

**HEAVY MOVABLE STRUCTURES, INC.
SIXTEENTH BIENNIAL SYMPOSIUM**

September 19-22, 2016

**Lowering a Cofferdam:
Alternate Means to Constructing a
Cofferdam**

Tyler D. VanderLinden, P.E.; PCL Civil Constructors, Inc.

Tom Petray, P.E.; Bittner-Shen Consulting Engineers, Inc.

**TAMPA MARRIOTT WATERSIDE HOTEL AND MARINA
TAMPA, FLORIDA**

LOWERING A COFFERDAM: ALTERNATE MEANS TO CONSTRUCTING A COFFERDAM

Tyler D. VanderLinden, P.E.; PCL Civil Constructors, Inc.; Seattle, Washington

Tom Petray, P.E.; Bittner-Shen Consulting Engineers, Inc.; Denver, Colorado



Figure 1: Rendering of the new Johnson Street Bridge (Reference 1)

ABSTRACT

Construction of Johnson Street Bridge's new bascule pier presented a number of challenges due to its size, proximity to the existing bridge, and soil conditions. As a result of these challenges, PCL explored potential alternative cofferdam construction methods during the procurement process to reduce costs, schedule, and minimize project risks. After the contract was awarded, PCL selected an alternative method which involved precasting concrete floor slabs, using custom concrete formwork as walls, and lowering the entire unit approximately 17 feet with a custom synchronized hydraulic cylinder system. The structure, which weighed more than 1,100 tons, was supported by 16, six-foot-diameter drilled shaft piles that were installed previously as part the permanent bascule pier support system, and were lowered using 32 hydraulic jacks.

The technical paper and presentation uses the Johnson Street Bridge as a case study examining one potential solution to complex site and schedule challenges due to deep water foundations on movable bridge projects. The report focuses on the following key elements:

- Site constraints and factors contributing to this type of cofferdam design;
- Engineering challenges;
- Planning the work;
- Executing the work; and
- Opportunity for future implementation.

INTRODUCTION

In December 2012, PCL Constructors Westcoast, Inc. was awarded the contract for replacement of the existing Johnson Street Bridge (“JSB”) in Victoria, British Columbia, Canada. The current Johnson Street Bridge, built 90-years ago, is a bascule bridge spanning the Inner Harbour of Victoria, British Columbia. The new bridge features a main bascule span in a parallel alignment to the existing bridge, and includes three lanes of traffic, two bicycle lanes, a pedestrian walkway, a multiuse walkway, and a walkway through the bascule “rings” that allow pedestrians to see how the bridge operates during openings. Once complete, the main span will be the longest single leaf bascule bridge in Canada. The one-of-a-kind bridge will feature tapering truss sections and varying geometry on the walkways.

The new bridge will be powered by hydraulic motors and gearing. The existing span, along with a parallel rail span, will be removed as part of the bridge replacement project

Following contract award, PCL evaluated various cofferdam concepts to construct the in-water bascule pier. A traditional driven pile design, precast float-in design, and a design in which the cofferdam was lowered using the previously constructed drilled shafts were all options PCL considered.

The following is a list of advantages and disadvantages the selected concept had over the other options:

- Advantages:
 - Cofferdam can be used as formwork (cost savings);
 - Minimal environmental and existing structure impacts;
 - Not dependent on site subsurface conditions; and
 - Reduced critical path schedule from traditional sheet pile cofferdam construction;
 - Flexibility with on-going design changes.
- Disadvantages:
 - Schedule could be further accelerated with pre-cast float-in (non-concurrent with shaft construction);
 - Engineering intensive (complex and integrated engineering); and
 - Subsurface conditions caused pile locations to vary complicating the design of the bottom slab.

