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DIRECTIONALLY DRILLED RAW WATER INTAKES, GRAND FORKS, NORTH DAKOTA

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ABSTRACT

The City of Grand Forks, North Dakota obtains drinking water from both the Red River and Red Lake River through a system of raw water intakes, shallow pipelines and pump stations. During flood events, the City often loses access to the system. In addition, the banks of the rivers are subject to land sliding, which can easily damage the shallow intakes. This proved particularly true during the record flood event in 1997, and resulted in the design of a new setback levee system by the U.S. Army Corps of Engineers. As a result, the City decided to construct a new gravity raw water intake system inland of the future levees. The design had to address the installation of pipe through soft and weak clay in a known landslide area to depths of up to 80 feet. Horizontal directional drilling (HDD) was chosen as the means of construction. Design issues associated with HDD included the potential for squeezing ground at the deepest sections of the alignment, the potential for hydraulic fracturing beneath the river bottom and at the exit points, river taps, penetrations though a large-diameter caisson pump station. Additional construction issues included bore accuracy and grade to handle design curves, control of squeezing ground at the caisson penetrations, and control of the bore annulus as a potential flow path for river water during construction.

INTRODUCTION

The City of Grand Forks, North Dakota lies in a broad ancient lakebed at the convergence of the Red Lake River and the Red River of the North. These two rivers supply the municipal drinking water system. In 1997, a record flood event occurred during the spring. The high river levels eventually flooded nearly three-fourths of the City and caused the evacuation of the entire community of 50,000 people. Previous floods had also plagued the system with contamination, damage to structures, and shutdowns. Damage resulting from the 1997 flood resulted in the design of a new setback levee system by the U.S. Army Corps of Engineers. This new levee system provided an opportunity for the City of Grand Forks to construct a new life-line water supply system that would be protected by the new levees, and be relatively immune from potential damage from winter ice, land sliding, and future floods. This paper describes the design issues and construction techniques used to successfully complete the intakes for the new water supply system.

CONCEPTUAL DESIGN

Hydraulic engineering along with long term operations and maintenance studies resulted in the selection of a gravity system using a centrally located underground pump station inside the future levees. Initially, intake pipes were intended to be two 30-inch-diameter by 2,350-foot-long pipes leading to the Red Lake River and two 30-inch-diameter by 1,200-foot long pipes leading to the Red River. The Red River intakes were changed during final design to one 36-inch diameter by 1,200-foot long pipe. The Red Lake River intakes remained unchanged. For successful gravity flow, the intake pipes needed to enter the pump station within 3 feet of El. 776.0 feet, an approximate depth of 56 feet below the ground surface. The river entry points approximately were El. 779 feet for the Red Lake River and 776 feet for the Red River of the North. Typical low flow river surface elevations were 798.5 feet for the Red Lake River and 796.7 feet for the Red River, which is 20 feet or more above the Pump Station intake elevation.

Preliminary design and operation constraints included:

- Gravity intakes to the pump station
- Pump Station location with little flexibility
- River tap locations within the river with relatively long distances from the pump station
- Construction in an urban environment
- Tight tolerances for the pipe entry locations into the pump station
- Right-of-Way restrictions requiring curved paths between the caisson and the river taps.

Subsurface information was available from the Corps of Engineers studies for the local levee design. Based on the available information, the project design had to address the installation of pipe through soft and weak clay in a known landslide area with slide plane depths of up to 80 feet. Horizontal directional drilling (HDD) was chosen as the desirable means of construction. Issues identified for the HDD process included:

- Potential squeezing ground along the deepest portions of the alignment,
- Potential for hydraulic fracturing beneath the river bottom and at the exit points,
- Method for river taps to prevent drill fluid from entering the rivers,
- Potential for river water to migrate along the bore path during and after construction,
- Penetrations through a large-diameter caisson pump station in an area of potentially squeezing ground
- Reasonable tracking methods and design bore accuracy and grade tolerances to handle design curves and depths.
- Potentially elevated corrosion conditions for unprotected metals placed in the clay soils.

