KGS GROUP

2023 CANADIAN CONSULTING ENGINEERING AWARDS

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is one of four earthfill block dams that contain the reservoir for the Caribou Falls

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The station and the dams were originally built in 1958 and have been operating reliably, only requiring routine maintenance and upgrades over the years. However approximately 60 years into its service life, Block Dam 2 sustained unexpected slope movements initiating the Caribou Falls Block Dam 2 Reconstruction Project.

OPG retained KGS Group to perform investigations, conceptual design through to detailed design and later to provide contract administration and dam performance monitoring for the construction and post-construction phases of reconstructing the dam. OPG awarded the construction contract to Peter Kiewit Sons Ltd. (Kiewit), and together, OPG, KGS Group and Kiewit (the team) executed construction of the project on a fast-tracked basis. OPG's vision was to protect the fragile environment and to find ways for the project to not only address the dam deficiency, but also benefit the local communities.

The project's complexity warranted the engagement of an experienced and diverse team of engineers, scientists, construction experts and technical support staff. The engineering expertise required for design and construction included geotechnical, geological, structural, hydraulics, hydrology and environmental disciplines. Overall direction was provided by senior-level project managers and expert technical advisors from all three parties.

Caribou Falls Generating Station

The unique and challenging geologic and groundwater conditions, confined work boundaries, strict environmental parameters and inherent risks of working on a damaged dam, drove our team to think outside of the box and identify innovative solutions while continually striving to deliver a quality product on budget and on schedule.

BACKGROUND

The Caribou Falls Generating Station (GS) has been producing clean, renewable hydroelectric power since 1958. The 92 MW station is located on the English River approximately 66 km northwest of Kenora and 13 km east of the Manitoba Border. Umfreville Lake makes up the station reservoir, and approximately 8 km downstream of the GS, flows from the English River merge with the Winnipeg River which continues onward into Manitoba. The region is densely forested with a rugged, hilly terrain that is generally controlled by shallow Precambrian granitic bedrock, shaped by ancient glacial processes. It's pristine, vast and beautiful with a rich history, encompassing several sacred sites of great importance to the WIN people, which can be seen along the winding road leading to Caribou Falls.

Containment of the reservoir depends on four earthfill block dams that span low spots in the terrain that would otherwise release the reservoir with flows circumventing the powerhouse and spillway structures. Block Dam 2 is located 1.3 km northwest of the GS on a narrow winding gravel road. It has an average height of 8 m and spans approximately 300 m between two bedrock abutments. It has an inflection at its midpoint, resembling the shape of a boomerang. Block Dam 2 was originally designed and constructed as a zoned rockfill dam with a clay core in the embankment and a clay blanket that extends 55 m upstream to help cut off foundation seepage.

In Ontario, the design, construction and operation of dams are regulated by the Ministry of Natural Resources and Forestry (MNRF). MNRF classifies dams according to the Hazard Potential Classification (HPC) system which is determined through an assessment of the consequences that could result from an inadvertent release of the reservoir. The HPC of a dam is used to set criteria for the design, operation and surveillance of a given structure. Block Dam 2 is assigned the highest HPC level of 'Extreme' and therefore warrants the strictest level of dam safety protocol.

After approximately 60 years since its original construction, significant movement suddenly and unexpectedly occurred on the slope of Block Dam 2. The upstream half of the crest dropped approximately 1.5 m in the eastern section of the dam, exposing internal fill materials and potentially compromising the integrity of the core beneath. For safety reasons, OPG lowered the headpond which resulted in lost power generation capacity. OPG immediately began an intensified surveillance and monitoring program. Investigations and studies to understand the root cause of the slump were initiated and remediation measures were explored.