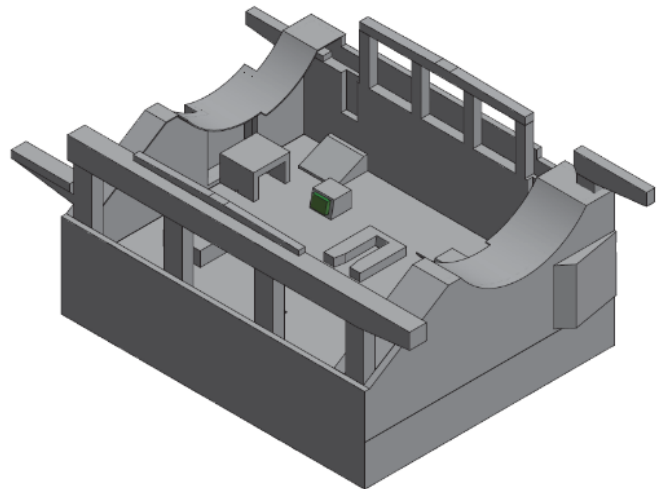


Figure 2: 3D Model of the New Johnson Street Bridge Bascule Pier

The net result was a cofferdam design that required more technical effort but offered significant cost savings over conventional cofferdams.

ALTERNATIVE FLOAT-IN COFFERDAM

Float-in cofferdams have been used on several major bridge projects in the United States and Canada including the Bath–Woolwich Bridge in Maine in 1998 and the Port Mann Bridge in Vancouver, British Columbia in 2009 (See reference 2 & 3). The cofferdam utilized for the Johnson Street Bridge is very similar to its float-in predecessors. However, the new Johnson Street Bridge cofferdam was constructed by suspending the components from the production drilled shaft piles and then lowered into place. Some characteristics the Johnson Street Bridge cofferdam shared with traditional float-in cofferdams include:

- A concrete bottom slab in the shape of a footing to act as both a cofferdam and a bottom form for the pile cap concrete placement.
- Tremie grouting of the annulus between the concrete shell and the production piles to seal the bottom of the cofferdam to the piles.
- A steel follower cofferdam to extend the height of the cofferdam to allow for submergence, construction in the dry, and function as wall forms.
- An internal bracing system to resist the hydrostatic pressure.

Some elements of the Johnson Street Bridge cofferdam that differed from a traditional float-in cofferdam include:

- Casting of modular precast panels to provide formwork for in-plan construction of the cofferdam base slab.
- Suspension of the precast formwork panels from the production piles over the high water elevation.
- Placement of cofferdam base slab reinforcing and concrete over the water.
- Construction of the steel follower cofferdam over the water.
- Lowering of the cofferdam with a synchronized hydraulic jacking system.
- Use of only the bond-shear capacity of the grouted annulus between the base slab and the production piles to resist hydrostatic uplift during the cofferdam dewatering and the downward force during construction of the pier footing at low tide elevations.

DESIGN

The design used to lower the cofferdam with permanent drilled shaft piles involved five distinct elements: precast formwork panels, cofferdam base slab, steel wall forms and bracing, lowering system, and tremie concrete annulus.

PRECAST FORMWORK PANELS

The formwork for the cofferdam base slab consisted of 16 precast panels in 10 slightly different sizes. Each of the precast formwork panels consisted of a 6.5 inch thick slab, an eight-foot-in-diameter corrugated pipe penetration, and a one-foot-thick drop panel at the pile interface. While the span for the precast slab was nearly 20 feet, it was utilized only as a form for the cofferdam base slab construction. This helped expedite schedule through quicker installation and elimination of removal. Due to site constraints, removing traditional falsework and formwork would be extremely difficult.