SITE CHARACTERIZATION

Subsurface conditions play a major role in the design, construction, and cost of underground pipe construction as the majority of the project cost is in the underground construction method. Different than expected conditions all too often result in claims for additional cost or reduce system performance with resulting added long term cost to the owner. Understanding of subsurface conditions is very important in managing risk (i.e. project costs) associated with subsurface conditions. Therefore, the objective of a site characterization program is to cost effectively provide sufficient understanding of existing conditions to select an appropriate design and to contract construction at a fair and unchanging cost. It is incumbent upon the geotechnical engineer to balance the cost of the explorations and analyses against the potential construction costs associated with specific issues.

Approach

The site characterization program for this project was developed using a team approach and a phased program to develop data and appropriate analyses. The team included construction specialists. Periodic team meetings were held to discuss the impacts of the conditions on the project design and cost. Identified conditions that could significantly impact the project were subjected to additional data gathering and assessment for final design.

The first phase consisted of gathering available information including significant data from Shannon & Wilson work associated with the Corps of Engineers design studies for the new levy system. This information proved invaluable and resulted in the need for only one additional round of subsurface explorations to complete the design. The second phase consisted of drilling nine project-specific test borings along proposed alignments to obtain soil samples for laboratory testing. In addition to the borings, three cone penetrometer probes were pushed to assess in situ soil properties, and piezometers and inclinometers were installed to monitor groundwater elevations and slope stability.

Selected soil samples were subjected to laboratory testing for comparison with Corps of Engineers data. Analyses of the data provided soil properties that were used in the design of the bores. These properties are presented in a companion report presented at this conference for the caisson design and construction, and will not be duplicated in this report.

The following sections summarize the results of the subsurface characterization program.

Geologic Setting

The geology influencing the Red River Valley is the legacy of Glacial Lake Agassiz and recent fluvial/alluvial processes of the Red River and its tributaries. During the glacial period, a continental glacier covered the entire watershed of the present day Red River and Red Lake River. Periodically, as the glacial ice melted and retreated northward, huge ice dams were formed which blocked the natural northerly drainage pattern. Glacial Lake Agassiz, which covered approximately 200,000 square miles, resulted from the ice damming and subsequent ponding of melt waters. At its maximum extent, Lake Agassiz is believed to have been approximately 400 feet deep at Grand Forks, and over time was filled with layers of generally fine-grained sediments. Since the draining of the lake, the Red River and the Red Lake Rivers have meandered across the bottom of the old lakebed resulting in sediment filled oxbow channels. Some of the sediments in these old channels consist of relatively clean gravel that is saturated and provides a good source of local water supply.

Stratigraphy

The generalized stratigraphy along the bore routes consists of:

- 29 to 39 feet of Sherack Formation consisting of medium stiff to stiff, clayey silt/silty clay down to elevation 791 to 797 feet.
- 41 to 47 feet of Upper and Lower Brenna Formations consisting of very soft to soft clay to an elevation of about 750 feet. The Brenna Formation is uniform glaciolacustrine clay, with little or no visible structure. The major source of sediment for the Brenna Formation was eroded Pierre Shale bedrock. Slickensides are commonly observed in freshly broken samples. The Brenna Formation is notoriously unstable as a foundation material throughout the Red River Valley.
- 48 feet of Falconer Formation consisting of medium stiff, trace to slightly sandy and/or silty clay with a trace of gravel down to about elevation 702 feet.
- 10 feet of Wylie Formation consisting of medium stiff clay to elevation 692 feet.
- Red Lake Falls Formation consisting of dense, slightly silty and clayey sand and hard, silty, sandy clay till with varying percentages of gravel.

The thicknesses and geologic units encountered in the borings were similar to the regional geologic profile of the Grand Forks area, as presented on Fig. 1.