INVESTIGATIONS: ROOT CAUSE OF SLOPE MOVEMENT

OPG carried out initial investigations to help characterize the site which confirmed that the foundation stratigraphy consisted of several soil types of varying thicknesses that were on top of an undulating and irregular bedrock surface. The eastern section of the dam was founded on a 9 m deep deposit of alluvial and fluvial soils consisting of soft silt and sand with dense cobbly gravel layers and sporadic boulders. The remainder of the dam was founded on a shallower layer of soft and weak lacustrine clay that varied from 1 to 4 m thick underlain by a thinner layer of fine silty sand overlying bedrock and all under a high groundwater table. The dam core and upstream impervious blanket were originally sourced locally and consisted of this same clay material.

The clay was naturally deposited by glacial Lake Agassiz approximately 10,000 years ago. Under close examination of test pit and borehole samples, the clay exhibited a unique physical property. Rather than having a soft, plastic texture, the clay here was blocky and crumbly, containing weakening fissures and gaps. An inadequate understanding of the strength and mechanical behavior of this altered type of clay was problematic and judged to be the root cause of several instabilities and failures of local structures in recent history.

Through review of original as-constructed documents and back-analysis using numerical slope stability modelling software, it became obvious that the slide must have occurred through the embankment clay core and the clay blanket. The precise root cause or event that triggered the upstream slide after almost 60 years remains unclear, and the stability of the rest of the dam was unknown. Given the high importance of maintaining the integrity of the dam, and not fully knowing why the slide occurred, OPG sanctioned the complete replacement of Block Dam 2.

Original Block Dam 2 after the slope movement

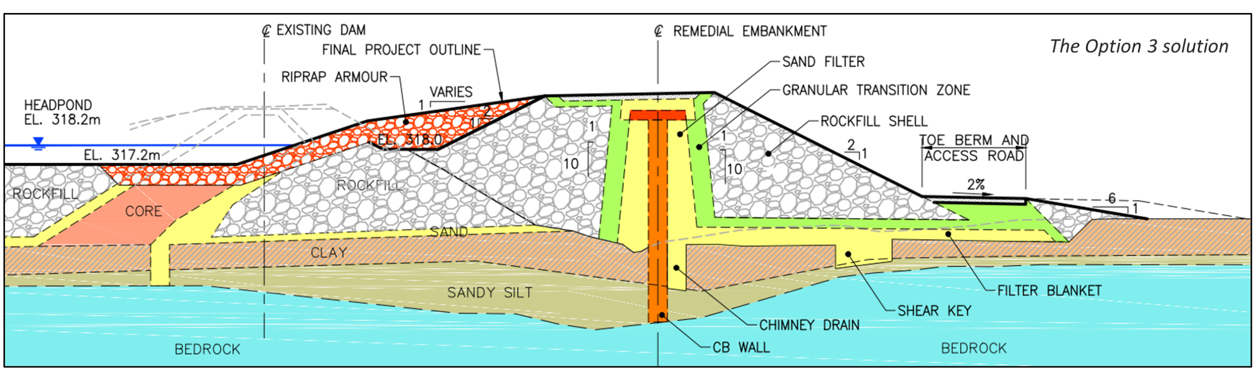
DEVELOPMENT AND EVALUATION OF RECONSTRUCTION OPTIONS

Reconstructing a very important dam that had sustained movement for unknown reasons is inherently risky. To manage these risks, OPG held review sessions with their dam safety expert panel throughout the entire design and construction process. The panel consisted of three internationally recognized dam specialist engineers that review high-risk design and construction projects for OPG. At quarterly intervals, KGS Group presented the progress of the design to the panel which gave them the opportunity to provide critical feedback, particularly pertaining to risk mitigation, design, analyses, monitoring and constructability. The input from the panel was directly incorporated at key stages of the project.