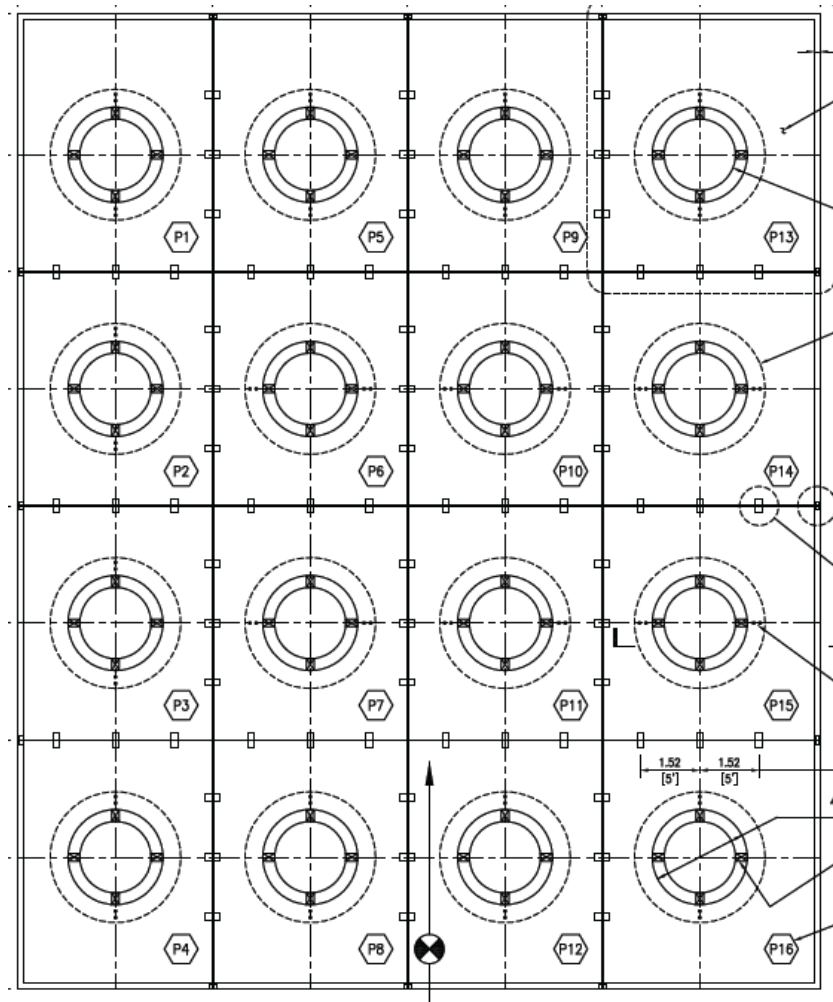


Figure 3: Precast Panel Slab Configuration

The precast formwork panels utilized 6,500 psi concrete to reduce the weight. Due to site and crane restraints the panels for this project had a 55,000 pound weight limit. The perimeter panels were constructed with a two-foot-tall curb to act as the side form for the cofferdam base slab. Given the complicated geometry and boundary conditions of the suspended formwork, a finite element analysis of the formwork panels was conducted in SAP2000 to determine maximum bending moment and shear values for design. Each of the 16 panels were suspended around a production drilled shaft pile and connected together by steel embed and splice plates. High strength threaded rods embedded in the drop panels were used to suspend the panels from the lowering system. The precast formwork panels weighed a total of 284 tons.

COFFERDAM BASE SLAB

After completing the formwork panel erection, the cofferdam base slab was constructed. The precast formwork allowed PCL to construct the heavy cofferdam base slab onsite and above the high water elevation of the Victoria Inner Harbour in dry conditions. The base slab consisted of a two-foot-thick concrete two-way slab.

There were two primary loading conditions for design of the base slab; hydrostatic uplift and concrete footing placement. The controlling load combination was for footing concrete placement at low tide. The design load for the cofferdam base slab was over 1,500 pounds-per-square-foot to support the wet concrete

for the seven-foot-thick footing. The cofferdam base slab consisted of 340 cubic yards of concrete and weighed 690 tons.