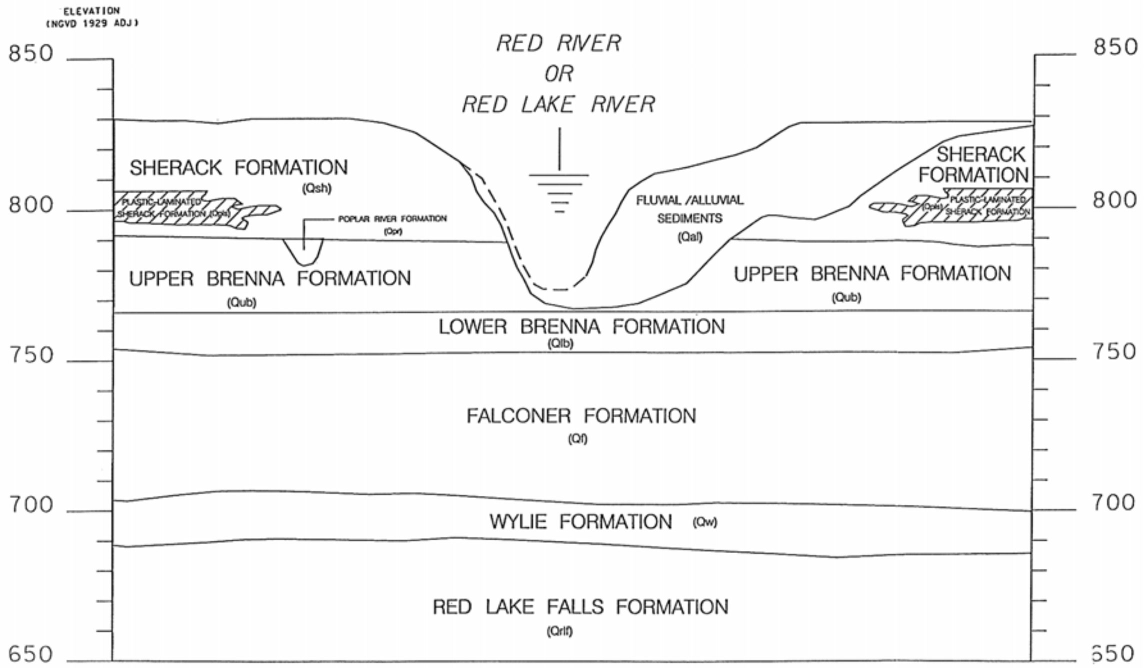

Fig. 1. Generalized Geologic Profile (after U.S. Army Corps of Engineers, 1998)

Groundwater and river water

Historically, the groundwater levels in the project vicinity have been difficult to determine, mainly due to the low permeability of the soils, but also because little instrumentation existed prior to the 1997 flood. As part of the U.S. Army Corps of Engineers (1998) levee design study, vibrating wire piezometers were installed along the riverbanks in 1998 and 1999. New piezometers were also installed as part of the exploration program for this project. Data collected from these instruments indicated that groundwater was present about 5 to 20 feet below the ground surface (approximately elevation 810 to 825 feet), and that groundwater levels near the river directly correspond to changes in the river level.

The rivers in this area are prone to flooding. The limited channel depth and relatively flat surrounding countryside results in a broad floodplain. Based on Corp of Engineers studies for the new levees, the design 210-year flood is elevation 836 feet.

DESIGN AND SITE ISSUES

Based on review of the first phase preliminary data and the design constraints, two potential construction techniques were selected for placing the intake pipes: horizontal directional drilling (HDD) and microtunneling. These two techniques require specialization not typically found in local contractors. To handle the potential corrosion problem, HDPE pipe for HDD or fiberglass microtunneling pipe were considered the desirable choices.

The second phase subsurface exploration and analyses program resulted in the following revised design and construction issues.

Common issues

- Construction required specialty service that few national contractors were qualified to perform.
- Separate contractors would likely construct the caisson and bores, so a construction sequence needed to be developed to control the overall construction.
- The pipe design depth needed to be below landslide influence zones or approximately 60 to 80 feet below the ground.
- The soil conditions and river water were corrosive to steel pipes that did not have positive corrosion protection.
- Variations in river elevations and frequent flooding influence construction, especially along the river floodplain.
- The riverbanks were susceptible to land sliding, thus pipe pathways should be located below the potential slide plane.
- Potential for deep water bearing gravel could impact ground stability
- The areas by the river were active sludge ponds so ground space was limited and restricted.
- Spoil disposal

Tunneling specific issues

- Length of drives was longer than commonly driven tunnels thus secondary tunneling shafts may be necessary, requiring additional property acquisition and permitting as well as presenting additional shafts and a tunnel subject to potential damage from flooding.
- Soft ground and shallow groundwater required the use of slurry or earth-pressure-balanced machine and a more sophisticated tunneling method.
- ROW required curvatures in the route. Tunnel machines, though they can make curves, are not efficient and it limits their drive length.
- River Tap with a tunnel machine would require a deep shaft in the river to recover the machine and to construct the intakes. These shafts add time and cost to the project, and could be subjected to damage during flood events.