With support from the panel, KGS Group and OPG explored three concepts to reconstruct the dam. Option 1 involved buttressing the toe with fill to counterbalance the destabilizing forces that were driving the movement. It required fill placement from barges in considerable depths of water. Option 2 consisted of excavating and re-shaping the upper half of the dam, thereby reducing the destabilizing forces that were driving the movement, effectively flattening the upstream slope and expanding the embankment shell on the downstream side to compensate. A third option was developed that kept almost all the work on the downstream side of the original dam while maintaining it as the construction cofferdam. With Option 3, a new dam would be built to modern standards with no long-term reliance on the old dam and its potentially compromised core.

Option 3 consisted of a new zoned rockfill embankment dam with a central cement-bentonite cut-off wall (CB wall) extending 15 m in depth through the embankment and foundation to make positive contact with bedrock. The embankment was designed to be initially constructed with a central sand core, straddled by gravel transition zones, and an outer rockfill shell. KGS Group designed the CB wall core to be constructed once the embankment was built to near full height using a continuous slurry trench method. This is accomplished using a long-reach excavator to remove the sand and underlying foundation soils while cement-bentonite slurry is pumped in from a batch plant. This innovative method uses the hydrostatic pressure imposed by the liquid slurry to maintain the stability of the sand trench walls during construction. Once cured, the slurry-filled trench becomes the new water retaining core of the dam allowing the old dam to be removed and reshaped to address the slope instability.

KGS Group employed the Analytical Hierarchy Process (AHP) to evaluate each option under selected criteria including risk, constructability, environmental impact, schedule and cost. Rather than prescribing a “correct” decision, the AHP helps owners find one that best suits their goals and understanding of the problem. It provides a comprehensive and rational framework for structuring a decision-making problem: representing and quantifying its elements, relating those elements to overall goals and evaluating the options. Through this process, and with endorsement from the expert panel, Option 3 was selected.



The Option 3 solution

ADVANCED SITE INVESTIGATIONS

To proceed with Option 3, a better understanding of the site was necessary. Along with conventional borehole augering and testing, KGS Group employed several state-of-the-art geotechnical and geophysical exploration techniques including a seismic refraction survey and seismic cone penetrometer tests to best understand the subsurface conditions. The field program was complemented with advanced laboratory strength and consolidation testing to determine the engineering properties of the site soils.

Seismic Refraction Survey

Seismic refraction is performed using an array of geophone sensors positioned along a predefined section on the ground. An energy source, usually a blank shotgun cartridge, is used to deliver a shockwave which refracts shear and compression waves off distinct geological layers. The timing and velocity of the return waves is used to estimate the type and depth of soil and rock units. KGS Group worked with Frontier Geosciences, a specialist geophysical firm from Vancouver, BC, to carry out a seismic refraction survey at the site. The survey provided a continuous inferred profile of the bedrock surface along with estimations of the overburden soil types and thicknesses below the proposed new dam. The interpreted bedrock depth was calibrated against more accurate boreholes and bedrock core logs that were strategically drilled at select control locations.

The seismic cone penetrometer test with pore-water pressure measurement (SCPTu) involves a rig-mounted cone-shaped probe device that is continually advanced into overburden soils. The cone is equipped with stress/strain transducers that measure tip and sleeve resistance, providing a continuous log of soil type and correlated estimations of key engineering properties with depth. The special 'seismic' variation of this instrument also provides shear-wave velocity measurements used for earthquake analyses. The results obtained from SCPTu testing is relatively instantaneous requiring minimal time for post-processing and report delivery. Here, the SCPTu testing allowed KGS Group to quickly obtain many probes across the site providing a dense spatial array of foundation soil information in a relatively short timeframe. The data obtained from the SCPTu was then calibrated against control data obtained from representative undisturbed samples through conventional borehole drilling and more accurate and standardized laboratory testing.

Advanced Laboratory Testing

The foundation clay governed the stability of the new dam, therefore advanced laboratory strength and consolidation testing was conducted. Strength testing included direct shear, consolidated undrained triaxial testing and ring shear testing to obtain a comprehensive understanding of the clay strength and mechanical behaviour. Constant strain-rate oedometer testing was used to help determine the B-bar response of the clay. The B-bar is the proportion of excess porewater pressure buildup to surcharge loading. The B-bar response is a critical factor in the planning and staging of embankment fill operations during construction to avoid the sudden failure of new structures.