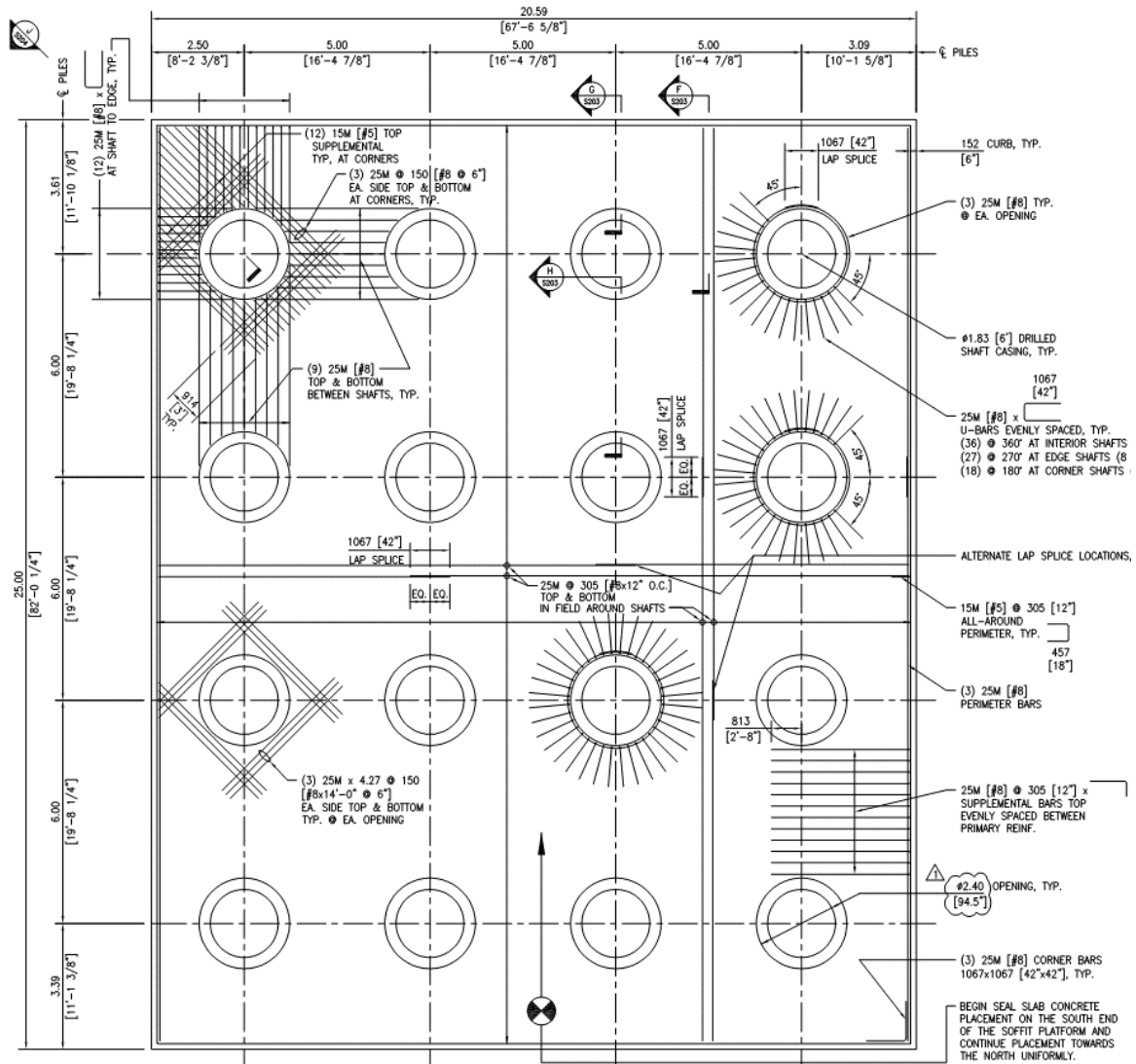


Figure 4: Cofferdam Base Slab

STEEL WALL FORMWORK AND INTERNAL BRACING

The walls of the steel formwork cofferdam were constructed with EFCO form girder panels. The panels served a dual purpose by providing footing construction in the dry, and providing the formwork for the perimeter of the pier footing and walls. The steel wall formwork was subjected to large hydrostatic force of up to 1,000 pounds-per-square-foot combined with tidal current and wind forces. A steel internal bracing frame was installed four feet above the footing elevation, which allowed for full height footing construction to be unimpeded by internal framing.