HDD specific issues

- Hitting required targets precisely and accurately in caisson is very difficult for the HDD process.
- Squeezing ground applies full geostatic loads to the product pipe and HDPE pipe could not support the long term loads.
- Hydraulic fracturing by the drilling fluid resulting from soft ground conditions could result in drill fluid release into the rivers and onto the ground surface.
- River tap requires that the drill hit targets in the river, control drill fluids to prevent releases into the rivers, and prevent the river from running along the drill path into the caisson under both short term and long term conditions.
- Pipe installation stresses and long term ground loads impacted pipe selection.

DESIGN SOLUTIONS

The challenge was to develop a tender that would be legal under existing law, and still permit only qualified contractors to do the specialized work. The solution was to develop a two-phase bid process and to focus the design for HDD as a more cost-effective solution. The first step in the bidding was to prequalify potential HDD contractors based on their response to the design documents. The nature of the total project scope suggested that a general contractor be engaged for the actual project construction and that the HDD contractor subcontract to the general contractor. The second step was to solicit bids from general contractors who were provided a list of pre-approved HDD contractors. At this stage, microtunneling remained a construction alternative. However, all contractors selected to use HDD for the construction method.

Construction sequence

The next challenge was to develop a constructible design that controlled two contractors working in the same space while facilitating flexible contractor methods. The solution called for the owner to provide a possible construction sequence. Yet, the contractor was not held to using the proposed sequence, and was permitted to price alternatives for completing the project.

The design team developed the following construction sequence.

- Construct the caisson shell.
- Drill a pilot hole to and through the caisson to permit accurate and precise penetration of the caisson wall for the intake pipes. Drill the pilot from the land toward the intake, permitting the drill rod to be placed into a pre-cored exit hole centered on the required intake pipe penetration location.
- Set large diameter casing pipe in the caisson between the caisson penetrations for the pilot to prevent river water infiltration and to permit the application of sufficient slurry pressure to the soil to retard ground squeezing during drilling.
- Complete drilling the pilot hole.

- Set casing in river to prevent river water inflow along the drill path.
- Ream and pull the product pipe.
- Cut through caisson wall with the reamer.
- Remove the river casing.
- Grout the river penetration and caisson penetration area to prevent river and groundwater infiltration.
- Remove the casing in the caisson.
- Grout the annulus between the caisson and the product pipe to seal water and squeezing ground.
- Set the intake screens.
- Complete the pump station and ancillary piping.

Pipe design

Pipe design was impacted by the corrosion concerns and by the relatively high long term soil loads. Because of the corrosion concerns, it was desirable to use HDPE pipe.

The maximum strength of HDPE pipe available at the time was DR 11 in the sizes needed for the project. To reduce the probability of placing the pipe in a potential landslide influence zone, the pipe needed to be at least 60 to 80 feet deep. We analyzed the stability of the soil at this depth with the following equation used by caisson contractors for clay stability.

$$N_t = \frac{\sigma_{total} - \sigma_{slurry}}{s_u} \tag{1}$$

where: σ_{total} is the total in situ vertical pressure at the depth being assessed; σ_{slurry} is the drill slurry pressure or other fluid internal pressure in the hole; and s_u is the undrained shear strength of the soil. It is desirable to have N_t values of 6 or less to reduce the potential for ground squeeze. Based on the analyses, it was determined that the ground in the zone of the pipe path would likely squeeze around the installed pipe relatively quickly, resulting in the application of full geostatic load to the pipe. Buckling calculations for long term stability of HDPE pipe indicated that the pipe would likely buckle under the anticipated long term loads. Therefore, steel pipe was selected by design with corrosion coating both inside and outside and with cathodic protection.

Hydraulic Fracturing

Hydraulic fracturing of soil is the result of drill fluid pressure in the bore annulus that is greater than the total pressure of the soil and the soil strength. Hydraulic fracturing is an inherent problem with HDD installations and is a cause of environmental concerns when the drill fluid reaches the ground surface or releases into a water body.