All of the data gathered from the investigations were compared against KGS Group's extensive database of laboratory testing and published literature of Lake Agassiz clays and other critical site soils. The comprehensive and advanced level of investigations were an essential investment to optimize the overall design and to manage the considerable construction-phase and long-term risks.

DETAILED DESIGN

KGS Group was tasked with designing the new dam to address safety criteria while building strategic elements into the design to facilitate constructability and allow the dam to be built within an aggressive schedule. First, the design team needed to identify potential failure modes, and then develop innovative solutions to address them.

The investigation program confirmed that the east area was governed by a deep layer of erodible silts and sands under high groundwater conditions. The risk of piping erosion, one of the leading causes of catastrophic dam breaches, needed to be carefully considered in this area. The grain size distribution and cohesionless nature of the soils in this area also made the proposed foundation vulnerable to liquefaction, which is the "quicking" effect of saturated silts and sands when subjected to vibration. During an earthquake, these soils temporarily behave as a liquid resulting in dramatic settlements and deformations of an overlying dam.

Elsewhere across the site, the foundation was dominated by Lake Agassiz clay. The investigation program confirmed the weak strength and the potential B-bar response of the clay which governed the design. The more pervious sandy silt layer that was "sandwiched" between the clay and the underlying bedrock could result in further strength reductions. Lastly, the design needed to address differential settlement to protect the slender and brittle CB wall core from undue stress and fracture.

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KGS Group designed the CB wall to address several aspects, but also to streamline the construction sequencing to meet an aggressive timeline. As a critical element of the new dam, the CB wall became the new hydraulic barrier to retain the reservoir. It was designed to do this within a confined footprint, allowing the new embankment to be built immediately against the downstream slope of the old dam to buttress and stabilize it first, before the new core was installed. Conventional open excavation and impervious backfill options to build a foundation cut off that close to the original dam would have risked undermining and destabilizing the slope.

Other conventional core and embankment materials, such as clay, often govern the critical path of a construction schedule due to the rigorous conditioning, placement and compaction activities that require ideal weather conditions. For a CB wall dam, the relative ease of first constructing a granular fill embankment followed by slurry trenching, that can occur in almost any weather condition, minimized the project's vulnerability to seasonal restrictions and weather-related delays. The design team further improved constructability and long-term performance by replacing 75% of the cement constituent of the slurry with granulated blast furnace slag (a by-product of steel production). This substitute delays the curing of the slurry, providing time to advance the slurry trenching operations sufficiently away from the setting slurry before it begins to harden, which could otherwise compromise the end-product through prolonged agitation during its change in state from liquid to solid. Slag also reduces the long-term permeability of the CB wall, versus just plain cement, improving its function as the core.

Earthquake Liquefaction Analysis

The region has a very low level of seismicity, however the dam's 'Extreme' Hazard Potential Classification by the MNRF warranted an earthquake assessment to confirm liquefaction potential. Ground improvement methods to densify liquefiable soils include vibroflotation and deep dynamic compaction which are expensive and require specialized contractors and equipment. Instead, KGS Group carried out a focused analysis using the SCPTu data obtained as part of the site investigations and optimized the new dam's geometry to resist potential earthquake induced instability. This illustrates the value of performing upfront geotechnical exploration to save a significant amount in construction costs.

Dam stability was addressed through innovative design elements including a 3 m wide foundation shear key, a toe berm, chimney drain and sand filter blanket. Shear keys are a slope stabilization tool pioneered in Manitoba and have been widely used by KGS Group locally and abroad. Here, a sand-filled shear key was strategically located beneath the embankment to intercept the most critical slip plane, providing additional strength to the foundation. The chimney drain, consisting of a filter engineered sand trench, was located through the clay foundation immediately downstream of the CB wall. Its function is to allow residual seepage under pressure, that might undercut the CB wall through bedrock fractures, to vent into the sand filter blanket and exit safely through the downstream toe drain system. With these mitigation measures, the design met the piping erosion and the stability criteria. met the piping erosion and the stability criteria even with the high B-bar response in the clay.