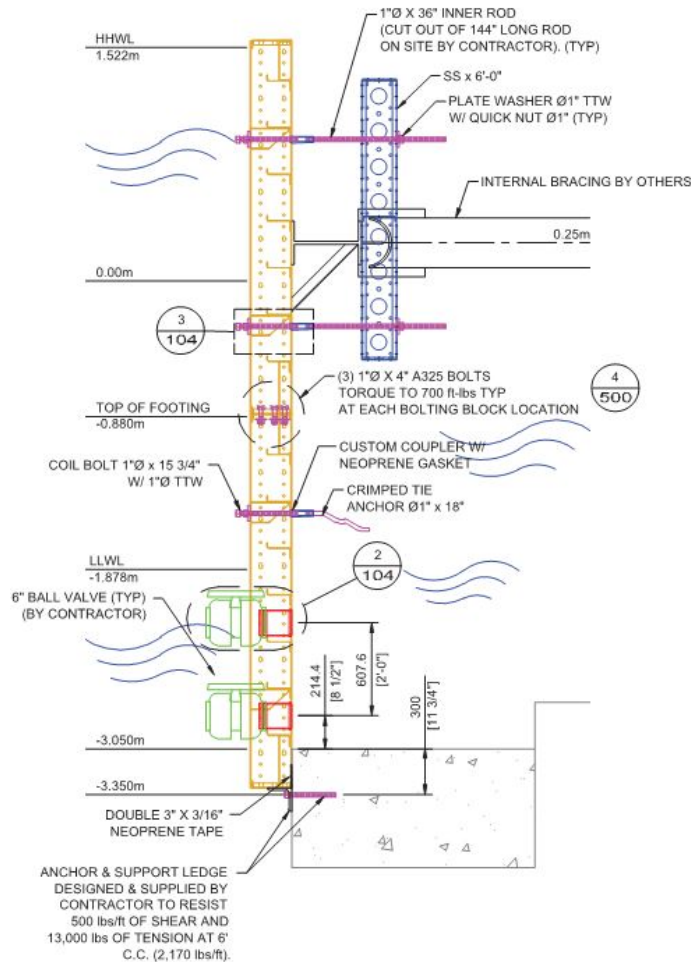


Figure 5: Cofferdam Wall Design

The number of internal framing members was minimized with only a single strut in the long direction and a pair in the short direction. This provided the maximum clearance for delivery of footing reinforcing steel and concrete.

Once the footing was constructed, the internal bracing system was removed so that the pier walls could be constructed without interference. After the pier walls were completed to above the high water line, the steel wall panel was completely removed. The steel wall formwork and the internal bracing weighed approximately 140 tons, bringing the total weight of the cofferdam in excess of 1,100 tons.



Figure 6: Steel Wall Formwork and Internal Bracing Prior to Lowering

LOWERING SYSTEM

The entire lowering theory was based on utilizing the 16, six-foot-diameter permanent drilled shaft piles to support the weight of the cofferdam structure, and a bar lowering method to get the structure to its final position. The design of the lowering system had to support the weight of the cofferdam and lower the cofferdam more than 17 feet.

The bascule pier foundation was not perfectly symmetrical about the drilled shafts. There were certain areas, specifically the corners, where the greatest loads existed. To eliminate confusion during fabrication or construction, the team designed the load transfer, or jacking beams, to resist the single worst-case loading scenario. After careful calculation, PCL decided upon a double W16x57 beam pack complete with multiple bearing plates and several stiffeners.

The precast panels were designed with four 2 inch, 150 ksi high-strength rods extending from the reinforced drop beam. These rods served a dual purpose: transfer the load of the structure into the jacking beams, and to provide the length to lower the structure (using couplers and bar extensions).

An Enerpac EVO Synchronous Lifting System was used for the lowering. The system was designed with 32 individual jacking points (two per shaft). To control the hydraulic jacks, two 12-point and one 8-point hydraulic power unit (HPU) manifolds were linked together by Enerpac. The 12-point and 8-point HPU manifolds are standard Enerpac items. Each single-acting jack was connected to its corresponding manifold with a hydraulic line that provided pressure readings.