Hydraulic fracturing can be a result of construction methods or soil and site conditions. For this project, the design team made the contractor responsible for their methods to insure that their method did not create drill fluid release to the ground surface and the owner took responsibility for determining a minimum depth of cover to reduce the chance of hydraulic fracturing under normal drilling conditions. Ground conditions that could create a potential for hydraulic fracturing along the bore path include inadequate ground cover and squeezing ground that could restrict the drill fluid return flow along the drill stems.

Adequate ground cover was assessed by calculating the total pressure of the ground and of the drill fluid pressure at a given depth using the following equation:

$$\text{F.S.} = \frac{\sigma_{total}}{P_{\text{drill fluid}} + P_{\text{dynamic}}} \tag{2}$$

where: σ_{total} is the total ground pressure at depth "D"; $P_{\text{drill fluid}}$ is the static pressure applied by the drill fluid at depth "D" calculated using a typical drill fluid return unit weight of 80 pounds per cubic foot; and P_{dynamic} is the dynamic pressure necessary to push the drill fluid up the hole. The dynamic pressure is a complex function and requires more research for realistic values. For our calculations, we used 0.3 pounds per square foot per foot of bore length, a value based on testing from oil field research. Note that the strength of the soil is possibly significant but was not included in the calculation to add some added factor of safety and because ground disturbance during construction may significantly alter the value. A minimum factor of safety (F.S.) of 1.0 is needed to provide sufficient ground cover to reduce the risk of hydraulic fracturing. Calculations indicated a minimum soil cover of 25 feet was needed.

Ground squeeze was assessed using the previously described caisson equation. Further calculations were completed to determine the minimum drill fluid pressure required having N_t=6 to provide a chance for a stable borehole thus an unrestricted annulus for drill fluid return. The required minimum drill fluid head at elevation 810 feet was calculated as necessary to reduce the chance for ground squeeze.

The results of the hydraulic fracturing analyses indicated that the driller would need to maintain a minimum fluid pressure in the bore equal to a static head at 810 feet to reduce ground squeeze and have a minimum soil cover of 25 feet to prevent hydraulic fracturing into the river. Since the caisson penetration was at elevation 776 feet, the contractor needed to have a method for applying pressure to the bore during drilling. The design solution for the ground squeeze was to construct a sealed casing crossing the caisson to allow drill fluid pressures higher than would be available from a head located at elevation 776 feet. The ground cover naturally reduces at entry and exit points and under crossings such as the river. The problem areas were the river taps where the drill needed to exit. The design solution was to drill the last pilot footage into the river without pumping drill fluid, then place a casing over the drill stem that extended the bore to the far river bank in the areas of the taps for the reaming process. This casing would extend approximately 60 feet into the riverbank along the bore path to provide ground reinforcement in a zone with less than 25 feet of soil cover. This solution would also prevent river water from flowing along the bore path during the reaming process.

Design constructability

The site contained soil and design issues that were atypical for HDD projects. To insure that the contractor accounted for these issues, the owner took responsibility for developing a potential construction method that the contractors could consider for the bid process. The owner's method addressed the design concerns, and the accompanying Shannon & Wilson, Inc. report described the details of the method and how the design method components addressed soil and construction issues. The contractor was not required to use the proposed method, however, discussion of different approaches were required in the documents to demonstrate how they handled the soil and construction issues. The following paragraphs summarize the proposed construction methods.

Working room is always a factor in the bore cost. Bores can be done in tight quarters but providing sufficient room during design can ease many problems. However, obtaining room in an urban environment with multiple property owners and in multiple states requires planning during the design. The final site layout, though not ideal, was sufficient for reasonable construction efforts.