Once cured, cement-bentonite is considered a brittle material. Therefore, the design of the thin core needed to consider the effects of fracturing due to differential settlement potential along the new dam due to the variable thickness of the foundation soils. The CB wall was therefore designed to allow for strains to occur within the CB wall. The core was also designed to make positive contact with the underlying bedrock, not only to address foundation seepage, but to also provide a solid base to support the CB wall uniformly across its entire length. As an additional measure, the core was fully confined within a sand filter zone that was designed to protect the core from seepage erosion should a fracture inadvertently develop.

Design in a Digital 3D Environment

KGS Group modelled the new dam superimposed over a digital terrain model (DTM) of the original ground surface in a simulated 3D environment using Autodesk Civil 3D software. This tool enabled accurate material and resource estimates, fully automated and quick regeneration of the model and quantities for each design iteration. It also facilitated 3D renderings of the finished product for open house material to support consultation with the WIN community. To support construction, the model files were uploaded directly into Kiewit's GPS controlled equipment fleet for accurate and efficient implementation of the design.

With the design complete and a tender package ready, OPG shortlisted a pool of qualified contractors and invited bid submissions. The contract aggressively specified that execution of the project be substantially completed within one construction season.

3D rendering of the original dam

Project during construction

CONSTRUCTION

OPG engaged Kiewit to reconstruct the dam with KGS Group providing contract administration, full-time resident engineering oversight and dam safety monitoring. Several members of WIN were hired at the onset of construction to join Kiewit's forces and participate in this challenging project. The team transitioned into the construction phase in spring and quickly ramped up to continuous 24/7 operations that carried on through to the end of construction. Daily conference calls with the management level of all three parties along with close collaboration between field personnel and the designer were essential to address the many unforeseen construction hurdles as they happened. All parties worked together to ensure that quality measures were adhered to, and collectively monitored the continually evolving site to identify and address issues as early as possible to minimize schedule impacts. Many key decisions and design changes to address emergent site issues were made through spontaneously scheduled workshop-style team conferences.

Foundation Excavation and Challenging Bedrock Conditions

Once the environmental control measures were in place, Kiewit broke ground in the spring beginning with topsoil stripping and foundation grading followed by excavation and backfilling of the shear key and chimney drain trenches. The trenches and the old dam – two key stability components of the new structure – were immediately backfilled to maintain stability. The fragile clay sidewalls and the trench depth did not permit human entry to perform conventional mechanical compaction of the granular backfill. Kiewit implemented remotely operated compactors that were lowered into the excavation using the excavator boom which allowed for safe and efficient compaction.

Upon stripping the overburden and exposing the east abutment, it became clear to the team that the Precambrian granitic bedrock surface and jointing was more irregular and problematic than anticipated. This area was originally covered in coarse shot-rock which is impenetrable to seismic refraction surveys and impossible to drill through. The east abutment was highly irregular with sub-vertical faces and a 15 cm wide open fracture that could create a preferential seepage path through the abutment. The team reacted immediately to minimize impacts to the already tight schedule. Kiewit provided a topographic survey and digital surface superimposed over a georeferenced air photo taken from a drone that Kiewit had dedicated to the project. The data was expedited to KGS Group's design team who immediately prepared the required design change that optimized the dam alignment and narrowed the core detail to avoid the irregular surfaces. A customized grouting program was designed to infill the open fracture and make it watertight.