To ensure each of the 32 jacks were acting synchronously, the three manifolds were connected via coaxial cable. A custom Master Control Unit (MPU) was built to control the jacks, HPUs, and be the user interface that allowed proper monitoring of the system. The MPU was connected to one of the HPUs via Ethernet cable and, because the HPUs were connected to each other via coaxial cable, the MPU acted as the central device that controlled all three HPUs.

The MPU screen shows each manifold as a separate tab, and each manifold tab shows each jack associated with that particular manifold. PCL's internal engineering department designed the overall lowering system and calculated the expected loads at each jack location. The expected load value for each jack was input into the MPU. If the pressure in the hydraulic lines exceeded that value, then the entire system stopped and could only operate again after manual input from the user. This was an exceptional safety device integrated into the system that helped prevent any major overloading scenarios. There were other safety inputs such as out of level maximums that also allowed confidence in the operation.

Victoria's Inner Harbour is a narrow inlet off the Strait of Juan de Fuca which connects the Puget Sound and Salish Sea to the Pacific Ocean. On any given day, the tidal fluctuations are in excess of eight feet. This tidal shift, coupled with the narrow properties of the channel, created significant currents, which the structure had to withstand without moving during lowering. As a result, a lateral jacking system was designed to help deal with these tidal fluctuations and keep the cofferdam lowering concentrically around the shafts. Each of the 8 lateral jacking assemblies consisted of a 30 ton jack nested in a structural beam which acted against a roller. Pressure gauges were installed on each jack to monitor the progress of the lowering.

TREMIE GROUTED ANNULUS

Once the cofferdam was lowered to its final elevation, plates were fitted at the bottom of the annulus between the piles and the base slab. Tremie concrete was pumped into the 42.5-inch-deep, 12-inch annulus between the piles and the eight-foot-in-diameter holes in the bottom of the cofferdam. A 12-inch annulus was selected to provide sufficient water movement and clearance around the permanent drilled shaft piles (accounting for as-built installation tolerances) during lowering. After the tremie concrete attained a minimum strength of 5,000 psi, the interior of the cofferdam was dewatered at low tide by closing four, 6-inch ball valves, which allowed water to flow in and out of the cofferdam during tide changes. Using two-inch-wide electrical submersible pumps, the remaining water could be removed at a desired rate of 12 inches per hour. Following dewatering, the lowering system and guide systems were removed and the piles cut to grade.

The tremie concrete annulus were designed to provide sufficient bond-shear strength so that no other mechanism was required for transferring the weight of the 1,100 ton cofferdam, the 3,000 ton footing, or the hydrostatic uplift forces to the production piles. The bond stress required to resist the maximum service load was 38 psi. Given the difficulty of inspecting the quality of the concrete connection and the long path the grout had to travel to fill the annulus, a test program was conducted to ensure proper grout consolidation. The test program was completed underwater using divers in the exact environment that the permanent placement would take place. In addition, the test tremie and sample concrete cylinders were cured underwater to accurately reflect the curing conditions of the production tremie.

CONSTRUCTION

Similar to the design phase, the construction of the cofferdam was categorized into major work activities:

1. Precast foundation and base slab;
2. Walls and internal bracing;
3. Lowering system; and
4. Sealing and dewatering.

PRECAST FOUNDATION

One of the challenges faced on the project was lack of space. This issue was exacerbated when it came time to build a casting bed for the precast panels. The solution was to build the casting bed and storage area on the existing bridge approach on the west side of the project, the other side of the project from the bascule pier.

Because PCL chose the precast cofferdam method, the panels could be constructed concurrently with the ongoing bascule pier drilled shafts. As a result, an eight-week-long activity was removed from the onsite critical path of the project.



Figure 7: Installation of the First Panels

After installing all 16 panels, the base slab work commenced. While the slab consisted of a significant amount of reinforcing steel, it was a simple slab to construct and place even over the water.