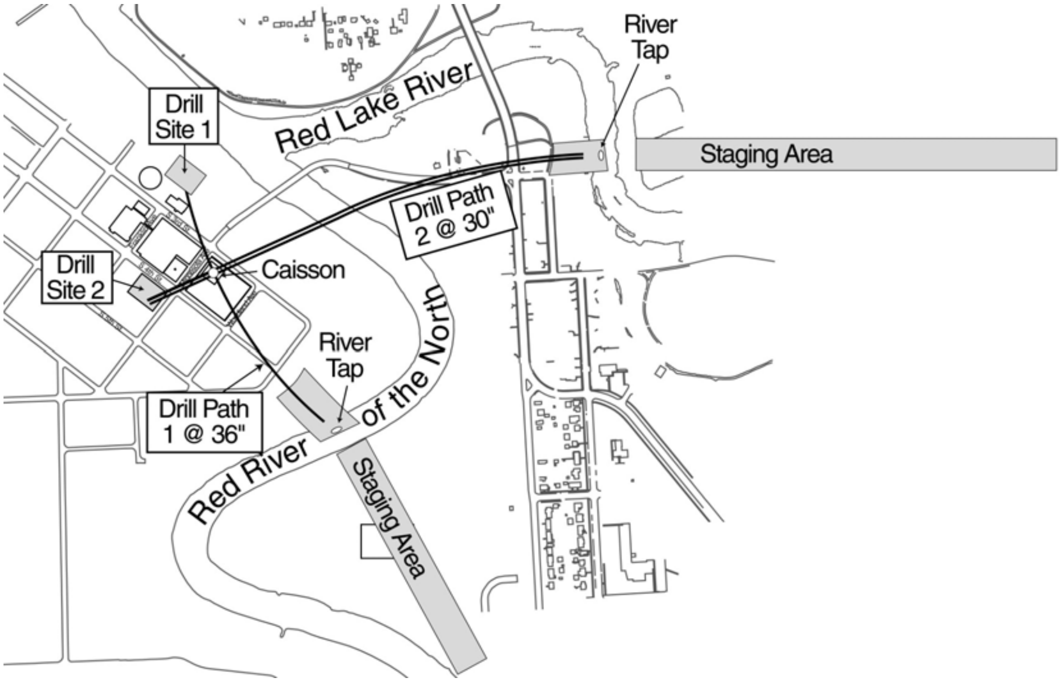

Fig. 2. Project configuration.

Precise and accurate pipe entry into the caisson was required to meet operational hydraulic and pump station constraints. The contractor was required to drill from the land toward the intake through the caisson. The caisson was predrilled at the design locations to permit HDD penetration. The drill rod would enter the non-critical side of the caisson and be carried across the caisson and placed into the predrilled pilot hole at the required location in the caisson for the pipe entry.

The soft ground anticipated along the bore was also present at the caisson penetrations. The clay could squeeze into the caisson at the HDD penetrations if not adequately supported. The design required stabilizing the ground with localized grouting prior to completing the penetration.

Reducing the potential for a long-term water path along the bore path into the caisson and under the new levy was necessary for the stability of the levee and to reduce leakage into the caisson. The design solution called for grouting at both ends of the bore after the product pipe was installed. Additionally, analyses of the soil indicated that over a relatively short time, the clay soil along the bore path would squeeze around the pipe and effectively seal the annulus against long term water migration from the river.

Potential for landslides to impact the pipe and intakes could occur in the areas of the intakes. The design solution was to select exit locations to reduce the probability for landslide activity, and to design a minimum depth for the bore path to be below anticipated slide planes. In addition, the use of steel pipe provided some factor of safety against potential tensile stresses that may develop in the pipe should ground movements occur.

Vertical and horizontal curves were required to stay within property limits, and the HDD approach was preferred. To track the progress of the pilot bore at the minimum design depths in an urban area, a wire line tracking technique was specified.

Slurry and spoil disposal can become a large cost to any project. The project owner took the responsibility for locating and procuring disposal rights at the local landfill, allowing the contractor to control the cost of the slurry disposal.

CONSTRUCTION

Michels Corporation was selected as HDD contractor, and elected to follow the owner's design construction sequence and outline methods. However, much was left to the contractor's ingenuity for developing the final construction method. The experience of this contractor paid off through their detailed planning and in the development of innovative solutions to design problems. While the main job of the contractor was to select the appropriate equipment and to develop the methods for fleshing out the construction approach, extensive flooding impacted the design and permitted work areas during construction. Thanks to the contractor's flexible approach, rapid redeployment of the pipe assembly area and removal of equipment during the flood events was handled in a professional and expeditious manner.

