.

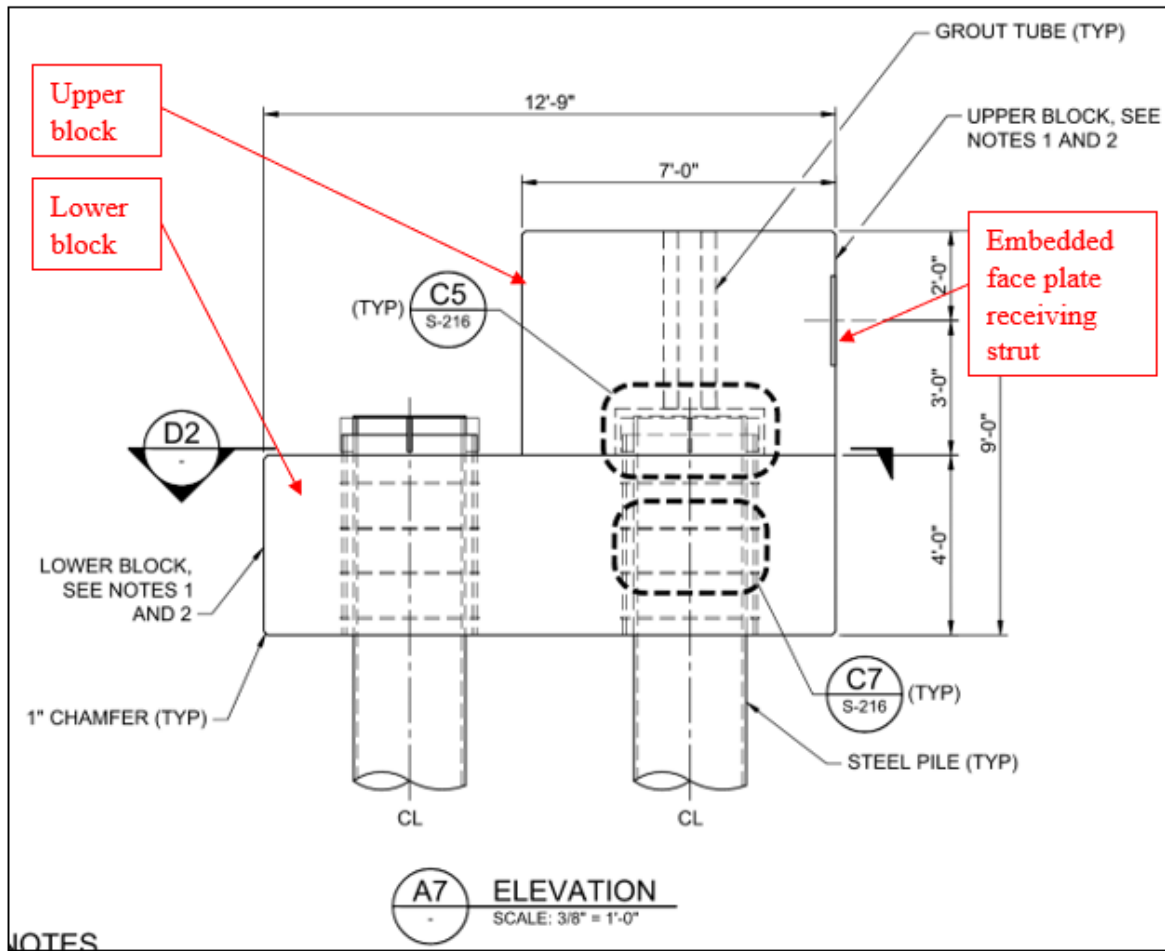


Figure 5: Elevation of foundation supporting a single strut.

LPILE software was used to produce the p-y curves of the ice at various elevations, the method of which was adapted from previous work in ice-rich permafrost (Crowther, 2015). Pile group effects were accounted for using p-multipliers applied to the p-y curves. These final curves were then imported into SAP2000 which was used to analyze the pile foundations. Axial capacity curves were produced for the piles under both “cold” and “warm” ice conditions for strength and service limit states. The “warm” ice profile begins at 29°F (-1.7°C) at the surface and decreases to 25°F (-3.9°C) at a depth of 40-ft (12.2-m). The “cold” ice profile begins at 28°F (-2.2°C) at the surface and decreases to 20°F (-6.7°C) at a depth of 30 ft (9.1 m). All design was performed using the “warm” ice profile, which accounts for the general climate change warming trend and conservatively estimates ice strength and creep properties. Strength curves were used as the capacity to resist short-term, ultimate loading while service curves were used to check long-term ice creep under sustained loads.