WALLS AND INTERNAL BRACING

To eliminate any temporary bracing requirements, the internal bracing system was installed first. Shoring towers were staged around the perimeter of the slab to support the whaler beams. As seen in Figure 8, installation started with the outside whaler beams first, followed by the internal bracing beams.



Figure 8: Completed Internal Bracing System

With the internal bracing system installed and serving as the template, exterior wall forms were installed. Four custom fabricated 8-foot by 6-foot EFCO forms were pre-assembled into 16-foot by 12-foot gang forms prior to being erected in place.

The main concern with the wall system was keeping it watertight. A combination of rubber and neoprene gaskets were installed between each form joint and interface to act as compressive membranes that would hold-up over a long period of time. In action, the joints between panels held up well and little leaking occurred. However, the joint between the steel forms and concrete bottom slab was the joint that leaked primarily. On Johnson Street, the steel forms connected indirectly to the concrete bottom slab using a steel angle. In future applications, it is recommended to make this connection directly and eliminate the angle so that the connection can be made as secure and watertight as possible.

LOWERING SYSTEM

The cofferdam was lowered using 32 individual, high tonnage jacks acting synchronously utilizing a central Master Control Unit. One unique element of the jacks was that they were each outfitted with “string pots” to monitor the height of each jack and to keep each jack at the same position relative to one another. This electronic string pot was also connected to its corresponding manifold and provided cylinder stroke information. After all of the jacks were installed, the cylinder stroke and pressure values were input into the MPU and the jacks were leveled (the 100 ton and 150 ton jacks had slightly different heights).



Figure 9: Typical Jack Assembly

When it came time to lower the cofferdam, a bar lowering method that included 2-inch-diameter, 150 ksi high-strength rods, spherical hex nuts, and dished bearing plates was used. The inner two rods carried the entire structure load throughout the lowering, with the two outer rods acting as “safeties” in the event of a rod failure. The safety rod hex nuts were consistently kept half of an inch above the loaded rod hex nuts to limit potential free-fall distance.