Fig. 3. Photo showing flooded staging area.

Construction of the caisson penetration had to be within a tight tolerance of the design location while controlling the stability of the soft soil and drill fluid and tool changes during drilling. The design called for a casing across the caisson to maintain fluid control and pressure for borehole stability during uphill drilling, and to permit an accurate penetration of the caisson wall. One hurdle was the difficulty in achieving this requirement in a caisson only 60 feet in diameter with 4 feet thick reinforced concrete walls. The design solution called for knockouts in the caisson. However, the driller still had to precisely hit the knockouts, so the contractor's solution was to drill a pilot hole with a small drill rig from inside the caisson to the target location, then place the casing and drill the remaining hole using a larger drill rig.

Fig. 4. Photo showing drilling pilot to drill rig.

Fig. 5. Photo showing large drill rig.

The contractor also had to address sealing the casing against the caisson, penetrating the caisson during both drilling and product pipe installation, tool removal and changing, and controlling unstable soils outside the caisson wall.

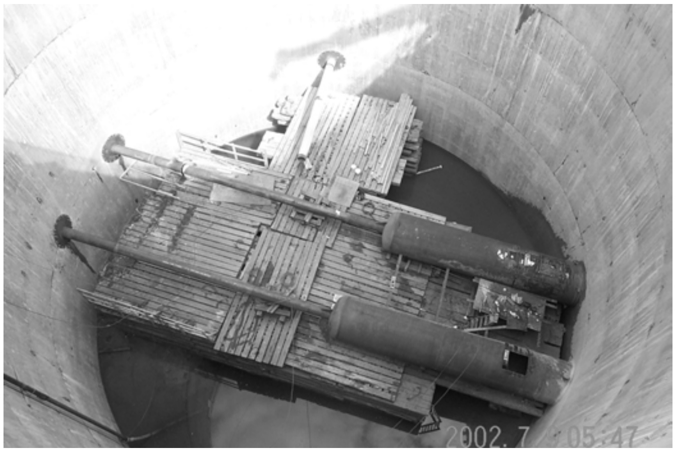

Fig. 6. Photo showing casings placed in caisson.

The contractor developed a pipe assembly and staging approach for the Red Lake River that required the pull to be over existing slurry ponds. In this case, the location of the river tap was fixed by existing facilities so moving the pipe staging area was not an option. The design exit angle was established to curve from the bottom of the river to take advantage of the bank for supporting the pipe, reducing the need for high supports during the pullback yet allowing a deep installation to avoid landslide issues. The contractor elected to use a series of floats to support the pipe during the pulling process.

Fig. 7. Photo showing pipe assembly.

Fig. 8. Photo showing float used to support pipe during pull.

The third contractor issue was sizing, fabrication, and installation of the river tap casing. The contractor elected to use a 60-inch diameter steel casing installed with a pipe ram.

Fig. 9. Photo showing 60-inch casing assembly.

Fig. 10. Photo showing 60-inch casing installation.

A fourth major construction issue was stabilization of the soft soil around the caisson during the caisson penetration, and establishing a grout seal after the pipe was installed. The contractor solved this problem with a compaction-grouting program performed by Denver Grouting. The compaction grout densified the soil and added concrete reinforcement support for the soil mass around the penetrations.

With all the planning, there were still plenty of construction problems that required field solutions. Here, contractor experience paid dividends. Examples included:

- Drilling obstructions located deep within the Red Lake River riverbank.
- Staging the Red River pipe assembly while preserving a historical site located in a critical area and identified after the start of construction.
- Demand for additional staging area and the Right-to-Occupy the area. They rented it from the City.
- Addressing the pull:

Fig. 11. Photo showing the Red Lake River Pull.

CONCLUSION

This successful project was the result of early involvement of construction specialists helping to ensure a constructible design. The presence of an innovative and open-minded design team, coupled with an open minded owner allowed for a variety of alternatives to be considered. A commitment to involving and educating the permitting agencies regarding the HDD process, and having an experienced solution-minded contractor fostered a solutions-oriented approach during the design process and throughout construction. This confluence of factors allowed this complicated project to be completed on time and within budget.

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