Constructability Considerations

The project’s remote location and limited construction window required special attention to reduce the likelihood of delays during construction. Considerations included the potential for

materials being damaged during transportation that could not readily be repaired or replaced, the system installation must go quickly, and the system must be maintained by station staff.

Hinge assemblies for the strut connections, including the pins, washers, and nuts, were custom designed and included grease fittings to ensure longevity. Strut connection components were die-stamped for easy assembly on site. Connection components were shipped and secured in separate reinforced plywood crates banded with stainless steel straps and placed inside a shipping container to prevent damage during transport. Lifting eyes were detailed for strut handling, and redundant eyes were added should one become damaged during handling. Internal diaphragms were included to ensure the struts float should they fall in the water. Pluggable drain ports were added to allow water drainage to support ongoing maintenance efforts. Ultra-high molecular weight polyethylene supports were added to support the load cells when they were installed.

A sensitivity analysis showed that installing the foundations slightly outside of the design positions and orientations could produce large gaps between the pile caps and strut mounting plates. Shim plates of various sizes were required to be provided to modify the system alignment in the field. Brass caps were cast into the precast elements to obtain accurate pile cap orientations. Concrete foundations were designed to be precast and with as few pieces as possible. Shear keys at the interface between the top and bottom blocks lock the pieces into the designed positions.

Using precast concrete allowed for stronger compressive strength and tighter fabrication tolerances than using cast-in-place concrete. Redundant post-tensioning bars were added to accommodate for damage during transportation. Insulation was added below the foundations to promote curing of grout products installed within the pile caps during construction.

Bridge design used an orthotropic deck to minimize bridge weight. A sacrificial timber wear deck was used to reduce damage to the steel deck plate. The bridges width and guard rail height were designed to accommodate snow removal operations. Fiberglass manholes were mounted to the soffit of the box girder flanges to reduce potential injury of maintenance personnel attempting to access the inside of the box girders.

Piles were installed using a template to keep piles within tight construction tolerances. A locally produced gravel infill was used to minimize the amount of slurry backfill, consuming potable water, which the station must produce. A thermistor string was attached to a pile on each foundation in a bent plate housing to allow for long-term temperature monitoring.

CONCLUSIONS

Installing a semi-permanent barge with transfer bridges and a mooring system at McMurdo Station presented a wealth of challenges due to the harsh environment, an extremely remote location, environmental contamination, climate change, limited on-site resources and equipment, shoreline geotechnical conditions consisting of fast ice, and the requirement for the floating dock to be held in place from shore rather than from the seafloor. A stiff-leg mooring system with rubber load cells was found to reduce system forces and displacements to within manageable ranges. A steel bridge with an orthotropic steel deck and box girders with pinned and slotted connections was found to adequately meet the project demands. Precast pile cap and abutment foundations were found to adequately transfer forces to the piles minimizing on site construction requirements. Deep slurried freeze-back piles in fast ice were capable of withstanding the design forces and creep demands.

REFERENCES

- Abell, J. P. (1995). The Trident Explosives Handling Jetty, Royal Naval Armaments Depot, Coulport: From Concept to Construction Contract Award. *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, (pp. 119-135).
- ABS (American Bureau of Shipping). (2023). *Overwintering a Barge at McMurdo Station*. Spring, TX: American Bureau of Shipping.
- Crowther, G. S. (2015). Lateral Pile Analysis Frozen Soil Strength Criteria. *Journal of Cold Regions Engineering*, 04014011-1 - 04014011-14.
- Glosten, Inc. (2023). *NSF McMurdo Offload Infrastructure Mooring Design Report*. National Science Foundation.
- Golder Associates. (2017). *Geotechnical Assessment Report McMurdo Station, Ross Island, Antarctica - Phase II*. National Science Foundation.
- Kvitek, R. G., Bretz, C. K., and Iampietro, P. J. (1998). McMurdo Station, Antarctica: Winter Quarters Bay Marine Debris Study, Final Report. Seaside, CA: NSF OPP.
- Michael Baker International. (2015). *McMurdo Station Shoreline Rehabilitation Recommendations and Basis of Design Summary*.
- NAVFAC. (2020). *Recommendations for a Modular Pontoon Offload Platform for Cargo Operations at McMurdo Station, Antarctica*. NAVFAC.
- PCCI, Inc. (2021). *Barge-Like Floating Pier Analysis McMurdo Station, Antarctica Final Report*. NAVFAC.
- R&M Consultants, Glosten Inc. (2017). *Wharf Study at McMurdo Station, Antarctica - Alternative Concept Analysis*. NAVFAC.
- Randall, R. F. (1995). The Trident Explosives Handling Jetty, Royal Naval Armaments Depot, Coulport: Construction Tow and Commissioning. *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, (pp. 136-148).