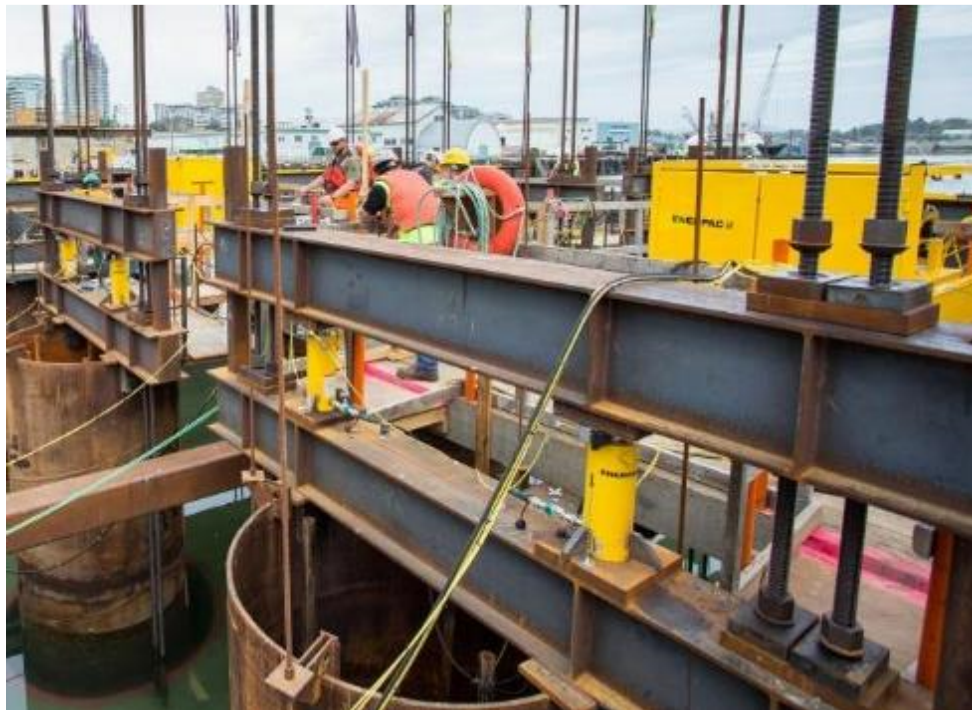


Figure 10: Detail of Bar Lowering Method

The entire lowering process consisted of approximately 45 cycles and was completed in three 10-hour shifts. Once the cofferdam had reached its final lowered position, prisms previously installed at each corner of the structure were surveyed and the lateral jacking system was utilized to position the cofferdam in the designated location.



Figure 11: Cofferdam in Lowered Position

Over the course of the lowering, the elevation difference between the NE and SW corner of the cofferdam was 2 inches, even with all of the manual checks and jacking system technology employed. This trend was noticed early on in the lowering process during intermittent surveying of the four corners. As a result of the survey, lowering continued until the lowest point of the cofferdam was at the final elevation. At that point, the four corners were surveyed and an elevation grid interpolated to each shaft location was created, essentially giving an elevation delta at each shaft location. The Synchro-Lift system has a function called “Tilt” in which the user can input individual values for each jack. The elevation delta values for each pair of jacks (one delta per shaft) were input and the Enerpac system leveled the structure with the push of a button.

SEALING AND DEWATERING

After the cofferdam was lowered, the next step was to raise the steel plates to seal the gap between the piles and concrete prior to concrete placement. The tremie placement was completed with no issues as a result of the time spent upfront with a full mock-up. After ample cure time, the ball valves in the EFCO forms were closed at low tide and the cofferdam was dewatered.

Following removal of the lowering system and access platforms, the relatively clean and dry cofferdam was ready for reinforcing steel. Because the cofferdam itself was not in the water very long, it did not require extensive cleaning like traditional cofferdams, which are submerged for a significant period of time prior to dewatering. Figure 12 shows the interior of the cofferdam following removal of the excess casing and a

thorough cleaning. The cofferdam served as the base of the main bascule pier footing, an over 7-foot-deep slab housing the support machinery and moveable span.



Figure 12: Completed Cofferdam

ALTERNATE DELIVERY TYPE PROCUREMENTS

One reason an alternate cofferdam design was utilized on the Johnson Street Bridge project was the use of alternative-delivery by the owner. On Johnson Street, PCL was able to work with the bridge designers (Hardesty & Hanover, LLP) to fine-tune the bascule pier design to support a non-traditional cofferdam design. Because the delivery model for the Johnson Street Bridge was design-assist, PCL had access to the designers to fine-tune the design, but not as much control and access as a design-build delivery. Construction innovation thrives in alternative-delivery projects, as can be seen on Johnson Street Bridge.

Alternative delivery provides an additional advantage when constructing moveable bridges. The Johnson Street Bridge is permanently operated by large hydraulic motors driven by a custom designed and built hydraulic power unit. If properly planned and implemented at the start of the project, the permanent hydraulic power unit for a hydraulically driven bridge can be utilized to lower a cofferdam to construct the bridge's permanent foundation. Utilizing the permanent HPU to lower a cofferdam like that constructed on Johnson Street would allow the owner to save even more money.

CONCLUSION

There are several factors to consider when selecting the means and type of temporary structures used to construct large marine foundations, many of them site specific. The successful use of the modular cofferdam system on the Johnson Street Bridge demonstrated the effectiveness of float-in type cofferdam construction for pile-caps in water where the caps are located below water, but elevated off the bottom.

REFERENCES

1. Bridge rendering (Figure 1) – MMM Group, LTD.
2. Bittner, R.B.: Deep Marine Foundations – A Perspective on the Design and Construction of Deep Marine Foundations, Deep Foundation Institute, January 31, 2009, pp. 215-228
3. Bittner, R.B.: Float-In Installation Of A 6,000 Ton Cofferdam Over The Top Of 63 6-Ft Diameter Pipe Piles On The Port Mann Bridge, December, 2011