Bedrock at the east abutment

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The team worked behind the foundation and excavation operations to install a network of piezometer instruments within the foundation soils to closely monitor the pore-water pressure reaction to the approaching embankment fill operations (B-Bar response) and validate the design assumptions. During embankment fill operations, the piezometric data was compared twice per day against threshold limits to confirm that the capacity of the Lake Agassiz clay was not exceeded. The B-bar response determined at the design stage allowed Kiewit to confidently use innovative equipment and techniques to place the intricate earthfill zones efficiently.

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CB wall construction needed to happen around-the-clock as the slurry was progressively curing. To maximize the distance between the agitation created by the excavator and the hardening slurry to avoid permanent damage, the slurry trenching had to proceed on schedule. The geotechnical investigations revealed that dense cobbly granular layers with sporadic boulders existed in the eastern section. To avoid the risk of getting stuck in these coarse materials with a conventional excavator bucket, Kiewit reinforced its fleet with two 49-tonne long-reach excavators equipped with three interchangeable implements: 1) The multi-ripper bucket with a series of offset teeth attached to a narrow bucket that was used to tear through dense gravel and pluck out boulders; 2) The hoe-ram, resembling a large jackhammer, dynamically impacted and broke up solid rock; and 3) the hydraulic drum-cutter with two sets of rotating carbide teeth that was designed to “chew” through reinforced concrete. Once the dense layers were removed, a standard bucket was used for bulk slurry trenching to form the CB wall.

CB wall slurry trenching operations

Even with the diverse set of tools at the team’s disposal, the tough ground conditions in the east area pushed the two heavy machines to their maximum capacity. Equipment break-downs, dense cobble zones, and boulders up to 1 m in size made for some tense moments, as this was the team’s one chance to build this critical dam element through this area. After ten long and strenuous days and nights, Kiewit successfully made it through, and continued to complete the entire CB wall after three more weeks.

Crest Finalization, Impoundment and Dam Offloading

With the CB wall sufficiently cured, it was time to commission and impound the new dam while the earthworks crews finalized the crest. Water was pumped at a maximum specified rate between the new and old dams until the water level between the dams was level with the reservoir. At the same time, Kiewit deployed a turbidity curtain in the lake to contain the silt laden water within the confined in-water construction area. Biologists captured and live released the fish that were trapped on the construction side of the turbidity curtain. Once the water level was balanced, and the fish safely released, Kiewit began excavation and removal of the old dam. A second crew worked behind the offloading operations to place geotextile fabric underwater supported by a dive team, and then dress the upstream slope with riprap armour.

The project was substantially completed a month ahead of schedule allowing OPG to proceed with raising the reservoir back to its normal operating level and restore the generating capacity of the generating station. While Kiewit demobilized, KGS Group's role transitioned into monitoring and surveillance of the overall performance of the dam under load – which to date, has been performing within its intended design parameters.

CONCLUSION

The project was a first-of-its-kind for the team to design and build a solution to reconstruct a highly important dam that had sustained substantial slope movements for unknown reasons. The project offered exciting challenges and complexities to the diverse members of the team, who responded by implementing progressive engineering solutions and construction technologies. The application of advanced investigation techniques, along with innovative materials, in conjunction with expert risk-based engineering judgement enabled the team to develop a reliable yet economical solution that integrated constructability improvement and schedule saving strategies at the planning level.

The project provided employment and skilled trades development to local community members, and a field trip for local First Nation high school students. This was an opportunity for them to experience an active construction site and to inspire careers in engineering or construction. The majority of the rockfill and aggregate products were purchased from the local quarry owned by the WIN community. Additionally, while onsite, the team carried out mechanical and electrical upgrades to the remote WIN youth camp, helped the community to open a new quarry for commercial development and acquired a new Zamboni for the WIN hockey rink.

Despite unforeseen challenges and adversity, the team persevered using a "One Team" approach. As a result, the project was successfully completed under budget and ahead of schedule without any safety incidents. It also benefited the WIN community and restored public safety and generation capacity while preserving the natural surroundings in this wild and beautiful setting.

The finished dam